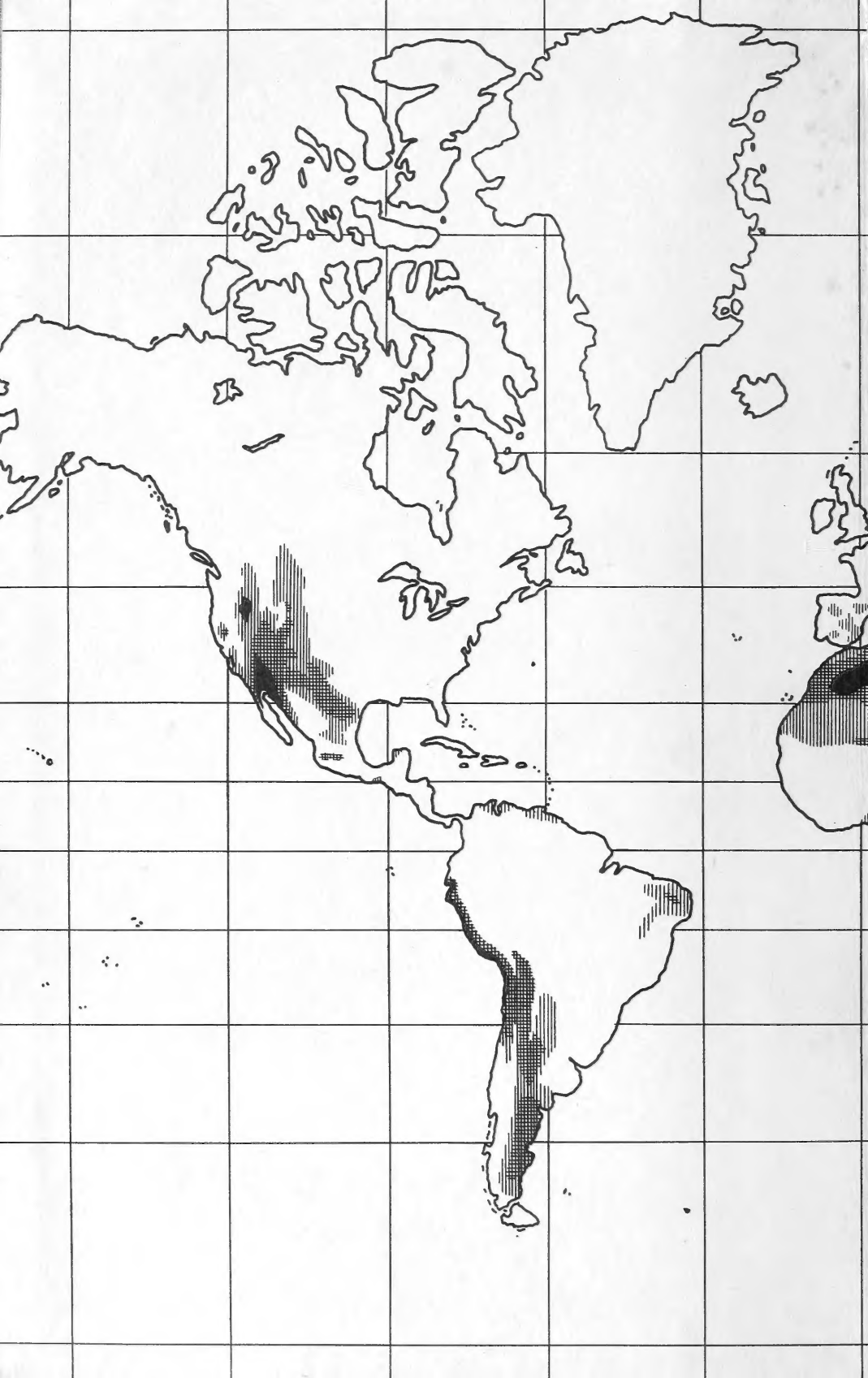


THE FUTURE
OF ARID LANDS







ARID LANDS

-  Extremely arid
-  Arid
-  Semiarid

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THE FUTURE OF ARID LANDS

Papers and Recommendations from
the International Arid Lands Meetings

Edited by GILBERT F. WHITE

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Preface

This volume sets down the efforts of scientists from 17 countries and from as many disciplines to assess the state of man's struggle to make productive and stable use of the world's arid lands. Areas of meager and undependable rainfall and of sparse vegetation commonly called "arid" account for roughly one-third of the land surface of the globe. Except where water is imported for irrigation, as down the Nile and Colorado rivers, most of that arid zone is sparsely settled and man lives in delicate adjustment to uncertain moisture and shallow soils. Unlike the other great land areas of low population density—the cold lands—the arid lands have been greatly affected by man's use and misuse, and the margins of grazing, cropping and non-agricultural activity are shifting, unstable frontiers of occupancy.

The future of that occupancy hinges in part upon success in maintaining the present resources base at present levels of living: range deterioration, water exhaustion, salt accumulation and accelerated erosion are among the hazards to permanent use. The future also hinges upon ingenuity in finding new and improved ways of increasing the usefulness of these great physical expanses: possibilities range from radical innovations in finding new water sources to patient application of principles known centuries ago.

The whole range of thinking is recorded here without attempting to reconcile differences of view or to fill obvious gaps. No single, clear answer emerges. Troublesome questions are identified and new avenues of attack are plotted. The individual papers and the group recommendations may be considered guideposts to scientific development in at least three ways. They mark a promising method of collaboration across both national and disciplinary boundaries. They point out specific areas of research in which more vigorous activity is needed. They suggest methods of thinking about the future that may play a significant role in shaping that future.

Several factors combined to bring together the scientists who took part in the International Arid Lands Meetings in New Mexico, April 26–May 4, 1955. A group within the Southwestern and Rocky Mountain Division of the AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE under the chairmanship of Peter Duisberg had felt that much could be learned from an international exchange of thinking on arid lands research problems. The national Association, interested in promoting the cooperation of scientific groups and also in bringing basic research needs to the attention of a wider public, lent its formal support and the able guidance of John Behnke to the enterprise. Under its broad program for fostering the development of arid lands the United Nations Educational, Scientific and Cultural Organization gave its strong backing and the weight of its experience in sponsoring other international explorations of this character in Israel, Turkey, France, and India. A program committee (listed elsewhere in this volume) was appointed by the Board of the Association to draw up plans for the meetings. It was decided to arrange a public symposium around a few key problems and to invite thinking without regard to traditional boundaries of academic fields. The chairmen were to offer summary statements at the conclusion of each session. At the same time it was felt important to provide for informal discussion among participants so as to make the most of possible exchange of ideas and experience among those who were at the forefront of their respective fields. Accordingly, a series of discussion groups were planned for the final day of the symposium, a two-day field trip was scheduled, and a conference was planned for a smaller group selected so as to represent the various countries and disciplines.

With this program in hand, financial aid was sought and obtained. The National Science Foundation, the Rockefeller Foundation, and UNESCO granted funds which made it possible to pay the expenses of some of the scientists who would not otherwise be able to attend, thus assuring a highly representative group. Substantial support was given by local business groups through a finance committee of the Division. The University of New Mexico generously served as host for the Symposium, and the New

Mexico Institute of Mining and Technology graciously entertained the Conference.

The program centered upon those areas of investigation where prediction of the future currently must be based upon insufficient understanding and data. The state of our knowledge and the need for new research are described in the Symposium papers as well as the Conference recommendations. They show the difficulty of judging the capacity of arid lands resources in the present state of knowledge but they also reveal certain ways of looking at the problem which bear heavy significance for the future.

The whole concept of the water budget provides a framework of thought in which much detailed analysis in climatology, hydrology, ecology, and geography begins to take on new importance.

Simple as it may appear, the concept of selecting, breeding, and improving plants and animals for arid conditions rather than concentrating upon adjusting the arid environment for plants and animals imported from humid areas opens out an enormous field for exploration.

When many disciplines join in viewing an old problem the traditional perspectives are challenged, and this is the case with views of priorities of water use in arid areas. The relative efficiency of various plant covers as water users, the proper allocations of water among upstream and downstream uses, and the importance of industrial in contrast to agricultural needs are among the priorities called into question. Radical revisions in public views of water priorities seem in prospect.

Two other trends in thinking about the future of arid lands showed strongly in the conference discussions. One was the emphasis placed upon integrated analysis of resources problems on a regional basis. In many instances the advantages were recognized of joining archaeological with hydrologic studies or of linking botanical with climatological and geomorphic studies. The trend is toward a cooperative approach to common problems. This does not necessarily mean full integration of basic surveys in the field but it does lead to a more nearly unified attack in such areas as the Upper Rio Grande basin.

Second, the natural scientists repeatedly emphasized the im-

portance of translating scientific findings into action at the level of operating farmers, herders, and land owners. This is a problem wherever science and technology advance in agricultural societies, but it has special relevancy to large-scale reduction in the zone's resources. Much of the deterioration of semi-arid lands now being used at low efficiency is due to such conditions as tenure, property rights, political control, social attitudes and taxes which impede application of new knowledge and techniques. The investigator of plant physiology or the geomorphologist sees his results gaining usefulness only to the extent that there are peaceful means of promoting social change toward accepted, wise ends. And this leads him to encourage research which will reveal the processes of decision in resource management or will point the way to public education.

Preparation of the proceedings for the printer has been greatly aided by Anne U. White. A separate report containing discussion on the final day of the Albuquerque Conference of "Problems of the Upper Rio Grande River" is to be published by local institutions cooperating through the Division's Committee on Desert and Arid Zone Research.

Although the papers from the Symposium and the recommendations from the Conference are printed in this volume, the more important scientific outcomes are not recorded. They are showing themselves and will continue to show themselves for years to come in the work of individual scientists who took part or have been influenced by the suggestions which emerged there. In this sense the Symposium was a point of departure rather than a summing up, and in this sense the future of the arid lands is in some part shaped by those who sought to assess its prospect in 1955.

GILBERT F. WHITE

Department of Geography
University of Chicago
May, 1956

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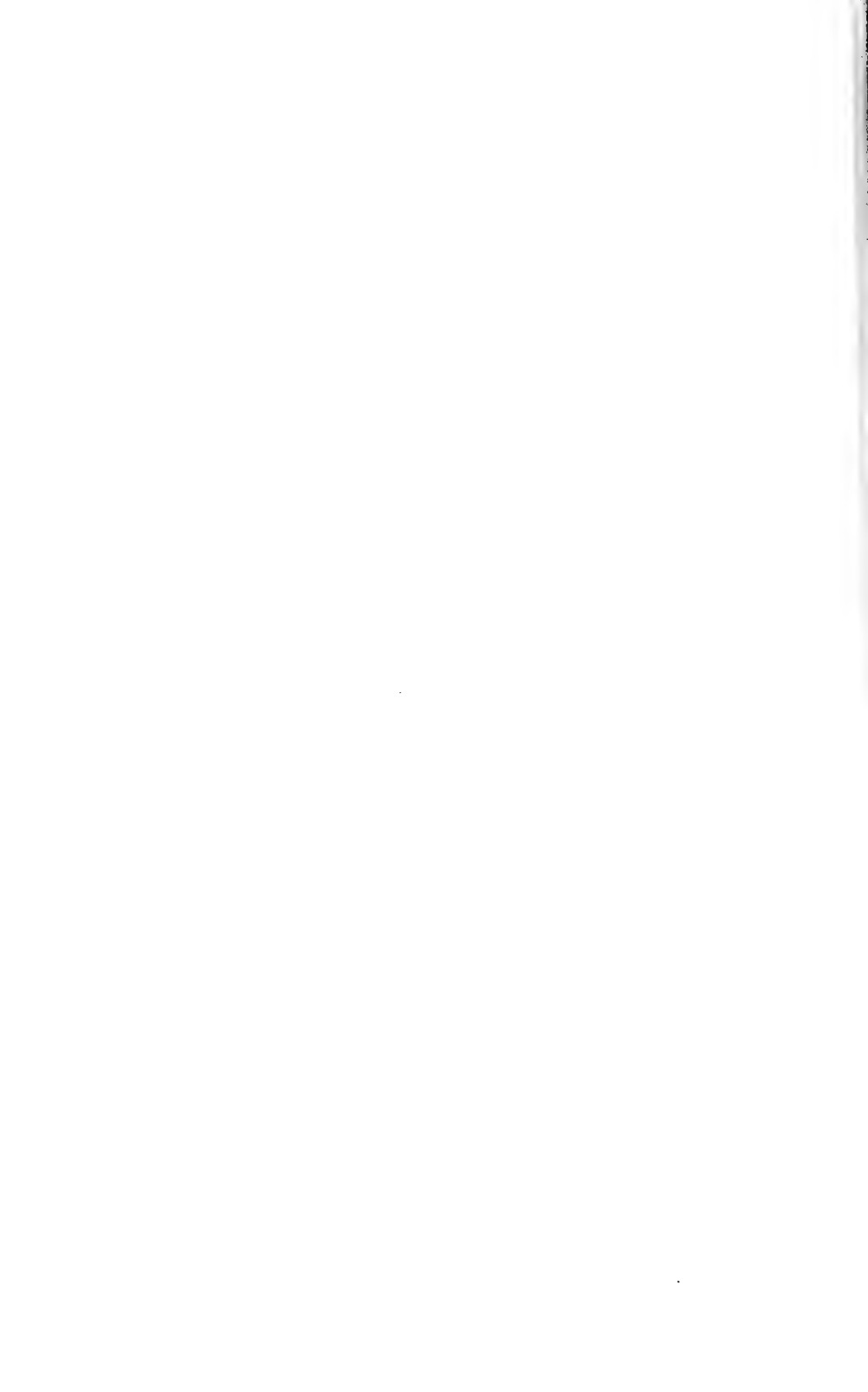
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The maps of arid homoclimates appearing in the end papers were drawn from maps prepared by Peveril Meigs for the UNESCO Arid Zone Program.



THE BROAD VIEW

What is the future of the arid lands?



History and Problems of Arid Lands Development

H. L. SHANTZ

Santa Barbara, California

Definition of the Arid Zone

The arid zone has not been precisely defined. Probably in no zone on the earth are there greater swings in precipitation, temperature, and aridity than in this zone. It is customary to characterize this area in terms of the minimum of precipitation and the maximum of heat and aridity. Rainfall in this zone is rare, localized, irregular, and often violent: precipitation in the more arid portions of the zone averages less than an inch a year, but more than the yearly average may fall in a single storm. The precipitation in the semi-arid parts may be as high as 30 or 40 inches a year, enough, if maintained, to move the area into the humid zone. The relative humidity in the extremely arid parts may drop to less than 5%. The highest air temperature on earth, 136° F, was recorded in 1922 in this zone at Aziza in Libya.

To define such a zone properly would probably not be possible, for if done the definition would be bound largely to a single factor of the environment. A definition based on climatic data would not be the same as one based on soils, on vegetation, on animal distribution, or on land use.

I would be inclined to include all the area from extremely arid to semi-arid in this belt. In this whole range the only safe assumption is that any year may be extremely arid. The more humid years will take care of themselves, but the more arid years set the pattern of use and must be anticipated and planned for if man is

TABLE I
Area of Arid Lands Based on Vegetation

Semi-arid		
Sclerophyll brushland	1,180,000	
Thorn forest	340,000	
Short grass	1,200,000	
Total semi-arid land	—	2,720,000
Arid		
Desert grass savanna	2,300,000	
Desert grass-desert shrub	10,600,000	
Total arid land	—	12,900,000
Extreme arid		
Desert	2,430,000	
Total extreme arid	—	2,430,000
Total		18,050,000
Percent	35	(Land area 15,970,000)

safely to utilize this area. Moreover, the methods of use best suited to arid lands are the safest means of utilizing the semi-arid lands.

The area of the arid lands may be estimated on the basis of vegetation, of climate, of soils, and by the area of interior drainage.

Estimates based on *vegetation*, expressed in square miles, are given in Table I.

The arid zone is designated sharply by vegetation. All plants are adjusted to drought conditions, are either xerophytes or the short-lived annuals. There are long rest periods during which there is little or no growth. The open plant cover with much of the soil surface bare is a characteristic of arid zone vegetation. However, drought rest periods are characteristic of many of the grasslands and monsoon forests beyond the boundary of the arid zone. Much of the tall grass or prairie and the tall grass and high grass savannas in the tropics have drought rest periods late in the season which stop growth and prepare these areas for the characteristic fires which sweep over them. However, drought is not the chief characteristic, and the plants are not xerophytes but are mesophytes.

The extreme arid, the arid, and the semi-arid *climates* of the earth have been mapped by Meigs (11), using the method developed by Thornthwaite (18). These estimates, expressed in square miles, have been supplied by Dr. Meigs and are shown in Table 2.

TABLE 2
Area of Arid Lands Based on Climate

Semi-arid		8,202,000
Arid		8,418,000
Extreme arid		2,244,000
Total		18,864,000
Percent	36	(Land area 51,970,000)

Drought due to lack of moisture is characteristic of the arid zone. There are areas at high elevations and at high latitudes with low precipitation where drought is not a characteristic. High temperatures are generally characteristic of the arid zone but they are not limited to this zone. The extremely high temperatures in the arid zone are largely due to the absence of water for evaporation or transpiration to cool the air. In the arid zone there is often a marked inverse ratio between evaporation rate as measured and the actual loss of water from the region. In an area with no water to transpire or evaporate the measurements of loss from a water surface or a wet bulb or any other measurement of dew point will be very high although no water may be lost from the land. Absence of precipitation has no damaging effect on vegetation if the soil has a supply of available moisture. This is evident in any irrigated region where drought can occur only when the source of irrigation water is cut off.

The vegetation cover is a measure of aridity, but here also there are difficulties in application. An example will serve to illustrate this difficulty and to emphasize the danger of assuming that measurements based on a single species can be applied to all plants, as is so generally done. The open sand blowouts in eastern Colorado were being invaded and partly held down in 1915 by *Redfieldia flexuosa*, *Psoralea lanceolata*, and the *Andropogons gerardii*, *hallii*, and *scoparius*, and an occasional plant of *Muhlenbergia pungens*. During the dry hot years of the thirties these plants were killed out, with the exception of the *Muhlenbergia*. One would have expected the open sand areas to be greatly extended, but just the opposite occurred for the sand areas were rapidly covered by *Muhlenbergia pungens*, a grass more at home on the hot arid sands of Arizona and New Mexico and before the hot dry years only occasionally present in eastern Colorado. Had the measurement of the years been made on the basis of the amount of

sand covered by vegetation, the conclusion might well have been reached that 1937 was a less arid year than 1915.

On the basis of *soils* about 43% of the land area of the earth is estimated to be of pedocals. These soils have dry subsoils. The moisture received at the surface hangs like a blanket above the dry subsoil. Moisture will pass down into the dry soil only if the water content of the surface soil has been raised above the field carrying capacity. This soil moisture is lost to the air by two methods. (1) Soil moisture in the first few inches can be evaporated into the air, but moisture does not move up by capillarity to take the place of the water lost, and the dry soil, be it of dust or of hard soil, protects the moisture below. (2) If there are any growing plants on this soil they absorb the soil moisture in contact with the roots and pass it out into the air by transpiration.

The soluble carbonates are carried down by the percolating soil moisture but they are not returned to the surface and gradually accumulate at the bottom of the moist layer. This carbonate layer marks the depth to which the soil is generally moistened by the precipitation. In much of the more arid region the carbonates are present in the surface soil, but the layer on the more humid side of the chernozems may be 3 feet below the surface. Three feet of soil would hold enough soil moisture to produce a luxuriant grass cover and such an area would not be called arid or semi-arid. These pedocals are not leached and are usually productive. The plant growth is generally terminated by drought and the dry vegetation is often burned off by fires started by man or by lightning. Lightning fires have repeatedly been observed in the short grass in eastern Colorado. Fire is also a characteristic of the sclerophyll brushland of the Mediterranean type where the hot and the dry periods come together and rainfall is confined to the cool period of the year.

A world map of *interior drainage* has been drawn by de Martonne and Larfrère (9) which outlines very clearly the arid zone as discussed above if we eliminate such areas as the upper Volga and the upper Shari which although they do not drain into the ocean come from relatively humid areas. The pedocal soils also extend beyond the arid zone.

The estimated area of arid land is 43% if based on pedocals, 36% if based on climate, and 35% if based on the natural vegetation, and about the same area is marked by interior drainage. Here then is an area of about one third of the land area of the earth in which moisture is the chief limiting factor in the production of plant growth and the dependent animal and human populations.

Plant Adjustments to Arid Conditions

Since both plant life and animal life originated in an aquatic environment great adjustments were necessary to enable them to survive in the air and still greater adjustments to enable them to live in the arid zone.

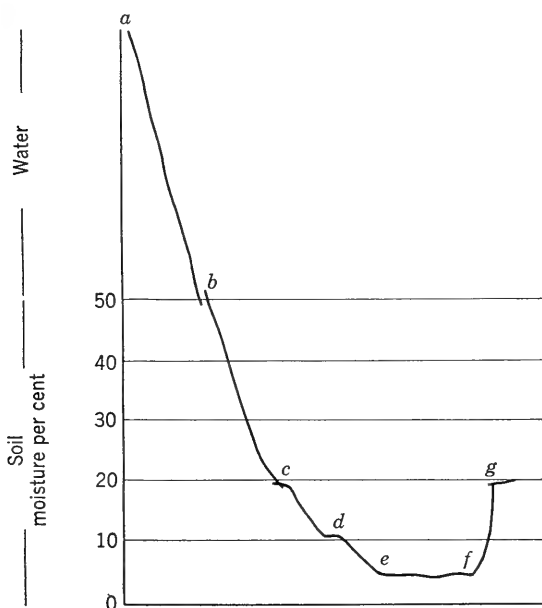


Figure 1. To illustrate relation of hydrophytes, mesophytes, and xerophytes to moisture supply in a loam soil: hydrophytes *a* to *c*; mesophytes and xerophytes *c* to *d*. Mesophytes die below *d* and xerophytes become dormant. Soil under desert drought sinks to about 5% or *e*. Rainfall at *f* raises water content to about field carrying capacity, 19.6% at *g*.

The adaptive features by which plants were able to move from a hydrophytic environment to a mesophytic and then to a xerophytic environment have been studied for many years (10). Still there is much misunderstanding with respect to these adjustments. Plants are separated on a very broad basis into hydrophytes, water plants, mesophytes, moist soil plants, and xerophytes plants characteristic of drought regions and which many people still think can grow in dry soil. These groups are not sharply separated and merge into each other, but they serve as most convenient groups in discussing the many adjustments. These groups are found under all climates, and their presence is determined by the condition of the substratum.

To make this clear a simple diagram is used (Figure 1). A loam soil is chosen to illustrate the relationships of the moisture retaining power of the soil. If the soil chosen were sand the values would still have the same definite relation, but the values would be lower and if a heavier soil were chosen the values would be higher. In order to simplify the graph only a few of the laboratory and field determinations of the moisture holding capacity are entered here.

In Figure 1:

Dry soil is at	0% (based on dry weight)
Desert dry soil under desert vegetation	5% (16)
Hygroscopic coefficient	6.8% (5)
Wilting coefficient	10% (2)
Field carrying capacity	19.6% (3)
Moisture holding capacity	50% (6)
Saturated soil	50%
Water table at	50%

In free water from *a* to *b* on the graph we would find floating, submerged, and amphibious hydrophytes. In soil conditions between *b* and *c* only hydrophytes would grow. Most of these hydrophytes would continue alive and grow if the soil moisture were lowered from *c* to *d* but would die below this point. At water contents between *c* and *d* mesophytes and xerophytes would grow, but below *d* the mesophytes would die and the xerophytes become semi-dormant or dormant. The soil moisture below *d* would be slowly absorbed and lost to the air and reduced slowly to about

one-half the moisture content at the wilting coefficient, or to about 5%, somewhat less than Heinrich's hygroscopic coefficient. During this period growth is suspended and the plant is in a semi-active or inactive condition often called estivation. Xerophytes have no more ability to grow in dry soil than mesophytes or hydrophytes with finely divided root systems such as rice.

When rain falls, the soil moisture rises from 5%, or even less at the soil surface, to 19.6%, or the field carrying capacity. No higher percentage can be added and no lower percentage if the soil is not confined and there is free contact with dryer soil below. Two inches of absorbed rainfall as compared with 1 inch moistens twice as much soil but does not increase the moisture in percentage of the dry weight of the soil. On the diagram growth begins again at *g*.

Hydrophytes cannot grow in the mesophytic and xerophytic habitat because of lack of abundant water, and mesophytes and xerophytes cannot grow in a hydrophytic habitat because of a lack of oxygen since they are adjusted to live only in the presence of air in the soil and around their stems and leaves. A liter of water at 20° C can contain the same amount of CO₂ as a liter of air at the same temperature but only 1/65 as much oxygen. In hydrophytes the major problem is to secure oxygen, and mesophytes and xerophytes cannot do this in a hydrophytic environment. Xerophytes have the principal problem of not succumbing to desiccation and are especially adjusted to prevent harmful desiccation. Mesophytes are not adjusted to hydrophytic or to xerophytic conditions.

In measurements of the water economy of mesophytes in containers, one of the difficulties is to maintain the water content in the container at the proper percentage range, that is, never below the wilting point and never above the field carrying capacity. When water is added to a container the water is raised to field carrying capacity, and if the proper amount of water is added, practically all the soil mass is moistened to this point. If half enough water is added half the soil remains dry. If more water is added swamp conditions are produced and none will drain out until complete saturation is reached. The plants will probably

suffer or die because of lack of oxygen. If they are watered from below, saturated soil or a water table is established at the bottom of the container. Therefore all experimental containers a few feet deep in which the experimenter expects the excess of rainfall or irrigation water to drain out will find only hydrophytic or swamp conditions which do not even approximate field conditions.

Let us consider some of the many adjustments xerophytes have made to enable them to survive and to grow in the arid lands. They must be able to grow under the following conditions. The climate varies from semi-arid to extremely arid. The relative humidity is often as low as 5 to 35%. The evaporation rate is high. The soils are pedocals moistened only at the surface and with a permanently dry sub-soil.

The *roots* of these plants are extensive but limited to the soil moistened by the precipitation. The root surface is large as compared with the aerial plant and root hairs are abundant.

The *stems* are small, often with deciduous leaves or none. Cladophylls or bracts or stems often function as leaves. The branches are often crowded together or are underground for protection.

The *leaves* are generally thick, small, firm, and leathery (sclerophyllous); they do not wilt but endure drought and recover when water is again available. Leaves are often deciduous.

The internal structures also show many adjustments.

The *roots* of xerophytes often have cork or sand sheaths near the soil surface.

The *stems* have cork or thick cuticular coverings. The stems often function as leaves, especially when leaves are absent, and have several layers of palisade tissue. The stomata are sunken or protected.

The *leaves*, if present, have the leaf lamina reduced or absent and the cells and stomata are small. They are sclerophyllous with much supporting tissue, do not wilt, but often roll or fold to protect the stomatal areas. The outer epidermal walls have thick cuticles with waxy or resinous coating. The stomata are sunken and protected. The epidermis often has woolly, scaly, or stellate hairs filled with air to reflect light. The leaves have several layers

of palisade tissue and small intercellular spaces. The spongy tissue is reduced.

The *drought-resistant succulents* show the same structures for preventing water loss but also have impounded water in roots, stem, or leaf, or all of these, and are able to continue growth when no water is available in the soil. They rapidly absorb water from summer showers, have an extensive superficial root system, are often globular or columnar, and have a large volume as compared with the surface. They resist drought by impounding water in the plant body.

The physiological adjustments are equally striking. Unlike the mesophytes, the leaf cells of xerophytes do not wilt when they lose water. The leaves are either dropped or, if they remain on the stem, they may lose as much as 40 to 80% of their water and still recover when water is again available. The reason for this recovery is that, unlike the mesophytes, the dehydration does not cause coagulation of the protoplasm or rupture of the protoplast to produce permanent and irreversible harm. A possible explanation of this condition is found in the high osmotic pressure of from 20 to 75 atmospheres and possibly the effect of hydrophylic colloids and sugars on the protoplast.

The ecological means by which plants meet drought conditions and grow in regions where droughts occur are of four types (8).

1. *Drought escaping* plants grow only where or when there is no drought. Here belong the summer and winter annuals of our Southwest such as the six-week grasses and the "ashab" of the Sahara. They usually grow under mesophytic conditions and except in the seed ripening and seed condition, do not encounter drought. They live through the hot, dry, drought period in the seed stage, a dormant stage similar to estivation.

2. *Drought evading* plants are plants economical in the use of the limited soil moisture supply. This is accomplished by wide spacing, by keeping the plants small with a small leaf surface and a small amount of annual growth. The root systems are proportionally very large. These plants are often very efficient in the use of water. Under like conditions plants may require as much as from 300 pounds to 2200 pounds of water to produce 1 pound of dry

matter—a variation of more than seven times (17). This range for different plants is about the same as the difference measured between the same plant grown in a semi-arid and an extremely arid climate. The grain crops grown most successfully in the arid zone are of this group. They have a short season, rapid growth, large grain yield in proportion to the straw, and a low water requirement.

3. The term *drought resistance* can be reserved for the succulents, which impound water within their plant body and are able to continue growth when soil moisture is entirely unavailable. They are admirably adjusted to absorb soil moisture rapidly as soon as it is available in light showers and to store it in their bodies. They are not characteristic of the extreme deserts.

4. *Drought enduring* plants estivate when drought occurs and they can resume growth as soon as water is again available. In other words, they become drought dormant. They also possess most of the characteristics of the drought evading plants by which they are enabled to prolong the growth period. The most important and prominent desert plants belong to this group. When soil moisture is no longer available, these drought enduring plants become drought dormant or estivate in the vegetative stage, while the drought escaping plants pass through the drought only in the seed stage. Many bacteria, fungi, algae, lichens, mosses, and ferns are able to endure drought.

Great adjustments are made by plants to enable them to grow in the arid lands. Great as are the physiological adjustments they are small compared with the variation in size shown by the drought escaping plants which will still ripen seeds when less than one thousandth of normal size.

Animal Adjustments to Arid Conditions

Animals show as great adjustments as plants do to enable them to survive in the arid lands (15). They too developed in water and they had to develop lungs or tracheal systems in order to secure oxygen from the air. They must also have a constant supply of water for their active growth. One of the important reasons why animals can live in the arid zone is found in their

ability to move about. Birds, insects, and large and fleet mammals can occupy arid lands if there is a water supply within their range. Smaller mammals and reptiles are more dependent on local conditions and have shown great adjustments to arid conditions. We may consider these adjustments under the same classification used in discussing the plants.

1. *Drought escaping* animals are those that avoid drought areas and are not found permanently in or dependent on the arid lands. One may include here animals that enter the arid region only when an adequate supply of moisture is available either as water or lush vegetation, or that can move to the water supply. By far the greatest number of drought escaping animals found in arid areas belong to the insects and the lower groups of the invertebrates. Many of these animals are able to complete their life history or the active part of it during the short period when conditions are favorable. Here belong most of the insects that abound on the summer and winter annuals. These forms pass the drought period as drought enduring eggs or larvae and resume their active life only at the end of the drought period. One might include all animals of the humid zone and in water habitat as drought escaping for they are not found in drought areas.

2. *Drought evading* animals show many adjustments even more striking than those shown by plants. The ability of animals to move has enabled them to burrow into the soil and thus live in an environment much more favorable during the day and confine their activity to the night and early morning when the conditions are not extremely arid. Partly as a result of this ability some of the rodents do not need to provide water for temperature control except in extreme cases. K. and B. Schmidt-Nielsen in their excellent summary have listed about a dozen genera of rodents from widely separated deserts which do not expend water for heat regulation (15). This is a significant example of the development of the same adjustment in widely separated areas by animals not closely related phylogenetically. They show certain gross morphological similarities. They all are leaping animals with elongated hind legs and small front legs, with reduced number of toes, and they have cheek or gular pouches.

3. *Drought resistance* in animals is different from drought resistance in plants in which large quantities of water are impounded within the plant body and growth is continued when no other water is available. Although animals resist drought differently the term drought resistance can still be used since normal activities are maintained. Dr. Schmidt-Nielsen's studies of the camel and the donkey in Algeria will do much to explain the physiological processes by which these animals are able to resist desert conditions. (See pp. 370-380). He has found no reason to agree with the common idea that the camel carries in pouches in his stomach a reserve of water to be used when no drinking water is available. Drought resistance in animals rests upon the physiological processes by which animals are able to concentrate the urine, stop perspiration, lose little water in the feces, endure dehydration, and still remain active.

The methods by which the kangaroo rat, jaroba, and some other animals avoid loss of water is by voiding nearly dry feces and concentrating the urea in the urine to as high as 23%. Some birds and reptiles can void urea and nitrates in solid form. Extensive studies of the kidney functions of these animals have been made and are under way to try to determine the exact means by which such concentration is accomplished. This ability might well be a deciding factor in enabling some animals to escape death by drought in an arid desert.

Drought resistance in animals has been accomplished in some groups not by impounding water but by the physiological process of developing metabolic water (II). Dry fat when oxidized produces 1.1 grams of water from each gram of fat. A gram of starch or sugar produces 0.6 gram, and a gram of protein 0.3 gram of water. The water formed by the oxidation of the hydrogen in dry food can be used to carry on the life functions. Protein has a great disadvantage as a source of water for it requires the loss of much water to remove the urea that is formed.

A great amount of work has been done on the kangaroo rat to determine the water balance under desert conditions (7 and 14). These animals can be kept on dry pearled barley almost indefinitely without any other food or water if the relative humidity

is not lower than 10%. They do not store water when abundantly supplied and do not lose weight on dry feed. They do not lose water to control temperature under normal conditions. When fed only on dry protein, dehydration resulted in a reduction to 67.2% of normal weight, or the animals lost nearly a third of their weight and died shortly afterward. But they are not forced to endure desiccation when feeding on a desert dry food supply of grasses and seeds. The kangaroo rat, pocket mice, and jarobas can maintain balance on a dry diet and thus resist dehydration. Babcock in his important work (1) on metabolic water in 1912 discussed its role in insects that feed on dry plant and animal material, for many are able to oxidize the hydrogen of their foods to obtain enough water for their normal life processes.

4. In the field of *drought enduring* we have the least physiological details, and yet we know that many rodents that do not develop metabolic water pass into an inactive state called estivation in summer from which they can recover when the hot dry period ends. There are many invertebrates that can be desiccated and recover quickly when water is again available. Many cases could be cited. Among the mammals the round-tailed ground squirrels and pocket gophers estivate during the hot dry periods, but apparently they do not suffer a very marked desiccation. They reduce the rate of respiration and heart beat and assume the temperature of the air around them and are inactive. This summer sleep or estivation still offers a most promising field of physiological investigation.

Primitive Man

Primitive man made remarkable progress in the use of the arid lands. In the field of animal husbandry he domesticated all of our animals with the possible exception of the turkey (13). His use of arid lands was made possible partly by grazing these lands with cattle, camels, goats, sheep, asses, and horses. Sauer traced the origins and dispersals of not only the domesticated animals but also many of the cultivated crops. Excepting the grazing animals and seed crops, most of the crops and domestic animals have developed in the humid rather than the arid zone. However, the

great nutritive value of the semi-arid and arid vegetation has attracted stockmen to these areas and probably from the beginning of man's use has had a part in pushing back the vegetation which had by tremendous adjustments established itself in this arid area.

In the field of crop production most of the plants used by primitive man were dependent on well-watered land. He brought into cultivation all the principal crops now used. At the edge of the arid zone he showed marked ingenuity in the profitable use of arid land for the production of seed crops. In the Sahara and other Asian and African desert areas he made great use of the "ashab" or temporary growth of lush weedy drought escaping plants. He also seeded short-lived barley, a very well-adapted plant, to produce a catch crop following a temporary summer rain. Every advantage was taken of flood water. Sorghum was planted close to the receding water edge and the planting was continued until the water had disappeared. This resulted in a field in which the plants were younger toward the center of the area.

In the Southwest of the United States the Pimas relied chiefly upon flood water and irrigation to produce their crops. They also made great use of wild plants. These include about 22 varieties of plants of which they used stems, leaves, or flowers, 4 that furnish bulbs, 24 seeds or nuts, and 15 fruits or berries. This may indicate why primitive man so far excelled modern man in the domestication of plants and animals. Mesquite beans were collected and the fruit of the saguaro was made into dried sweetmeats, jams, and jellies. All suitable fruits of cacti were used. The fields were prepared and planted to cotton, maize, squash, watermelons, beans, and devils claw. The Papagoes practiced dry farming with or without flood water. Maize, wheat, barley, beans, and cotton were the principal crops.

The Hopi are outstanding as successful crop producers under arid conditions. With a very low rainfall, they developed irrigation and dry farming to a degree hardly reached by modern agriculture even with the aid of such powerful weapons as soil physics, soil chemistry, plant physiology, and plant genetics. Hopi maize grown in fields of varying sizes and shapes presents an interesting

study. Planted usually on land that has received some flood water, the soil is cleared for planting. Holes are dug with a stick down to moist soil and 15 to 20 grains of maize are dropped in the hole. Although ordinary varieties of maize cannot reach the surface if planted over 3 inches deep, Hopi maize because of a greatly elongated hypocotyl can be planted as much as 14 inches under ground. Whereas ordinary maize develops three roots from the seed, Hopi maize develops only one, which can be pushed deep into the soil in search of moisture. These two adjustments make Hopi maize superior to other varieties in an arid environment. A hill of dense stems protected at first by a rock and later by many leaves is not easily damaged by drifting sand. Planted 6 to 8 feet apart the roots can slowly elongate into a large soil mass available to them. Beans are next in importance, and squash and melons are grown without irrigation. Peaches and a few apricots and apples are grown on the sand hills. The Hopi also irrigate land when and where water is available. Here onions, chili, wheat, sorghum, tomatoes, potatoes, grapes, garlic, cucumbers, tobacco, and false saffron are grown. The tepary beans were domesticated in prehistorical time and are now important crops of this region.

To primitive man one great advantage of the arid zone was the ease of curing and preserving food in the dry air. Seeds can be stored and such plants as squash and melons cut into strips and dried to be kept for future use.

The use of all features of the natural environment by primitive man is well illustrated in South Africa where the Bushmen and Hottentots depended so largely on the fruits of the mtsama melon, the wild watermelon, an annual plant which gathers moisture from the desert soils during the growing season and stores it in the small thick rind melons which hold it for months. The melons could be cached in the desert sands and used largely as a water supply when needed. Travel in the Kalahari was possible only when this source of water was available. Again in the extremely dry Southwestern African desert the *Acanthosicyos horrida*, a shrublike spiny cucurbit, furnishes in its large fruits both water and valuable oil seeds for food and drink when no other water is available. The barrel cactus serves as a like source of water in

cases of emergency. Those who die of thirst in the desert are usually lacking in resourcefulness.

Ancient Man

It is difficult to determine how far ancient man pushed his agriculture into the arid land. Here is not included the oasis type of development, in which great advances were made. Originally the Nile Valley was watered naturally by flood waters. The oasis type was either supplied with water by small streams or water was raised from wells by a dillus operated by a camel or a donkey or by a hand-operated chaduf. These methods are ancient as is also the use of the old aqueducts or foggaras. Ancient man also used flood plains and constructed large rock terraces to hold back flood waters. All desert forage within travel distance of drinking water was used by domestic animals. I find little to indicate the use of any land but that well-watered by either precipitation or irrigation from springs and running water in the ancient accounts available in the Bible, Koran, Book of Mormon, Talmud, Cato, Virgil, Theophrastus, Pliny, or many others. The many references to and the discussions of agriculture deal with lands well watered.

The development of olive culture by wide spacing and clean cultivation is a fine example of ancient man's use of dry land. Grain and legumes were also grown extensively. It is probable that a more thorough search of ancient literature, possibly in the writings of Mago, the Carthaginian, which are not available to me, will throw light on the use of semi-arid lands by the Carthaginians. There is evidence that grain culture was an important industry on their arid lands.

Modern Man: Our Attempts at Dry Land Agriculture

The use of the so-called dry land could be traced in many parts of the world on the better or semi-arid lands. I am most familiar with the development in what was generally known as the Great American Desert. J. W. Powell's *Report of the Lands of the Arid Regions* in 1878 (12) was exceptionally comprehensive and sound. He recommended not less than 4 square miles as the size of a homestead and stated that "In those localities, and, so far as I am

aware, in all others where dry land has been successfully farmed, the soil is sandy, and this appears to be an essential condition."

Sand or sandy soil offers an especially favorable environment, for sand or sand dunes act as sponges and absorb all water that falls, and except for a few inches at the surface do not pass it back to the air by evaporation. One walks for miles through desert with no sign of animal life to come upon a small sand dune marked by mammal, bird, reptile, and insect tracks. Here the penetrability of the soil to water results in an increased animal and plant population. The meat eaters are naturally found where the plant eaters abound.

The Homestead Law in 1862 made possible the acquisition of 160 acres of land by a residence of five years. The Timber Culture Act in 1874 enabled settlers to acquire title to 160 acres of land on condition of growing a certain amount of timber. In 1916 the 640 acre Homestead Law was passed and was confined to land suitable only for grazing and the production of forage. In the meantime the grasslands of the Great Plains had attracted the cattle men. Migratory cattle became abundant on the range about 1866 and increased to millions in fifteen years, but in 1886 the cattle boom, which had reached its height in 1882, came crashing down. At that time there was a great influx of homesteaders in Eastern Colorado. A few favorable years resulted in an agricultural boom based chiefly on maize and potatoe production. A few cattle men remained in this region, mostly in the sand hills. Then came the drought of 1893-94, so severe that all but a few settlers left the region. By 1908 about 13% of the land had been plowed, and about half of this plowed land was in crop and about half was abandoned and returning to short grass, the original plant cover. In 1949, 96% of this land was plowed, and not an acre was going back to grass. It was largely in wheat and summer fallow.

The beginning of dry farming was greatly influenced by false conceptions and by propaganda. There was a feeling, supported by propaganda, that, if the loss of water from the surface could be stopped or retarded, capillarity would raise water from the water table to produce the crop. It was easily demonstrated that a great depth of dry soil lay between the moist surface soil

and the capillary fringe, and no water could be secured from the water table by capillarity.

It was also thought that a dust mulch maintained by repeated cultivation would prevent water loss and therefore provide a solution of the water problem. Again it was easily proved that a dust mulch provided no more protection to the moisture below than the same amount of hard soil (3), that the only advantage of the repeated cultivation was in keeping down the weeds which would otherwise pull the water out of the soil. This same effect was accomplished in Australia by overpasturing the land with sheep. But the dust mulch had two very serious, harmful results. In a heavy rain, and many of the rains are of this character, the soil sealed over, prevented water penetration, and caused a heavy runoff. The dust mulch was also subject to wind erosion and was a predisposing cause of dust storms. A cloddy surface was much more desirable for preventing blowing and for increasing water penetration.

Another bad practice was introduced by the advocates of loosening up the subsoil by blasting, deep plowing, and by the subsequent use of a sub-soil packer. Closely allied to these harmful practices was the deep planting of fruit trees. The roots of such trees came promptly to the surface where and where only could they find moist soil. The use of manure and nitrate fertilizer had to be abandoned for they caused the loss of the crop by drought. In the short grass the nitrates released in fungus fairy rings killed out the short grasses.

The conservation of moisture transcends all other arid land problems. All precipitation should be absorbed by the soil and held there until needed by the crop. Weeds should never be allowed to compete with the crop, even before the land is seeded. The moisture should be used as soon as practicable by short season drought evading crops which are thinly seeded or widely spaced to allow a large amount of moist soil to each plant.

In eastern Colorado maize was the crop used by the earlier dry farmers. Now wheat has crowded out most of the other crops and as a result of the sustained price about 70% of the land is devoted to this crop.

Human Extension of Desert Lands

Man, prehistoric, ancient, and modern, has been responsible for greatly increasing the desert lands. His herds have removed much of the scanty cover of nutritious grasses and shrubs, and thereby favored the non-palatable ones. His path has been marked by ruins of human settlements. It is doubtful if desiccation has been the cause. The cause seems to have been over-use. Within the life span of many of us beautiful areas of desert grassland have been reduced to bare soil and useless weeds by over-grazing, the short grass of our high plains have been replaced by wheat and summer fallow, followed by the dust bowl, and the brushlands of the Mediterranean type have been reduced to non-palatable brush by fire followed by grazing of the young sprouts, a practice generally employed and one very detrimental to palatable plants. It is almost impossible to reverse these destructive trends under increasing population pressure, but it must be done if future generations are to find the resource in as good condition as we found it.

Great areas of our most productive soils are being occupied by cities, highways, landing fields, reservoirs, recreational areas, and factories, in which the crop production capacity of the land is lost. It is possible that some of this unproductive occupancy can be halted by shifting some of these uses to more arid land. The arid zone is a delightful place in which to live during at least a part of the year, and it affords a retreat to many who can choose their place of abode and to some who find health only on the arid lands.

Future Lines of Development

In general the ancients used flood waters by using naturally flooded areas and by building deflectors and large stone terraces to retain flood water in selected places. It was, in fact, a type of irrigation agriculture. The Indians of our Southwest did the same, but they took every advantage of the natural drainage areas, allowing nature to concentrate water in channels, fans, and temporary pools. Dry farming is based on a very different principle: to catch the water where it falls, hold it in the soil, and

utilize it as soon as possible by a crop adjusted in its demands to the supply of moisture in hand.

We have by no means fully utilized the highly adjusted plants of the arid lands so rich in fibers and valuable chemical components. Duisberg (4) has pointed to many of them, but the field is still largely unexplored. Esparto and guayule are examples of useful products developed by nature in this zone. In this field M. C. Caldwell of the University of Arizona has found most promising antibacterial compounds which indicate that these desert plants have produced many substances which may fit into the important field of antibiotics. The genetic work of Gordon Whaley of the University of Texas points to a great resource of genetic material in the grasses of this arid belt. These are only a few examples of what seems a promising field of research. There are probably many chemical components developed in these drought enduring plants not present in plants grown and developed under a less exacting environment.

We know far too little from the standpoint of physiology and water economy to attempt a reasonable management of range plants. The plants that are the largest and produce the most forage are favored in the management with no questions asked as to the economic use of the valuable water supply. To choose the largest may be very misleading. If A, B, and C are grown together in the same soil mass we may choose A with a water requirement of 900 as a better plant than B with a water requirement of 600 or C with a water requirement of 300 pounds of water to one pound of dry forage. In this case by choosing the plant on the basis of production, we are choosing the least efficient plant of the three. Not until we have a physiological balance sheet of the principal components of the range can we separate the inefficient from the efficient.

We also know far too little of the water balance of animals. In attempting to improve the food supply for the Navajos the prairie dog was poisoned and destroyed in the area. But to the Navajos the prairie dog is a delicious morsel. We do not know that the cow or sheep can produce as much food with a ton of grass as can the prairie dog.

Primitive man used the rodents as an important food supply.

With the exception of squirrels and rabbits, modern man has almost neglected this group as a food source. Rodents probably are the greatest consumers of plant material and on these 20,000 species man and other carnivores could largely depend for food. They among mammals seem to have made the greatest adjustments to life in an arid environment. Yet modern man has regarded them largely as pests and competitors of his larger domesticated mammals. It would seem possible to explore this resource as a food source for man, as have the more primitive peoples of the earth.

Nature set almost impossible tasks for the plant and the animal world. Water, the substance about which all life was developed, would seem to be all essential. Here in the drought deserts nature has provided a minimum of supply. At the same time the temperature and other atmospheric conditions demand the greatest amount of water. In the plant world the challenge has been met wonderfully and almost all of the earth surface has been occupied. The same is true of the animal world.

Modern man has been given mighty instruments to extend this use. So far he has relied largely on engineering skill to lead waters into this desert region from regions of ample supply. He has not accomplished much in economical use for he still grows crops during the hot dry part of the year at a very high rate of water consumption. Neither has he attempted under irrigation to improve the efficiency of these irrigated crops in the use of water. Ground water has been too generally regarded as a renewable resource but experience has often proved it to be largely non-renewable.

He hopes to demineralize sea and alkali waters when the demand justifies the expense, thus to aid in a small degree nature's great distillery which pours over the land an average of about 30 inches of water of the highest quality each year. He likewise hopes to control to a degree the distribution of this rainfall and to direct it to more arid areas.

One thing he can hope to accomplish and that is to stop the enormous loss of water to the ocean, when it is so badly needed on land adjacent to the streams that carry it away.

Nature has produced a magnificent controlled area occupying

about one-third of the land surface. Here is an experiment already planned and carried out. All we have to do to advance our knowledge in the field of the more complete utilization of these arid lands is to study and interpret properly what nature has already accomplished. Here is a great field for the physiologists. Here also is a rich resource for genetic exploration and the geneticist can be well guided by the physiologist as to the means by which plants and animals can be better adjusted to this rather extreme environment. Can the geneticist breed an animal that can live on metabolic water or can concentrate the urea in the urine, or can he produce a maize plant with only one seed root and with an elongated hypocotyl? Nature has pointed the way.

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The Role of Science in Man's Struggle on Arid Lands

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History tells us a great deal about the relationship of man to his land in arid regions. Broadly it tells us that man can live on such lands, but to live well and to prosper he must make full use of science and technology for the combined use of all the resources.

First, "arid lands" as used in this paper must be defined. Included specifically are those regions in which the normal soils, although perhaps productive of grass and browse, are usually too low in moisture for the dependable production of cultivated plants without irrigation. Many of the characteristics of arid lands thus defined are found in slightly less dry regions where the soils will support crops of cereal grains in alternate years without irrigation if special practices are followed to conserve moisture.

The boundary between the sown and the unsown is wide and shifting. Under extreme pressure for food, cereal growing commonly pushes out onto arid soils too dry for sustained production.

The Balance We Seek

The central problem of land use and human living in arid regions, as elsewhere, is to maintain a reasonable fit between society and resources.

Among very primitive people, comparatively isolated and having few tools, perhaps one may talk about a "natural balance" of some sort. But such a concept has limited relevance today.

True, there are limits beyond which the use of renewable resources of soil, water, and vegetation cannot be intensified without trouble. Once we go beyond such limits it is always difficult and usually painful to restore their optimum use. Overgrazing of ranges, overcutting of forests, or excessive tillage on farm lands may initiate new cycles of erosion hard to control. Restoration of the soil may call for very difficult physical and social adjustments. The continued overdraft on the local ground water, using it faster than it recharges, can mean only reduced water some day and severe social penalties on someone.

Such limits on resource use are only partly fixed in nature. They depend as well upon man's skill, patience, and industry. Using the principles of science, we invent new tools of enormous power—in engineering, in biology, in soil and water management, and in administration; and we adapt them to local conditions. Even more important than the tools yet invented are the basic skills of science, the skills of basic research by which we get the principles for inventing still more.

An attempt "to return to nature," to a way of life without technology, would condemn the majority of the world's population to starvation and death. This majority has learned in recent years that starvation is unnecessary. In fact, the present unrest in the world about food and opportunity is not due to material shortages in terms of the past. Never was there greater abundance. The unrest is due to a new realization of the enormous shortages we have in terms of what is possible with the full use of modern science.

We are seeking a cultural balance or, more accurately, a cultural dynamic of relationship between resources and people for efficient sustained production. For this we use all the skills of science and engineering. The relationship we seek is hardly a balance, except perhaps momentarily along the way from one point of efficiency and abundance to a higher one.

Where Do We Stand?

First, I shall review some of the basic aspects of arid land resources.

Climate

Arid regions have little rain; and the little they do have is often exceedingly irregular. It may seem a bit ironical to many that desert landscapes, such as those of Death Valley in the United States, are dominated by erosion features. With too little moisture for a protective plant cover, the infrequent but severe storms cause severe erosion.

Rainfall and temperature have been recorded for large parts of the world for some time now; but these alone do not give a precise definition of environmental conditions. The water in the soils, for example, is partly a matter of total rainfall, as modified by slope, plant cover, and soil permeability, and partly a matter of evaporation, which depends upon humidity, cloudiness, and wind, as well as upon the temperature.

Nor do the total or average values for these factors tell enough. The patterns of each factor, in relation to the others, through the seasons, must be defined. Many arid lands near the Mediterranean, for example, have the most rain during the coolest months and the least during the hottest months. Others, such as those near us here in Albuquerque, have the reverse pattern; both rainfall and temperature are highest together. Even with the same totals and annual averages, these are quite different environments for soils and plants.

Renewed efforts are being made to define climatic types and to classify them. Description is difficult because a climatic type has no morphology in the sense that a rock, a plant, or a soil has a morphology. The "morphological" definition of a climatic type depends upon what the climatologist decides to be relevant seasonal patterns of factors that he can measure and of the allowable limits of variation over a long period of years. He cannot "see" what he fails to define. His notions of the relevance of factors and of variations within them depend, in turn, upon studies of the effects of the climatic environments upon soils, water, plants, animals, and people.

The results of these combined studies are leading to better definitions and classifications of climatic types. The closer the network of observation stations of long record with complete data,

the more accurately these climatic types can be defined and shown on maps (5, 9). The interpretation of such maps in terms of plant growth and available water, even where highly accurate, depends upon a knowledge of the interactions between the local climatic type and the local land form and kind of soil.

Within one climatic type, for example, a pervious soil of medium texture can take in water, even of sharp showers, and hold it for plant growth; whereas impervious soils refuse water, shallow ones cannot hold much, and loose, sandy soils allow the water to pass beyond the reach of plant roots. Yet water falling on thin soils over cracked limestone or basalt, finds its way into the deep substratum from which it appears again in springs or artesian wells, or may be tapped by pumping.

Such basic relationships between soil and climate are significantly modified by variations in plant cover and soil use.

Detailed studies of the interactions among climate, ground water, land form, soils, and plants are increasing in several parts of the world and are furnishing a continually better basis for assessing the potentialities that we have and the critical problems of use.

Especially do these results give an essential part of the firm basis we need for transferring plant materials, techniques, and the results of research and experience from one place to another. But climate data alone are not enough. In fact, unless the other resources and the existing social patterns are well known also, the use of climatic analogues alone may give a sense of scientific security in faulty conclusions less reliable than the direct impressions of an observant traveler.

A challenging aspect of climate is the variation of its features from year to year and from century to century. There is abundant evidence in the rocks, in the soils, and in the cultural remains that climates of various parts of the world have changed drastically many times. Studies in some regions show that they have gone through several cycles of change. The recent studies of radioactive carbon in buried wood and soils have greatly foreshortened our geological time scale. Drastic differences must have existed in many areas less than 9,000 years ago; and there have been highly significant cycles within this recent period.

Drought prediction for a few years ahead has great immediate interest. Although one can arrange the data from previous years by cycles, up to now none of these can be projected into the future as a sound basis for prediction. Yet the problem is so important that active research is continuing, and the chances for such long-time predictions steadily improve with studies of the mass movements of the upper air and the factors which influence them.

Recently some people have tried "to do something" about climate, or rather about the weather. We have no firm basis for guessing how important cloud seeding may turn out to be, nor will we until the scientists in this field have spoken more clearly than they have so far.

Geomorphology

The land forms of arid regions and the processes by which they are modified differ importantly from those of well-watered regions. Only in recent years have there been the detailed studies necessary to forecast the evolution of land forms well enough to plan enduring engineering measures and land-use schemes with reasonable certainty. In fact, world history is crowded with examples of such failures to predict landscape changes that ruined the works of man. Some of these failures were inevitable. Irrigation works and cities were located in places where it was inevitable that they would be destroyed by the natural processes of landscape change. Other failures were stimulated by overuse of the soil or by failures to build or to maintain simple protective works that would have been practicable for controlling the movement of water and of soil by wind or water.

The geomorphologist has the task of sorting out the relatively stable from the relatively unstable landscapes and of predicting the changes that will be induced by changes in water courses and in the use of the land.

Because of the low rainfall, arid soils generally have a sparse plant cover; thus normally the soil is exposed directly to wind and to running water. The fine particles of dry soil exposed to severe wind blow away, often to great distances. The sand moves more

slowly with the wind and gets piled into a variety of deposits. An exposed soil surface continues to lose fine soil until bedrock or hardpan has been uncovered; or until enough stones have been exposed to form a protective desert or erosion pavement.

Fine soil material exposed to the forces of running water, including the infrequent but torrent-producing storms of the desert, is carried down to the quiet reaches of the streams. Catastrophic erosion with cutting and down-grading of whole regions can be initiated by changes in the grade of streams or by some weakening of the plant cover. Examples include earth movements that raise the land above the normal grade line of the streams. The grade of a stream may also be changed by cutting through one layer of rock into another softer one or by earth changes that shorten its course. The straightening of well-graded winding streams, for example, may so increase the new grade of the stream that down-cutting is stimulated through the whole of a drainage basin. Great changes in climate toward desert conditions have brought about devastating natural erosion. Even showers of hot volcanic ash have killed the vegetation and initiated a new erosion cycle; so has fire and overuse by grazing animals.

I should not want to minimize the effects of man in causing instability of soils. But the tendency has often been to overlook these natural changes and potential changes and to assume that all active erosion has been caused by overgrazing or other wrong land use. Yet where the erosion is in fact due to other causes, grazing control or other simple soil management practices cannot stop it.

Many of the predictions about the stability of landscapes have come from historical research. Such research can be most helpful, but only if done thoroughly. One can be led into serious error by leaving out some of the critical factors. For example, some old cultural ruins around the Mediterranean and in the Near East, now covered with sand or erosion debris, were not in agricultural regions. The original towns or forts were established primarily as military posts and to serve transport routes. Although some agriculture, or rather gardening, may have been attempted on a small scale, the processes of sedimentation that covered some of those

ruins were not really influenced much by land use. Other cities were located in places where their destruction was inevitable.

Scientists in this field are only now getting into good position to sort out the unlike situations and the reasons back of them. [See, as a good example, Leopold and Miller (4).] Obviously, research in geomorphology is most productive when associated with parallel researches in climatology, soil science, hydrology, botany, and archeology.

We must avoid building dams and irrigation canals, for example, in places where they will soon become choked with sediment or be undercut, regardless of our soil management practices. Other less critical areas can be used successfully only if precautions are taken to insure no weakening of the surface that would initiate severe erosion. Still other areas are comparatively safe and no costly precautions are necessary.

I should like to emphasize that such situations cannot be evaluated in general or by superficial examinations. They are not directly related to any one of the factors taken by itself. The only reliable course is detailed investigation of all the features of each drainage basin, one by one.

As a detail in this connection I should like to add this further caution: We cannot always assume that all the soil erosion we see is more or less equally responsible for the silting of our streams and reservoirs; commonly it is the sediment from a few critical stream banks or gullies that is doing most of the damage. In such areas control measures need to be pinpointed, not generalized. In areas of greatest erosion potential grazing may need to be avoided altogether, although commonly light grazing of grasslands gives a better cover than none at all.

Ground Water

Advances are being made in our knowledge of ground water storage and recharge. Although a good vegetative cover is essential to soil stability in many landscapes, it does not follow, as many formerly assumed, that maximum vegetation gives maximum water yield, either in the ground water or in surface storage. Especially where the main source of mountain water comes as

snow, trees that hold this snow in the air, away from the ground, actually reduce the water intake of the soil. Yet one cannot easily generalize. For example, on a thin sloping soil over cracked limestone, pine plantings may slow down runoff and give added water to the substratum, thus restoring springs or wells in the adjacent lowland. On a sloping deep soil of little rain, vigorously growing eucalyptus trees can use so much water that springs and wells in the lowland dry up. Nor does undergrazed grassland necessarily give the best situation. Moderate grazing commonly leads to more spreading of the plants and less chance for runoff between the bunches of grass. Thus on many soils moderate grazing gives both optimum production of livestock and optimum water yield.

Much interest is developing among engineers in the possibility of control of underground water storage in contrast to storage by dams. In hot, dry areas evaporation losses from artificial ponds are enormous. If the water can be stored underground, these losses can be avoided. But such storage is useful only where leaking through deep cracks or contamination by salt can be avoided and where pumping costs are not excessive.

Tritium may be a splendid new tool to help in the study of water shortage.

Radioactive hydrogen with an atomic weight of three, or tritium, is produced in the upper atmosphere by cosmic ray bombardment and is brought to the earth as a component of rain water. The longer the time the water vapor remains in the air, the higher the content of tritium. Hence the normal amounts for various regions differ, but they are fairly constant for any one place, barring unusual disturbances. Tritium formation ceases when the rain reaches the earth and that present in the water decays at a known rate: its half-life is about 12 years. Thus by comparing the tritium content of a water sample with that of the rainfall in the same region, one can estimate the time since the water fell as rain.

Libby and his co-workers (1) have made extensive studies of water from wells, springs, rivers, and other sources with interesting results. Since the life of tritium is short and its content in rain is small, dating by this means is probably limited to periods under

100 years. Rather elaborate techniques and apparatus are needed and several factors affect the interpretation of the results; yet the method holds promise for studying the fate of the rainfall in critical areas and for calculating the contribution of recent rainfall to ground water, streams, and plant growth.

Despite some fair progress, we need more detailed data on supplies of ground water, rates of recharge, and conditions affecting recharge. That is, we need more application to specific areas of current methods for hydrological definition.

Still adequate use is not being made in many places of the data already in hand. It has been definitely shown that ground water is being used in some areas far faster than the recharge. This has been explained to the people in these areas. In some areas the people have developed local voluntary associations or legal schemes to protect the water supplies. Good progress has been reported from North Africa for example, where herdsmen have worked out ways to protect their water supplies for livestock and for feed reserves against the dry years.

In other areas, legal and administrative devices to deal with the problem are lacking. In these, social research and invention are lagging behind physical research and invention.

Soil

Ibn-al-Awan, the Moorish agriculturist of the twelfth century, began his great book on agriculture with the sentence: "The first principle of agriculture is an understanding of soils and of how to distinguish those of good quality from those of poor quality." But despite such admonitions, many people have wasted their lives trying to irrigate unresponsive soils.

It was not until about the end of the nineteenth century that examinations of soil were made as a part of a more or less routine evaluation of their potential use and capabilities. At first, texture, slope, salt content, and wetness or depth to the water table were the features considered. Even such limited studies were largely confined to the young alluvial valleys where it was convenient to use irrigation water. It is only in the last few years that studies have been made of the old and stable upland soils of the desert

where the full effects of climate and living matter are recorded in the basic morphology of the soil.

Since World War I researches on the soils of arid regions have begun to throw light on their genesis, and considerable work has been done recently in parts of Australia, North Africa, the western part of the United States, and elsewhere. Important studies had started before that time in what is now the Soviet Union.

Because of the unique environment, the characteristics of soils in arid regions differ importantly from those of other regions. At the recent Desert Symposium in Israel I summarized these differences and their implications (3). I should emphasize, however, that in the detailed appraisal of the potentialities of arid soils we must continually recall that individual properties, such as texture and structure, have a different significance from those of soils of humid regions where much of the scientific research about soils has been conducted.

Detailed examinations of soil characteristics in field and laboratory are especially critical to predictions about the use of arid soils for irrigated crops because the soils are being studied in an obviously different environment from the one in which they will be used. The bringing of large quantities of irrigation water onto the soil amounts to giving it artificially a humid climate. Soil characteristics of little or no significance to native plants are very important to the productivity and stability of soils under irrigation. These include the porosity, texture, mineralogy, salinity, and reaction of deep layers.

The combinations of soil characteristics that are most nearly ideal for irrigation are not necessarily those best for continued production of native forage without irrigation. For example, nearly level, deeply pervious, salt-free loams of good structure are nearly ideal for irrigation. A sloping soil consisting of about equal amounts of fine soil material and basaltic rock fragments to several feet would be useless for crops under irrigation; yet with the concentration of moisture around the roots it would probably give double the yield of uncultivated forage plants.

Despite the great gaps in our knowledge we have learned a good deal about arid soils in recent years. We now have reasonably

good soil survey methods that have been tried out successfully in several countries (7, 8). We have learned to sample soils for laboratory work in relation to genetic soil horizons and geological layers and with regard to the marked influence upon soils only a few inches apart of both the kind of plants above them and of small differences in water relations. These improved techniques have made it possible to make the predictions from soil surveys more quantitative and to extend greatly the use of data from laboratories and small field plots.

Reliable methods are now available for classifying soils according to defined kinds of soil that can be evaluated quantitatively as to productivity, both without irrigation and with different systems of management under irrigation.

Laboratory methods are now available for characterizing the chemical properties and moisture relations of soil samples with an accuracy that permits us to predict changes in the physical and chemical properties of soils with irrigation (10). These new technical tools, developed mainly during the last fifteen years, make possible far better decisions between arable and nonarable soils and between different systems of soil-water management for specific crops.

The results of modern researches make it possible to determine with reasonable precision the amount of moisture required at different depths for the best growth of important crops. We now have practical devices for measuring this moisture in the soil. The tolerance of various kinds of plants for different degrees of saltiness and alkalinity, under different sets of soil conditions, is becoming known with some precision. We have even, perhaps, the possibility of using these techniques for identifying more efficient plants to use as breeding stock.

Suitable instruments for measuring soil moisture and for the control of irrigation water now make possible well-controlled field experiments for studying, on different kinds of soil, the interactions among moisture levels, fertility levels of the several plant nutrients, and plant spacing in order to give the data required for calculating the most economical combinations of inputs with variable costs for the individual items.

All these new results together make us realize that a large percentage of the water now being delivered to irrigated lands is wasted, not counting losses through evaporation from reservoir pools and from poorly engineered canals. In other words, farmers could get a great deal more out of the water they are using, certainly twice as much; and I think they will do better after the educational work catches up more nearly with the research results.

As a concluding remark about irrigated soils, I should like to emphasize the great importance of maintaining high levels of plant nutrients. Very few irrigated soils give good yields of crops without abundant fertilization. Most of them need additional nitrogen since arid soils are low in organic matter; many need additional phosphorus; some need potassium fertilizer, especially after long cropping; and many need one or more of the minor nutrients.

Since early times the horticulturist on irrigated land has been plagued with chlorosis, the loss of normal green color in the leaves of plants. We know that much of this trouble is due to deficiencies of zinc, iron, and other minor nutrients. Only within the last three or four years have the new chelates furnished an effective iron fertilizer that may go a long way toward correcting this troublesome deficiency.

Since the addition and control of water are expensive, economical production depends upon good husbandry in all other phases of the farming enterprise.

Plant Distribution

Plants may be assumed to be in themselves indicators of the combined effects of the growth factors in the spots where they are grown. Even on uncultivated soils, however, the influence of the type and condition of the vegetation as modified by use must be evaluated along with the basic soil and climate.

Most plant scientists had formerly assumed soil (or the "edaphic factor") to be one of the fixed features of the landscape along with climate and relief. Actually the plants themselves have a great deal to do with the soil under them. In arid lands, for example, some plants are salt collectors much more than others (6). Large differences exist in the physical and chemical properties of soils

only a few inches apart, depending upon the type of shrub above them. The relationship between plant and soil in the natural landscape is so intimate that rarely can we say that one is due to the other: they evolve together.

Actually, useful plants (and useless ones) are distributed unevenly over the world. One need think only of the great value of subterranean clover to Australia, and of the great harm done in Australia by the prickly pear cactus from the United States, now being brought under biological control by introduced pests. Research is now going on in order to find out where other useful transfers may be made.

Plant scientists are probably making their greatest contributions to more efficient grazing just now through improved plant selection and better management practices. Perennials with drought resistance, or at least drought tolerance under heavy use, are being identified. Such plants include palatable shrubs as well as grasses and legumes.

Research has found ways to increase these good species through management and to spread some of them through seeding. For others, practical methods of collecting seed are not yet available. Although we must be on the lookout for good exotics, greatest progress is being made with local varieties that have persisted for a long time.

Along with selection and reseeding, where possible, is the usually overriding matter of management, of controlled use. Almost phenomenal effects of temporary rest or "guarding" of the range to bring it into a high state of production have been reported from many parts of the world, especially where adequate measures for controlling water by contouring, terraces, spreading, and the like can be installed. Such guarding for even two years has raised the level of productivity of old ranges several fold; and the new high levels can be maintained through controlled use.

Besides the normal cultural practices, the new methods for weed control are proving to be important tools for the ranchers and farmers in arid lands. Already brush is being eradicated from arid lands for as little as three dollars per acre. Many differential plant-killing hormones and other chemicals are in practical use, and testing is going forward with thousands of new kinds. We can

confidently expect continued improvement in arid land management through our ability to remove the useless plants that waste water so that we may conserve it for the good ones.

Despite this progress, I feel that plant breeding will make as great or even greater long-time improvement. Most of our outstanding results from breeding new varieties, in contrast to selection alone, have been of plants to be grown under favorable conditions of soil and water. Crops grown under irrigation in arid regions, such as cotton, alfalfa, corn, and potatoes, have been greatly improved through breeding. In unirrigated arid regions, however, we shall be breeding plants for growth under severe limitations of moisture.

We know that most of our plants are highly inefficient in their use of water and light. As plants proceed with their basic function—the manufacture of plant food by photosynthesis in sunlight—they are required to take in carbon dioxide. In most of them, as they take this in, water can escape. But the extent of this water loss varies widely. Basic researches on these processes can give our plant breeders new plant materials. Some plants can even take in large amounts of water from humid air, such as that over the plants during a cool night. Some plants can fix nitrogen, or at least sustain other organisms that can. It is now known that this ability is not limited to legumes like clover and alfalfa.

If characteristics of plants such as drought resistance, drought tolerance, and low water requirement can be related to specific genetic patterns, I see no reason why the plant breeder cannot combine them with other desirable characteristics as he has already done with disease resistance.

Thus besides selection and testing of plants collected from arid lands, I feel that the basis for breeding plants for arid conditions has improved. Such breeding on a significant scale, except for lucky accidents, will be preceded by more fundamental research of the genetic basis for the primary growth factors in promising species and varieties. The newly emerging discipline, sometimes called "physiological genetics," holds great promise for giving us far greater potentialities than can be had from plant selection alone.

The long-time potentialities of such plant breeding, based on

fundamental studies of physiological genetics, applies also to crops grown under near-arid conditions. Here I am thinking of cereals, including crops like grain sorghum, to be used for feed as well as for food.

Other Research

So far I have spoken mainly about lines of research that are directly related to arid lands. Before we come back to some of the specific problems, we should remind ourselves of the many other researches that may have important special implications in the arid region.

Perhaps one of the first of these that comes to mind is the possibility of low-cost production of potable water, or even irrigation water, from the sea or other brackish sources. Active research is going on in this field; but from what I can discover the industrial chemist has a task to bring down the costs.

This problem is not unrelated to the future developments of low-cost power. Wind power has already proved to be practicable in many parts of northwestern Europe. It may have a place in those arid regions with nearly continuous wind. Or perhaps the current research on ways of converting sun power to electric power may lead to practical inventions.

Then too, modern medical research is telling us a lot of new things about human health in hot countries. These results in the hands of the engineering specialist in air conditioning may greatly increase the efficiency of labor and the ease of living in places where most Europeans have not formerly been able to adjust themselves.

Soil-Use Problems

Despite this reasonably optimistic picture of accurate methods for predicting the harvest and the effects of management under grazing, dry farming, and irrigation, our soils are not yet used under anything like optimum sustained production. In other words, the potentialities of the arid lands of the world are very much higher indeed than our present realization.

Although good methods for research are available, they have

not been generally applied. We have either inadequate soil surveys, or none at all, for a large part of the arid lands. Many important kinds of soil are still very poorly understood, to say nothing of their relations to vegetation and climate.

Lest what I have said so far lead to overoptimism, let us summarize the soil-use problems under grazing, dry farming, and irrigation.

Grazing

The productivity of arid range lands varies within wide limits from essentially zero to something like 200 pounds of beef per acre (or say 30 pounds of mutton and 10 pounds of wool), depending upon the local soil conditions and effective rainfall. Thus operational units of comparable size in terms of livestock production vary enormously in terms of acres. For this reason alone the units on poor soil tend to be too small for the individual family or village, and this leads to overgrazing. Since soil moisture is variable, there is a tendency to overstock in moist years and for such overstocking to continue into average or drier-than-average years with resulting overgrazing and damage to the basic potentialities of the vegetation and, finally, even of the soil itself.

Once serious overgrazing has taken place, the carrying capacity falls far below normal and its recovery depends upon a temporary sharp reduction in stocking together with reseeding, contouring, water spreading, and other measures to control the water and keep it in the soil.

Then, too, the effective use of grazing land usually depends upon sure supplies of feed for critical hot, dry, or cold periods. This means that grazing land needs to be associated with irrigated land or with arable land in the mountains or in favorable spots where hay or feed crops can be grown. Improved techniques for wells and for surface water storage lead to more watering places and thus spread the livestock evenly over the range. This helps to control the use of the range.

In predominantly grazing areas generous amounts of water should be allocated to use as livestock water and to irrigate

emergency feed crops. Effective local schemes are necessary to give firm protection of water supplies for such use. In fact, water and favorable soil for feed crops on a small area can stabilize the grazing economy of a region several hundred times its size.

The economic, social, and administrative problems for range improvement are really more difficult now than the purely technical ones. The areas most needing reduced grazing and careful management are often the very ones where local residents most strongly feel that they cannot reduce their livestock, especially if marketing facilities are inadequate.

In large parts of the world, arid grazing lands could support several times the present numbers of livestock if well-known management practices could be installed during a temporary period of reduced use. Even where experiments have demonstrated greater production of livestock products from half or less the numbers of animals, it is not easy to convince local herdsmen to reduce numbers.

Although we have made much progress in the basic and applied research among the natural sciences related to range management, much less has been done in the social sciences aside from production economics. Associations of farmers and ranchers in grazing districts and soil conservation districts have helped. Still these devices fall short of meeting the problem in many places.

Dry Land Cereal Growing

During periods of unusual moisture and with strong economic pressure, or local demand for food, many arid soils are broken out for cereal grains. This happened during both world wars in parts of the United States as well as in many other countries. In parts of the Near East, cereal growing presses very hard against the desert all the time.

Near the margin between arid soils and other soils, higher yields on a more nearly sustained basis can be expected on deep soils of good structure than on thin soils with low water-holding capacity or on structureless sandy soils easily subject to serious blowing. But once these thin or sandy soils are in cultivated fields, it is hard to get them back into grass. Here again the most

difficult phases of the problem are economic. Let us suppose that a farmer starts a cereal grain farm on a holding of some 600 acres on soil unsuitable for crop use on a sustained basis. A great many have done just that. In a few years when it is clearly established that the soil cannot be maintained in production except under grass, how is he to manage to enlarge his unit? A unit economical for grazing would be much larger. During the transition period of reseeded and low-carrying capacity, how is the farmer to live and pay expenses? Large numbers of cultivators on the edge of the desert in the Near East, for example, were born into such a situation.

Despite advances in natural science, clear answers to the tough problems of adjustment are lacking. More nearly appropriate institutional techniques are needed.

Irrigation Farming

The improved methods for irrigation farming have already been explained. It has been estimated that we have many more millions of acres of arid soil in the world that could be developed (3). Yet irrigation can be overdone. Where arable soil exists only in small areas, intermingled with land suitable only for grazing, the cutting out of these small irregular areas for industrial crops, such as cotton and sugar beets, harms the use of the region as a whole. It is by conserving such soil areas for hay and feed crops, rather than using them for other crops, that efficient use can be made of the range land.

Even at best irrigation is an expensive undertaking. If it is to be done, it should be well done so that water is properly controlled and so that other limiting factors, such as low fertility, salinity, hazards of soil blowing, and waterlogging are avoided.

We have the scientific techniques to make these determinations. We have fairly good methods for the economic analyses of the results over short-run periods; but good methods for appraising the long-run economic benefits and costs of irrigation are lacking.

Thus, given accurate soil surveys, current research results for guiding the physical management of arid lands are more nearly adequate to our present problems than those for guiding their social management.

Combined Resource Use

We know that the use of rural land depends also upon the use of other resources. The more modern science and technology are used, the more delicate becomes the balance among separate lines of production and among individual resources (2). Even similar kinds of land produce very differently in unlike economic environments. An efficient agriculture at high levels of labor income requires industry, transport, education, and medical facilities in the same region.

Perhaps no example of the principle of combined use is more striking than the growing competition for water in arid lands. We must think not only of the competition within agriculture, which I have already mentioned, but also the competition between agriculture, industry, and urban use. Where highly valuable mineral deposits can be exploited only with methods requiring large amounts of water, this use competes directly with irrigation. We cannot assume offhand that it is wrong to use water for industry and thus deny it to agriculture. Rather, we need to develop through research, applicable criteria for appraising the long-run benefits to society of alternative combinations of uses.

Only rarely can any single segment of modern economy succeed by itself in any community or region. To do so requires that it have an enormous relative advantage. For example, where an area is so wholly agricultural that all public services must come out of agricultural income alone, the soil must be excellent indeed. Actually, some of the best agricultural areas of the world are located on soils that were of only mediocre quality to begin with. This is because agriculture generally thrives best where industry and other resource uses contribute to the general economy and share in the cost and benefits of the social services.

Thus there is more to the appraisal of arid lands than examinations of the soils, vegetation, and water. We must look at the other resources and the relation of their use to agriculture and to social services. Obviously, we must include fuel and power for industry and mineral resources for mines and factories. Where roads and social facilities serve two or more enterprises, efficiency is far greater than where they serve a single one. And perhaps

above all is the question of how we shall divide the water without its overuse.

At such an international conference it may not be out of place to emphasize again the need for international cooperation and joint planning. Many excellent opportunities can be realized only by the pooling of resources, including water, that are arbitrarily divided by country boundaries. For example, United States and Mexico and the United States and Canada have worked together for their mutual benefit. Going back again to the Near East, the agriculturist can only hope for full peace and cooperation so that the planning of combined resource use can become effective.

Summary

I have tried to create the impression that science has found out a lot about arid lands. Progress has been substantial during the last twenty years. But this progress has been mainly within individual disciplines. It is not balanced; some fields have progressed more than others. Some lines of research have been weak on the fundamental side. I should say that this is true in biology. Here, for example, great potentialities for advances in plant breeding depend upon more fundamental researches in genetics as related to plant physiology. My experience leads me to the view that the economic and legal researches, basic to improved institutional devices, are less advanced than research in most fields of natural science.

Great opportunities for science to serve the development of arid lands lie in more emphasis upon basic research, in the wider application of accurate methods for basic resource surveys, and in the integration of research results from the several disciplines in ways that make possible good predictions for combinations of resource use in communities and regions. Perhaps we need more team research. At least I think we do. And special emphasis should be given to joint research with both natural scientists and social scientists on the same team.

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The Challenge of Arid Lands Research and Development for the Benefit of Mankind

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It is a pleasure on this occasion to remind the people of this part of the United States that we in Australia owe much to the wonderful work done by George and William Benjamin Chaffey, those Canadian brothers who established Etiwanda as an irrigation unit on the Santa Fé trail and later Ontario in California. In 1886-87 they went to Australia to begin the irrigation programs on the Murray. Where before had been arid land supporting rabbits and a scattering of sheep, Renmark and Mildura developed the thriving centers of production.

Let us examine the title "The Challenge of Arid Land Research and Development for the Benefit of Mankind." First, it is a challenge, and a challenge indicates a contest or struggle, so that sooner or later one ought to take a side. If we look at the end of the title, which reads "for the Benefit of Mankind," there ought not to be much doubt about which is the side to take.

Arid lands, wherever they may be located, especially if they are hot, are characterised by intense blue skies by day, immense distances in a shimmering atmosphere, sparse vegetation and still sparser animal and human population, with a limited and erratic rainfall of less than 10 inches in a good year. Yet we recall that great civilizations were developed in arid areas crossed by great rivers, the Tigris-Euphrates, the Indus, and the Nile.

How big is the challenge so far as area goes? It is difficult to get precise figures, but it is generally believed that the total land surface of the earth is of the order of twenty-five thousand million acres and of this, at present, about two thousand five hundred million, or 10%, are under some form of cultivation. But it is also estimated that about six thousand four hundred million acres are arid, in other words, about one-quarter of the total land surface of the earth. That is to say the arid area is just over two and a half times as large as the presently cultivated area.

Potentialities of Arid Lands

The end of World War I saw the end of large scale settlement in, and development of, new lands by pioneering individuals in whom the spirit of adventure or the desire for a freer life was strong. Came World War II with a startling realization of the precarious way in which most nations lived, a way fraught with all the explosive possibilities of further bitter struggles between peoples.

Today we know that Malthus was just ahead of his time and we have to ask ourselves whether adequate food requirements of the people can be provided from present sources with all the technological experience available to us. We suggest that two possibilities arise, one a reduction in the rate of growth of the population of the world and the other an increase in production of foodstuffs not only just to feed people on a minimal diet but on a diet nearer to the optimal. With the control of the rate of population growth we arid zone people have little or nothing to do. We do say, however, with regard to the second, that it is possible to increase world food supplies by increasing production from present areas and by bringing into production additional land at present uneconomically used.

By applying technological knowledge to the fullest extent in what are at present underproducing areas, a great increase in food production by individual growers is possible. India, for example, possesses irrigation works on a great scale, and nowhere else in the world is so large a population dependent on irrigation for food supplies. Nevertheless it is estimated that less than 10% of the runoff of her rivers is utilized.

When we come to consider the possibilities in arid lands, it is recognised that the efforts of individual growers can play but a small part in the development of new areas of production or the re-establishment of production in great areas which used to be fertile in ancient times and are now out of use. I refer to the millions of acres in the valleys of the Tigris-Euphrates, the Indus-Chenab, and the Nile, in the dry north of Ceylon where still are to be seen the remains of ancient irrigation channels and reservoirs. It is estimated that in Latin America over twelve million acres are susceptible of development, and an area bigger than Egypt's productive land is said to be available in the middle Niger. The re-establishment of these ancient areas and the development of new areas require the joint efforts of research institutions, of governments, and the instrumentalities of the United Nations, such as FAO, WHO, and WMO, not forgetting the international financial authorities.

Let us now look at some of the problems with which those charged with arid land development have to deal. I propose to list them under the following heads of water, soils, plants, animals, and man, to give you what must obviously be a very sketchy outline of some of the salient features of each, and then to come to a conclusion.

Water

Water is placed first for obvious reasons, and adequate information about the water resources of a region is essential to a safe usage of that water for full development in food production, domestic use, and industry. In the desert one conserves every drop of water for the maintenance of life, in great urban centers we turn a tap and water flows, but sometimes restrictions are placed on turning those taps. In other lands the fresh water from great mountain ranges flows several thousand miles to the sea and constitutes a fresh water delta of tremendous size in the ocean.

Rainfall

Whence comes the supply, great or small? The answer is rainfall, and this is the beginning of what is called the hydrologic

cycle and the controlling factor in the hydrologic cycle. Some of the rain soaks into the ground, some runs off in streams, some is evaporated, and some is transpired by vegetation. That which is evaporated or transpired by plants, like stream waters, may travel great distances, but ultimately it again falls somewhere as rain, snow, hail, fog, or dew. In tropical areas rainfall may actually be beyond the capacity of man to use, as with the Amazon, but in arid and semi-arid areas, rainfall is low, and every effort must be made to conserve usage to the best ends. This applies even when an arid area is using imported precipitation as in Egypt, where the Nile valley is dependent in the main for its supply of water on the rainfall in the Abyssinian highlands.

One of the first problems in the hydrologic cycle of arid areas is that of accurately measuring precipitation. Because rainfall is generally low, it can be very local and extremely sporadic, and this erratic distribution both geographically and in time makes for considerable discrepancies in accurate measurement.

While on the subject of rainfall, thought naturally turns to the fascinating possibility of rain-making, and a preliminary report by the World Meteorological Organization entitled, "Artificial inducement of precipitation with special reference to the arid and semi-arid regions of the world," prepared by the Technical Division of WMO Secretariat from reports received (4) should be noted:

From the consideration of the regional reports quoted in this paper, the following conclusions might be drawn:

1. Operations which have so far been carried out have produced results that could be termed, at best, inconclusive; neither the complete failure of the methods employed nor the certainty of getting substantial increases of rainfall have been demonstrated.

2. The most favourable meteorological conditions for the artificial inducement of precipitation are to be sought in regions and during seasons where natural precipitation is most likely.

3. Present day techniques, either "cold" or "warm" cloud seeding, have very little value, if any, in augmenting the precipitation in areas of very low rainfall or during dry periods in regions of normally medium rainfall.

These tentative conclusions should not be taken as the expression of a negative attitude towards studies and experiments on the artificial

modification of clouds and precipitation. On the contrary, they indicate that further effort is necessary.

It is therefore recommended that:

(a) new scientifically designed and rigorously checked experiments be undertaken in all regions where there is a possibility of success;

(b) precise methods of evaluating the amount of precipitation resulting from such experiments be developed;

(c) in all research experiments and applied operations, the collaboration of the meteorological authorities be sought, in order to ensure the greatest reliability in conducting the experiments and assessing the results;

(d) information on all projects already carried out or those in operation now be released and made available to all scientific workers, putting development of science before commercial and other interests.

It is well known that advanced civilizations formerly occupied what are today arid regions. Excavations show the remains of reservoirs, canals, fortifications, and human habitations, presuming an intensive and extensive cultivation by a large population. Such is the case in India, Pakistan, North Africa, the Near East, and even in the desolate region of Lob Nor in Central Asia there are remains of oasis towns and irrigation works. The disappearance of these civilizations may have been brought about by severe climatic changes or by the doings of man not for the benefit of mankind.

Tixeront, our colleague from Tunisia, in asking whether it is possible to forecast weather over long periods, points out that we have not yet sufficient, reliable records, but he states that in Tunisia they use one of nature's records in the growth rings of trees and one of man's in archaeological studies. The meteorological service of Tunisia studied the climate of Aïn Drahem from 1736 to 1955 by examining the growth rings of an oak tree. The inference drawn was that from 1736 to 1790 there was significantly more rain than later, and this seems to be confirmed from historical documents which refer to abundant crops in the eighteenth century. (See pp. 91-92.)

Tixeront considers that a study of the ruins of Arab and Roman irrigation works, of historical texts, of the continuity of cultivation methods, and of the cultivated plant species indicates that the climate is stable and has not become decidedly drier. Simi-

larly it was reported at the conference in Jerusalem in 1953 that all the historic, botanical and archaeological evidence pointed to little change in climate during the last eighty years or so in Israel and India.

Tixeront points out that droughts do occur and we ought to become aware of their statistical probability, and he makes a plea that we study all the climatic factors which may lead to the development of drought periods, as conversely to flood times.

In practice in Tunisia information from historical and archaeological sources has been used to good effect. The planting of olive trees at the same spacing as used by the Romans in dry farming is successful today. So, too, wells, cisterns, and irrigation channels of Roman origin give a guide to modern siting and use.

In semi-arid and arid areas transpiration and evaporation, or to put them together as Thornthwaite does under the term evapotranspiration, constitute the major factor in the recirculation of rainfall into the air, but it is notably difficult to measure satisfactorily because of differences in plant cover. It is becoming clearly evident that in some instances an increase in crops or pastures or tree cover may severely tax the capacity of ground water supplies, and in general a balance has to be struck between the needs of crops and the water supply. Lysimeter experiments in South Africa indicate that only about 3% of rainfall goes lower than the root zone of veldt grasses. Phreatophytes, plants which grow their roots down to the water table like alfalfa, are notable for their efficient transpiration. Indeed, I have on occasion recommended the use of alfalfa to drain waterlogged orchards in irrigated country. Worthless phreatophytes may waste millions of acre-feet of water in some arid country.

In order to assess the water requirements of an area, wherever it may be, some way of measuring evaporation and transpiration must be used, yet strange though it may seem, we have not yet achieved exactitude even in reading evaporation pans. Thornthwaite, who has devoted his scientific life to the study of climate, has proposed a method of estimating the water need of a region so that it is possible, if the rainfall and the evapotranspiration are known, to determine how much additional water, if any, is needed by way of irrigation. He defines the total water need as

the amount of water which will return to the atmosphere from a surface completely covered with vegetation when there is in the soil sufficient moisture for the full use of the vegetation at all times, and this he calls the "potential evapotranspiration." (See p. 73.)

One way of determining evapotranspiration is by the "vapor transfer" method based on the rate at which air near the ground is mixing with air above it at a given height and by measuring the difference in water vapor content at the two levels.

It is possible also to measure rainfall, the inflow of irrigation water, and the outflow water, regarding the amount which does not run off as evapotranspired.

Latterly specially designed soil tanks 4 square meters in area and 70 centimeters deep, in which plants can be grown under field conditions, have been set up in a number of places, each tank being surrounded by a large buffer area to ensure greater accuracy in results, but not enough are yet in use to give the range of variation from one area to another. Meantime Thornthwaite and his colleagues have come to the conclusion that the computation of potential evapotranspiration for any place can be done from data on air temperature and latitude alone. With these it is possible to determine the water needs of an area and, as it were, keep accounts whereby the most economical use may be made of irrigation water.

Underground Water

Having briefly referred to rainfall, using that as a general term, we may naturally turn to what happens to the rainfall apart from evapotranspiration. Some infiltrates the soil and other layers and goes underground, where it may be stored or move slowly in suitable layers gradually toward the sea. The most generally used method of determining infiltration is to examine the data of the use and fall of water in wells, although today radioactive isotopes are available to make evident the movement of water through permeable strata. There are in the United States about seven thousand observation wells, and approximately 5% of these have automatic recording equipment.

The examination of an area for underground water in the first

place calls for geological knowledge and properly the use of geologists to make the survey with or without the aid of geophysics. By this means exact records would be kept of all the wells or bores put down, the strata through which they went down, the quality and quantity of the water, and so on. Such a survey would enable estimates to be made of the total volume of the underground supply, of its area and depth in a confined source, or of its flow if unconfined, and the region of flow in the aquifer. It may be of interest to remind you that below the Nile there is an underground river about 560 miles long reaching from about 80 miles south of Luxor to about 70 miles north of Cairo. According to Mohamed El Sayed Ayoub, one-time Inspector General for Nile Control, the mean width of the stream is 10 kilometers, the strata of sand and gravel in which it flows ranges from 100 meters to 300 meters in depth, with a water storage capacity of nearly 500,000 million cubic meters, and the water takes nearly 100 years to arrive at the head of the delta. Each year 1,400 million cubic meters are used for irrigation, another 1,000 million cubic meters are planned to be used on 25,000 acres of a new irrigation project, about another 1,000 million cubic meters are used by plants, and nearly 4,000 million cubic meters flow into the delta unused.

This great aquifer under the Nile and the Nile itself receive their water from distant sources, but were they to rely on local rainfall for the infiltration and stream flow they would be dry each year for six months.

The Thal Development Authority

I would like at this stage to tell you briefly the story of another great arid area which is being reclaimed, the reclamation of which illustrates regional organization of the order of the Tennessee Valley Authority. I refer to the Thal desert area in western Pakistan. It consists of a triangular area of nearly five million acres with a base of 65 miles along the Salt Range to the north, and a length of about 175 miles to the apex at the south, and is in the Punjab between the Indus, Jhelum, and the Chenab. Tradition, supported by geological evidence, has it that the Indus

formerly flowed down the middle and deposited huge quantities of sand and silt and later changed its course to the west. The superficial sand dunes arise from fine material blown from coastal and desert regions of Sind and Rajasthan.

The vegetation consists of low brush and scanty grass on which camels browse. There are no indications of early occupation, such as are found in other parts, prior to the fourteenth century, when a few tanks of about an acre each were constructed by the Emperor Sher Shah Sun.

The question of developing the Thal area was first considered in 1870. No action was taken until 1901 when a Colonization Bill authorized the construction of a canal to the Shamlat area, but nothing was done until 1936 when the distribution of the waters of the Indus and its great tributaries was considered. Work on a Thal Project was begun in 1939 but was held up because of World War II, and channels were filled up with sand when in 1947 the flood of refugees from India moved into Pakistan. Of these 250,000 are being settled in the Thal.

In late August 1949 the Thal Development Authority was established, to be responsible for the full development of an area of 834,500 acres, with an area of 638,000 acres to be developed by private enterprise with the assistance of the Authority.

It was believed that the agricultural development of the area and the establishment of villages and small towns throughout the area needed the balance of industrial development, and so today there are sugar mills, cotton textile mills, a woollen mill, and a cement factory in the area. Some 640 villages have been established, each with forty or fifty houses on a total of 100 acres, with a green belt all round each village and a timber area of 50 acres alongside.

Each settler is allowed 15 acres of land at not more than a mile and a half from his village. These acres he must cultivate satisfactorily.

The authority of the TDA originally covered the million and half acres commandable by canal for irrigation, but in 1953 a wider scheme was examined for parts of the three and a half million acres not commanded by canals. In certain belts masonry

wells have for years been used to supply water for small holdings. The aquifer consists of sand layers with a water table at 40 to 60 feet in ample quantity, and so a tube well scheme has been initiated. How successful this will be remains to be seen because percolation is heavy and evaporation, with summer temperatures up to 120°F. is high, but it is hoped that each well can irrigate 150 acres. Early in 1954 Australia supplied tube wells to the TDA under the Colombo Plan.

It seems safe to prophesy that in perhaps a decade there will be need to study a salt problem in parts of the Thal, and FAO is already at work in Pakistan on this problem in the Indus valley.

In arid and semi-arid areas where the need for recharging the underground water is acute there are often long periods of no rain, interspersed with short bursts of storm rains with extremely rapid runoff, carrying astonishing quantities of surface material of sizes ranging from silt particles to boulders. These storm waters are gone in a relatively short time, and the problem is how to make good use of what are sometimes quite large supplies, by spreading and slowing down the rush of waters, by the use of dams and tanks, by selection of the site for percolation, and so on.

It is impossible in this composite paper to do more than indicate the complexity of the problems concerning water supplies. The U. S. Geological Survey has prepared a list of thirty ground water problems needing research, and in arid areas the general problem of the development of water resources to the fullest economic capacity will always be a vital one.

Salinity Problems

Rainfall is relatively free from salts, and where rainfall is adequate for agricultural production excess soluble salts in the soil are leached away in the drainage water, but where rainfall is low, leaching is reduced and salt accumulation can occur. All irrigation waters contain salts dissolved from the rocks and soils through which the water moves. Some years ago Scofield studied irrigated areas in this part of the United States and described the salt balance as the relation between the amount of salts being delivered in irrigation water and the amount removed from the

area in drainage waters (2). This concept backed by suitable methods for its application may be valuable in preventing salting and in remedying existing salt conditions.

Hayward, of the U. S. Salinity Laboratory at Riverside, has prepared a most comprehensive review for UNESCO of research on plant growth under saline conditions (3). In it he refers to the classification of saline and alkali soils, the quality of waters for irrigation, the physiological bases in plants for salt and alkali tolerance, the effects on plant growth and on seed germination, and then succinctly reviews the position in Australia, India and Pakistan, South and Central America, and North America.

As human, animal, and plant bodies are so largely made up of water it is little wonder that the ability of man to live is dependent on having plenty of good water. Reference has been made to the relationship between population and food supply. The same sort of relationship obtains between population and water supply. It is little wonder then that men think of those seemingly inexhaustible supplies of water, the seas and oceans, and wish it were economically feasible to desalt sea water in immense quantities. On one occasion a sincere good wisher asked me whether it would be possible to construct a canal from the Mediterranean through the Negev desert to the Dead Sea using desalted sea water for irrigating the desert and raising the level of the Dead Sea waters with the drainage. The answer is that success in producing large quantities of fresh water economically from salt water is not just round the corner. There is no magic wand, but research is going on in many parts, and there is little doubt that the day will come when in some arid areas it will be possible to provide desalted water at lower cost than, for example, water transmitted over great distances.

Howe, of the University of California, prepared for UNESCO an excellent summary of research on the utilization of saline water and we have heard during this series of meetings from Powell, a member of the Advisory Group to the U. S. Secretary of the Interior on the Saline Water Conversion Program (see p. 257.) This program was established by the U. S. Congress under Public Law 448, and the research projects financed by grants in

aid under this enactment are already highly productive, especially in assessing the merits and costs of producing fresh water from saline supplies. The Saline Water Program is due to end in July 1957, but I am sure we hope that it may be extended beyond that date.

Soils

Soil, the base on which food production on a scale to satisfy world needs rests, must now be considered. It is not proposed to go into any detail about arid soils, because Kellogg can write books about them. Suffice it to call attention to a few characteristics such as their low content of organic matter and so of nitrogen, the fact that they are more usually alkaline than acid and so may develop permeability problems with irrigation, and their sometimes rather high content of soluble salts. Despite these characteristics, with suitable fertilizer treatments crop yields under irrigation can be remarkably high and large scale prosperous communities may be established, as witness the position in the United States and in Australia.

I cannot do better than quote Kellogg's summary to his introductory paper at the Jerusalem Desert Research Symposium (1) as follows:

Several important areas of needed soil research are the following:

1. Morphological study of the soils of relatively unexplored regions and their classification as a basis for preliminary reconnaissance mapping and appraisal. Previous soil experience has been highly concentrated on alluvial soils and especially in areas easily reached by existing transport. Soil scientists have had inadequate opportunities to make detailed studies of arid soils remote from present population centres. Even in places where water is scarce, principles of great fundamental value to our knowledge of the formation and development of arid soils can be learned—principles important generally and to the stabilization and use of arid soils for grazing even though they cannot be irrigated.

2. Relation of soil permeability to drainage and salt removal. We need to know more precisely the lower limit of permeability, especially in subsoils and substrata, for satisfactory management with different kinds and amounts of irrigation water, the factors that control the permeability, and how permeability may be modified by chemical treatments, growing plants, and water management.

3. Development of structure and water-holding capacity in arid sandy soils through use of better adapted green-manuring crops, organic soil conditioners, or in other ways.

4. Better methods are needed for appraising the salt balance in whole watersheds where irrigation water is taken from streams and the drainage water is returned into the streams to be used again for irrigation at one or more lower levels.

5. More precise studies are needed of the soil properties that lead to chlorosis in plants and of ways to modify them.

6. The reasonable alternative combinations of plant nutrients, water supply, plant spacing, and cropping systems need to be tested in order to find the most nearly optimum ones for each kind of soil in terms of harvest, sets of practices, and the long-time effects on soil productivity. The results must be set forth in the specific terms required for calculating costs and input-output ratios needed in farm budgeting.

Plants

In the section on climate reference was made to the fact that there is little evidence of any marked climatic change for the worse since man used or misused the land for living. The effectiveness of the rainfall has however been seriously reduced by man's overuse of plough, the axe, and the grazing animal, particularly the goat. Marginal areas have become man-made desert areas, and it is in this sense that the desert is advancing. In any attempt to re-establish marginal areas for better production and living conditions it is necessary to survey and map the existing plant cover, whether natural or cultivated, and also land use. These are being done or are planned by FAO working with national authorities.

The main task is to attempt the regeneration of a better plant cover and to do this while the population is engaged in gaining a living from the area. To study such natural regeneration as may occur it is essential to have as guides in this work enclosed or protected areas which are ungrazed. Sometimes the results may be startling. One thing cannot be done, and that is go over from one area in one part of the world to another area in another part and at once begin to apply procedures in the expectation that they will be successful. Much experimentation is needed to select suitable plants, to get them to seed, to germinate, and to grow in these very old environments.

It is dangerous to disturb the land surface more than necessary, even with good intent, because of the possibility of soil removal or seedling scarification by the sand-loaded winds which blow in the hot season. I have seen this in the Thal desert of Pakistan where we are making trials with a number of plants. It seems to me that the provision of some shelter from these searing winds is essential and this can begin around nursery areas and in strips suitably placed across the prevailing winds. The limitless horizons of the desert are very interesting to write about but they are no good for proper land care.

I come from a land where it has been necessary to introduce and establish every kind of plant food for man and his animals, with the exception of the native grasses and top feed dry climate trees like the mulga (an *Acacia*). We have successfully introduced every kind of fruit and vegetable which can be grown anywhere and we are still testing many grasses and legumes. So has the United States, where I think trial introductions from all over the world total more than 65,000. Outstanding in Australia has been the success of the establishment of subterranean clover, which has meant untold millions to the sheep men of southern Australia. *Phalaris tuberosa* and rye grasses (*Lolium* spp.) in the south, *Cenchrus* spp. in the west, and Rhodes grass in Queensland are other illustrations. The United States and Australia use alfalfa, called by Australians lucerne. (The American name is nearer the Arabic which means the good plant.) I refer to this to illustrate the possibilities of plant exploration for grasses and legumes, particularly in old arid areas. Much must yet be done in this field, and it is good to hear from Whyte about the work which is in progress at the moment under his guidance in FAO (See p. 185).

In the detailed studies that are essential with respect to any of these introductions there will be plenty of scope for selection and genetical studies of those that show promise of establishment. We have now, for example, a number of established strains of subclover, and it may be that *Trifolium hirtum*, native of Turkey and now established in California, will develop ecotypes.

It is obviously necessary to learn what are the physiological factors which enable desert and near-desert plants to survive

long periods with limited water supply under conditions of excessive insolation, very high day temperatures and low night temperatures.

Animals

Draz, Director of the Desert Range Development Project in Egypt, also referred to the need for a thorough understanding of the ecological, logical, genetic, and physiological bases which will enable the selection of plants and animals most suited to arid conditions, and drew attention to the importance in animals of heat tolerance and heat dissipation, about which much is still to be learned. He stressed the idea that it is short-sighted to look down on local breeds which have become adapted to the conditions of living in the environment (See p. 335).

Man

Whatever research work is done in any or all the fields we have so far considered, the end result should be for the benefit of man. It is appropriate, therefore, to think at this stage about man himself, his well-being and living conditions. One striking feature of man in the desert is his nomadism. While it may always be that some movement of flocks must occur to and from grazing areas, it does not follow that the shepherds remain nomads. It is unnecessary to do more than remember how very different the lives of men, women, and children are under nomadic conditions from those enjoyed in the dry climate of New Mexico. Any changes in modes of living must mean great social adjustments for those people.

Ladell, Director of the Hot Physiological Research Unit in Nigeria, dealing with the influence of environment in arid regions (in a paper in press) points out the wide range in temperature which man has to live under, as for example at Basra where the mean monthly minimum varies from freezing to 83°F and the mean monthly maximum from 67° to 109°F. Under these conditions there is also little cloud and scanty vegetative cover so that the ground radiates heat, and dust-laden air radiates still more. Add to this wind, and water loss from the body may proceed

faster than physiologically desirable. He refers to heat acclimatization, by which is meant the physiological changes resulting in an improvement in work following exposure in a hot environment, and he believes that man can live under conditions more severe than occur in the hottest parts of the world. Protection from direct solar radiation is desirable in the form of a light broad-brimmed hat or a canopy on a tractor over the driving seat.

Good housing is essential—cool by day and of a kind to give adequate protection at night. In this respect the thick-walled, small-windowed, pisé houses of the Near East, Pakistan, and India are types.

Water is the essence of life, and it seems a pity that because of religious beliefs or tradition desert dwellers do not take to the use of galvanized iron tanks to store roof water.

Desert dwellers may suffer from prickly heat and from malnutrition and vitamin A deficiency which leads to slow healing of wounds.

We who live in comfort find it hard to realize what life is like without electricity or gas, without water in pipes, without refrigeration and radios, air conditioning in buildings, good roads and fast cars, and so forth. But many thousands live where hydroelectric power is not available nor where fossil fuels like coal and oil can be used. So we turn to such sources of power as wind and sun.

Successful wind-driven generators up to 70 kilowatts capacity are operating in Denmark, and two prototypes of 100 kilowatts are functioning in the United Kingdom. Much thought is being given to automatic regulation in variable winds in order to make the fullest use of wind power. It is most important to choose the right site for a windmill.

The use of wind power to pump water either directly or through the use of electricity should result in saving bullock power and thereby acreage for human food.

Solar energy has already been put to work for cooking and heating water and we saw demonstrations of equipment in action at New Delhi, India, in November, 1954. The problem is to reduce the cost to within the means of the average Indian. In

California hot water heaters have been installed on the roof with insulated hot water storage tanks.

Considerable thought and experimentation is being devoted to the possibility of developing a solar engine. Abbott of the Smithsonian Institution has long pioneered in this field.

Need for Scientific Teamwork

I have merely touched on a few points in a few of the many fields of research in which we must achieve results.

In any scientific work it is first essential to survey the field. In this case it is a survey of the fields. Therefore it is a highly complex operation calling for teamwork of the highest order. I do not deprecate individual effort. Indeed some of the greatest contributions to knowledge have been made by the Newtons and Einsteins. But in the title of this paper, "The Challenge of Arid Land Research and Development for the Benefit of Mankind," it is impossible to avoid the inference that we must have teamwork, and that teamwork should be between individuals, between universities and research institutions, and between peoples—in other words, between United Nations organizations.

Particularly does it seem appropriate that we who belong to those sections of mankind that enjoy the highest standards of living should see a plain duty to help in every way possible to benefit the less well-off sections of mankind. I often think how wasteful it is that the billions of money are expended in defending part of mankind against possible aggression by another part of mankind when they could be spent in research work of this sort for the benefit of mankind. Imagine our young folk being called up for service and electing to serve for a period in one of the fields we have been discussing during these meetings. But that is Utopian.

It seemed to me that the title of this paper required me to be a sort of missionary, and if I have succeeded in confirming in the reader a determination to support in every way practicable the efforts of scientists, the work of institutions and above all the great work being done by UNESCO, FAO, WHO and others, I am amply rewarded.

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VARIABILITY AND PREDICTABILITY OF WATER SUPPLY

Questions

How predictable is precipitation in an arid region?

Are there distinct drought cycles?

What are the prospects for usable ground water occurrence in arid areas?

What is the practicability of locating and estimating volume and rate of natural recharge of underground water supplies?

Within a given watershed, to what degree can the water sources and water yield be determined?



Climatology in Arid Zone Research

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The problems of the arid regions are climatic in origin and stem from the imbalance between the water supply and the water need. Two obvious proposals have been suggested in order to relieve this disparity between water need and supply: (1) increase the water supplies through artificial induction of rainfall; (2) make better use of the existing water supplies by study of the water requirements of crops and avoidance of overirrigation. This paper will be directed toward the second—ways in which existing water supplies may be utilized more effectively.

One cannot determine the amount by which precipitation fails to supply the water needs of crops unless these water needs are known. Thus, it is first necessary to determine the water need. This most important climatic element is defined as the amount of water which will return to the atmosphere from a surface completely covered with vegetation when there is sufficient moisture in the soil for the use of the vegetation at all times. I have called this the potential evapotranspiration (10, 17).

Measurement of Evapotranspiration

Precipitation is easily measured by means of rain gages and has been recorded in most settled areas of the world. It is not easy to measure evapotranspiration, however. In fact, no weather service in the world yet determines this important element, and the little known about its distribution has been pieced together from various scattered determinations.

Scientists have tried various ways to determine the amount of

water used by plants. Experiments which attempt to measure the water loss from a leaf or a branch detached from the plant, or from isolated plants in special pots, are highly artificial, and generalizations from such studies have sometimes been greatly in error. The only method that measures the evapotranspiration from a field or any other natural surface without disturbing the vegetation cover in any way is the so-called vapor transfer method (14). Water vapor when it enters the atmosphere from the ground or from plants is carried upward by the moving air in small eddies or bodies of air that are replaced by drier eddies from above. If we determine the rate at which the air near the ground is mixing with that above it and at the same time measure the difference in water vapor content at the two levels, we can determine both the rate and the amount of evapotranspiration.

This method is not easy to understand or to use. It requires physical measurements more precise than are usually made. However, the method can and should be perfected for it will answer many important questions for climatology and biology.

There are other ways of determining both water use and water need. In some irrigated areas rainfall, irrigation water, and water outflow are all measured. The fraction of the applied water that does not run off is the evapotranspiration. In a few isolated places, mostly in western United States, irrigation engineers have determined the evapotranspiration from plants growing in sunken tanks filled to ground level with soil in which water tables are maintained at different predetermined depths beneath the soil surface (19).

Since 1946 increasing thought has been devoted to the problem of measuring the water use of plants under optimum soil moisture conditions, and an instrument has been developed and standardized (4, 18). It consists of a large soil tank so constructed that plants can be grown in it under essentially field conditions and can be provided with water as they need it. The tanks are 4 square meters in area and contain soil to a depth of approximately 70 centimeters. They have means for subirrigation from a supply tank designed so that actual amounts of water used can be accurately measured, or they can be irrigated by sprinkling from above.

The latter method proves to be much more satisfactory in practice. When it rains, any excess water drains through the soil and is similarly measured. Thus, evapotranspiration can be determined as a difference since every other term in the hydrologic equation is measured. A number of these evapotranspirometers are now in operation in widely scattered areas of the world. Many additional installations are needed if we are to understand the variation of evapotranspiration from one area to another.

The analysis of the observations of evapotranspiration from collaborators in various climatic regions of the earth has revealed that it is easy to get erroneous answers, particularly in arid areas where measurements give values that are likely to be too large (5). The errors occur when the vegetation on the area surrounding the tanks is not the same as on the tanks or when the soil moisture inside the tanks differs from that in the soil outside.

There are three possible sources of energy for evaporation or evapotranspiration: solar radiation, heat that reaches the evaporating surface from the air, and heat that is stored in the evaporating body. However, with no external source of energy, the surface temperature of an evaporating body would quickly drop to the dew point of the air and evaporation would cease. Consequently, evaporation can occur as a continuing process only while energy is being received from some outside source.

The sun is the original source of all energy that is involved in the transformation from liquid to water vapor, but not all the energy that is received from the sun is used in evaporating water. Some of the incoming solar radiation is immediately reflected from the surface back to the sky. For a vegetation-covered surface about 25% of the incoming radiation is lost in this way. Also a certain percentage of the incoming radiation is radiated from the surface back to the sky, the amount depending upon the temperature of the earth's surface and on the sky above. This amount is often between 10 and 15% of the incoming radiation.

After deducting the losses due to reflection and back radiation, the remainder, which is known as the net radiation, must be partitioned into three parts; that which heats the soil, that which heats the air by convection through contact with the soil surface,

and that which is utilized in evaporation. Recent measurements have shown that when the soil is very moist more than 80% of the net radiation is used in evaporation. As the soil becomes dry, the evaporation rate declines and more of the net radiation is devoted to heating the air and soil with little remaining for evaporation.

The potential rate of evapotranspiration is realized only when the area of the evaporating surface is large enough so that all the energy for evaporation comes from radiation and none from advection. Obviously, the area of a standard evapotranspirometer (4 square meters) is too small and can give reliable values only when it is surrounded by an extensive buffer area identical in vegetation cover and soil moisture. If the area of the evaporating surface is large, the influence of the air passing over it becomes small and solar radiation is the primary source of energy for evaporation. Under these circumstances the atmospheric humidity is unimportant. If the air is moist, the temperature of the evaporating surface will rise to a point, above the dew point of the air, at which the evaporation will just use the energy that is available. Similarly, in dry air, rapid evaporation will lower the temperature of the evaporating surface until the evaporation is in balance with the available energy.

When a psychrometer is used to determine the humidity of the air, a thermometer bulb is moistened and becomes an evaporating surface. The water evaporating from the wet bulb thermometer cools the bulb. The surface area of the bulb is small, and the amount of water vaporized is very small. Heat flows into the water film on the bulb from the warmer surrounding air, and the evaporation process will reach equilibrium at a rate and at a wet bulb temperature at which the energy appropriated from the air is just sufficient to maintain the evaporation. Solar radiation contributes almost no energy to this process. The water evaporated from the wet bulb moistens the air, but the amount is so minute that the effect on the moisture content of the air is completely negligible.

The Piche evaporimeter is also small with an evaporating surface of approximately 13 square centimeters. The evaporation from the surface of a Piche evaporimeter is likewise incom-

petent to raise the humidity in the air to any significant degree. Here, most of the energy used in evaporation comes from the air.

The Weather Bureau Class A evaporation pan is 4 feet in diameter, and on a summer day in a dry situation it may evaporate 2 gallons of water. Solar radiation contributes an important share of the energy for evaporation, the amount depending on the turbidity of the water and on the albedo of the pan, which varies greatly with type, age, and condition of the material of which the pan is made. Additional energy for evaporation is available from the air. The amount of water evaporated from the pan will do little to modify the moisture content of the air; but immediately over the water surface the humidity is raised, the moisture gradient reduced, and the evaporation impeded. The extent of this influence depends on the rate at which fresh air passes across the evaporating surface from outside.

An extreme example of the effect of evaporation on the humidity of the air is taken from a series of observations made during the period 1907-10 in connection with an investigation of the evaporation from Salton Sea in the Colorado desert of California. The sea had been formed accidentally in 1904 while the Colorado River was out of control and pouring into the dry bed of Salton sink. When the river was again confined to its channel in 1907, Salton Sea consisted of a sheet of fresh water 45 miles long and 10 to 15 miles wide with 440 square miles of surface area. The sea was expected to disappear in 10 or 12 years so it was recognized as presenting an unexcelled opportunity to study evaporation on a large scale in an arid climate (1).

Evaporation pans were exposed at various heights on towers over the sea surface and over the land at several locations away from the water. Unfortunately, the pans were not all the same size and were not uniform as to height or exposure. Nevertheless, the results for 1910, the only ones that I have been able to find, are very interesting. Table 1 gives the annual total evaporation for the calendar year. Four other stations located up to 40 miles away from the sea gave results that are similar to those from Salton Sea Tower 1. At Indio, the evaporation from a 2-foot pan, 10 feet above the ground, was more than 200 inches.

The actual evaporation from Salton Sea was determined by

TABLE 1

Station	Location	Height of Pan (ft)	Diameter (ft)	Evaporation (in.)
Tower 1	1500 ft inland	Ground	2	164.50
Tower 1	1500 ft inland	40	2	193.44
Tower 2	500 ft at sea	2	4	108.65
Tower 2	500 ft at sea	45	4	137.71
Tower 4	7500 ft at sea	2	4	106.45
Tower 4	7500 ft at sea	45	4	140.02

measuring inflow, outflow, and change in water level. The results for three years are as follows:

Period	Evaporation (in.)
June 1, 1907–May 31, 1908	51
June 1, 1908–May 31, 1909	59
June 1, 1909–May 31, 1910	69

The average annual evaporation for the 3-year period was about 60 inches.

The evaporation from the inland ground pan was more than two and one-half times that from the sea and that from the two pans mounted 2 feet above the sea surface, 80% greater than from the sea. The similar evaporation from comparable pans on towers 2 and 4 indicates that the rate of evaporation from the sea is nearly uniform, beginning a short distance from the shore. The much smaller evaporation from the 45-foot high pans over the water than from the 40-foot pan over the land proves the existence of a "vapor blanket" over the water and shows the strong reciprocal relation between the moisture structure of the air and the evaporation.

The evaporation from Lake Okeechobee in the humid climate of Florida has been determined by careful measurement of precipitation, surface inflow, and outflow (3). Inseepage and outseepage were not measured but are believed to be small. The lake is 600 to 800 square miles in area. At the same time, the Weather Bureau has maintained a standard 4-foot evaporation pan at Belle Glade, on the south shore of the lake (6). The comparative mean monthly evaporation in inches is as follows:

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Lake	2.54	2.86	4.20	5.66	5.98	5.36	6.04	5.83	4.55	3.96	2.71	2.47	52.16
Pan	3.22	4.05	5.79	6.64	7.25	6.28	6.32	6.36	5.33	5.03	3.77	3.01	63.05

In this example, in a humid climate, where the lake evaporation is 83% as great as the evaporation from the pan, it is seen that size of evaporating surface is a much less important factor than in an arid climate.

Thus, it is evident that measurements made with evapotranspirometers are subject to serious error. To insure that the observations are reliable it is necessary to keep an area around the field tanks under high soil moisture. The size of this buffer area varies with the climate; it must be much larger in the arid climates than in humid.

Conditions Affecting Evapotranspiration

Although the various methods of determining evapotranspiration have many faults and the determinations are scattered and few, we get from them an idea of how much water is transpired and evaporated under different conditions. We find that the rate of evapotranspiration depends on five things: climate, soil moisture supply, plant cover, soil type and texture, and land management. There is considerable evidence to show that, when the root zone of the soil is well supplied with water, the amount used by the vegetation will depend more on the amount of solar energy received by the surface and the resultant temperature than on the kind of vegetation growing in the area. Soil type and texture and farming practices likewise have little effect on the rate of evapotranspiration under high moisture conditions. The water loss under optimum soil moisture conditions, the potential evapotranspiration, thus appears to be determined principally by climatic conditions.

Using the most reliable measurements of evaporation and transpiration that are available a valid and practical relationship between certain climatic parameters and potential evapotranspiration has been obtained. This relationship permits the computation of potential evapotranspiration for any place from information on air temperature and latitude alone. The relationship is given and its use described elsewhere (11). Work is proceeding toward the development of a new formula that is based on sound physical principles. In the meantime, the present em-

pirical formula is being widely used in various water balance studies.

Needed Inventory of Arid Climates

It has long been recognized that in any adequate program of desert research a first step would be an inventory of the dry climates of the world. In 1951, at the first session of the Advisory Committee on Arid Zone Research in Algiers it was recommended that maps of the arid climates be prepared. As a result, Meigs drew up for UNESCO a series of homoclimatic maps of the arid zones which delineated the basic arid and semi-arid regions by means of the moisture indices of my 1948 classification. These maps were published in a provisional edition in 1952. They represent a starting point in such an arid zone inventory but they fail to provide all the information possible from such a mapping of arid and semi-arid regions, information which must be made available for a complete understanding of arid zone problems (12).

Water Surplus and Deficiency

Since rainfall and evapotranspiration are due to different things, through the year they are not often the same either in amount or in distribution. In some places more rain falls month after month than the vegetation can use. The surplus moves through the ground and over it to form streams and rivers and flows back to the sea. In others, the rainfall is deficient in one season and excessive in another, so that a period of drought is followed by one with runoff. In still other areas, month after month, there is less water in the soil than the vegetation could use if it were available. There is no excess of rainfall and no runoff, except locally where the soil cannot absorb the rain water as it falls. Consequently, there are no permanent rivers and there is no drainage to the ocean.

From a comparison of the monthly march of precipitation with potential evapotranspiration at different stations, it is possible to obtain a clearer picture of the periods of water surplus and deficiency and to bring into perspective the nature of the water problems in an area. Figure 1 shows the march of precipita-

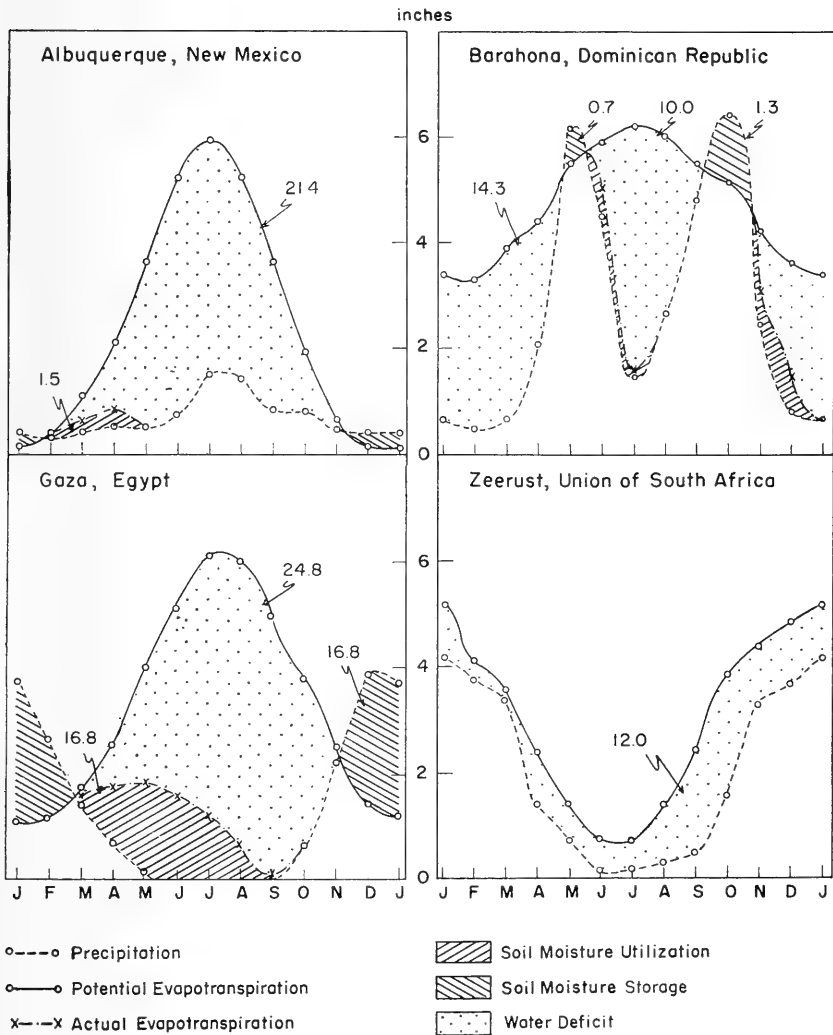


Figure 1. The water budget at four selected stations.

tion and potential evapotranspiration at four places in arid or semi-arid regions of the world. Because of variations in precipitation at these four places there is a considerable variation in the periods of moisture surplus and deficiency which they display. At Albuquerque, average precipitation never exceeds 1.5 inches

a month, whereas the summertime need for water is as high as 6 inches a month. Only in the winter does the meager precipitation equal or exceed the reduced evapotranspiration, and a slight storage of moisture in the soil occurs. The moisture deficiency in summer is large, being over 21 inches. No form of moisture conservation would make agriculture possible here. Irrigation would be an absolute necessity.

Precipitation is highly variable at Barahana, Dominican Republic. It is less than 2 inches per month in the winter and again in July, and more than 6 inches per month in May and October. As a result there is a considerable deficiency of moisture during both the summer and winter, amounting to over 24 inches for the year, while there is some soil moisture recharge in spring and fall.

Gaza is the only Egyptian station which has an average water surplus at any time of year. On account of its Mediterranean type of climate, the precipitation at Gaza is concentrated in the winter half of the year and exceeds the water need of that period by a considerable amount. As a result there is storage of moisture in the ground and a water surplus of 2.7 inches in January and February. However, due to the lack of summer rainfall and the high summer water need a moisture deficiency of over 27 inches occurs in summer. Thus, in spite of its more than 15 inches of precipitation a year, agriculture without irrigation is extremely hazardous because of the poor distribution of rainfall through the year. At Zeerust in the Union of South Africa, the march of precipitation closely follows that of water need. In no month does precipitation equal need so that there is no soil moisture storage. However, because of the fact that precipitation and need are nearly parallel and fairly close, the area chronically suffers from hidden drought. Agriculture may be possible without supplemental irrigation but would be far more successful with it.

The values of moisture surplus and deficit have been combined to form a moisture index which is the basis for the division of land areas into moisture provinces. The use of such an index in delineating moisture regions is a well-accepted practice. The need of a second index, the annual potential evapotranspiration itself, to

define climatic provinces is not well understood. Recent studies have indicated that crop growth is closely related to potential evapotranspiration, or the water use of plants (15). Thus, the annual potential evapotranspiration provides an index of the growth potential of an area. A single parameter, annual potential evapotranspiration, because of its dependence on the energy balance, can serve both as a moisture and a thermal index.

The indices are important in defining world climatic regions. Their greatest value, however, lies in specifying at every point a thermal growth potential and the degree of moistness or aridity of a climate. In other words, the indices are continuously distributed about the earth and do not exist merely along inter-provincial boundaries, as do Köppen's limits.

As part of a task which the Laboratory of Climatology has undertaken for the Office of Naval Research, maps are being prepared of precipitation, potential evapotranspiration, water surplus, water deficiency, and the moisture regions for all parts of the world on a scale that is consistent with the density of the climatic network. As an example, maps of Japan, Korea, and Formosa were made in scale 1:1,000,000. Maps of the entire continent of Africa have been completed in color, using the new American Geographical Society base map on a scale of 1:3,000,000. It is anticipated that the mapping of the entire earth will be completed within a short time. These large-scale maps give a clear picture of the distribution of the arid and semi-arid regions and add considerably to an understanding of their water balance problems. For instance, from such detailed maps it is possible to work out exactly the overall irrigation needs and the water supply that is available from precipitation. Such information is basic in any intelligent evaluation of the water resource potential.

Variability in Climatic Factors

The inventory of the arid and semi-arid regions of the world should go farther than merely making available the average annual distribution of the different moisture regions. It has long been recognized that variability is one of the main characteristics of dry climates. The reliability of precipitation becomes less as the

amount decreases, so that in dry regions one might expect great yearly changes in the extent of the arid and semi-arid zones. As part of the inventory it is necessary to determine the year-to-year shifts in the extent of the climatic regions and to make available the information in graphical or cartographic form. Good examples are the maps showing the year-to-year variations in climatic zones over the United States which I prepared for the U. S. Department of Agriculture in 1941 (9). From these data it was possible to determine the number of years each of the different climatic zones occurred over different areas. Figure 2 shows the frequency of arid and semi-arid climates over the United States based on the period 1901-39. Information of this type, when coupled with the detailed data on the moisture regions of the world, would provide a much more adequate basis for the interpretation of moisture problems than is presently available.

In addition to determining the year-to-year fluctuations in the geographic distribution of the broad-scale moisture regions it is desirable to know the probabilities of occurrence of values of the other important factors which constitute the water balance. In

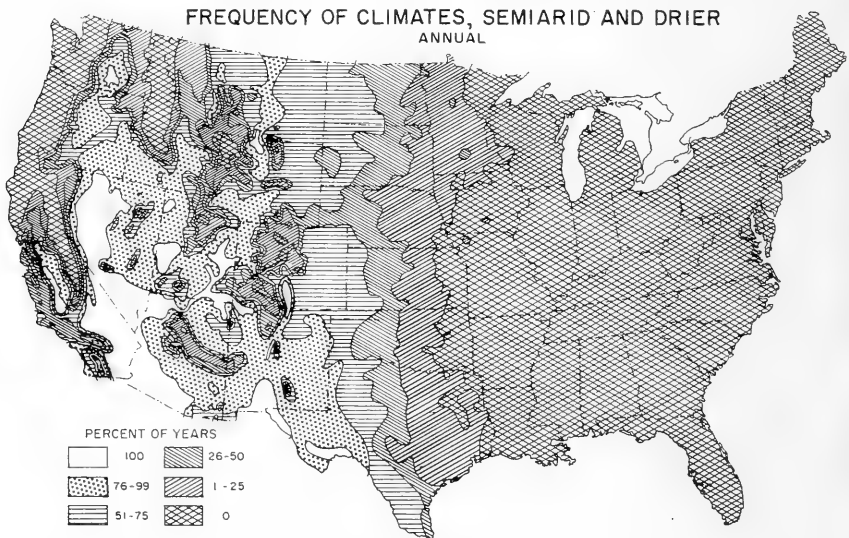


Figure 2. Frequency of semiarid and drier climates in the United States.

arid climates the moisture deficiency is the most significant value than can be determined from the water balance bookkeeping procedure since it gives an indication of the severity of the water problem and reveals how much water must be supplied in other ways. It is thus necessary to carry the bookkeeping procedure one step farther to determine the year-to-year fluctuations in the moisture deficiency and to derive the probabilities of occurrence of different levels of deficiency. Figure 3 gives the magnitude of the water deficiency in the Missouri Valley area of the United States for the period 1920-44. This region is one of critical importance in any research on arid and semi-arid zone problems as it marks the transition zone between regions where agriculture is feasible without irrigation and where it is not. Average annual values have little meaning in this region. The limit of economically feasible agricultural production can vary so greatly over the region from year to year that probabilities based on a number of years of observations must be studied in any intelligent approach to the problem.

Daily Water Balance Bookkeeping

It is possible to compare the precipitation with the evapotranspiration or water need on a daily as well as a monthly basis. If this is done and a regular account is kept of the day-to-day additions and withdrawals from the soil moisture bank, it is possible to determine when moisture is lacking and replace it through irrigation. This insures that there is never any deficit of water in the soil and also that there is no overirrigation and wasteful misuse of the water resource. An irrigation schedule can be derived as a natural result of the daily bookkeeping of precipitation and water use.

Until recently the most common practice of farmers had been to watch the crops for signs of moisture deficiency and to irrigate an undetermined amount when such signs were recognized. This practice was far from satisfactory, for when the crops showed signs of distress, a considerable reduction in yield had already occurred. The irrigation bookkeeping procedure eliminates this problem by telling when and how much to irrigate before any deficiency exists in the soil.

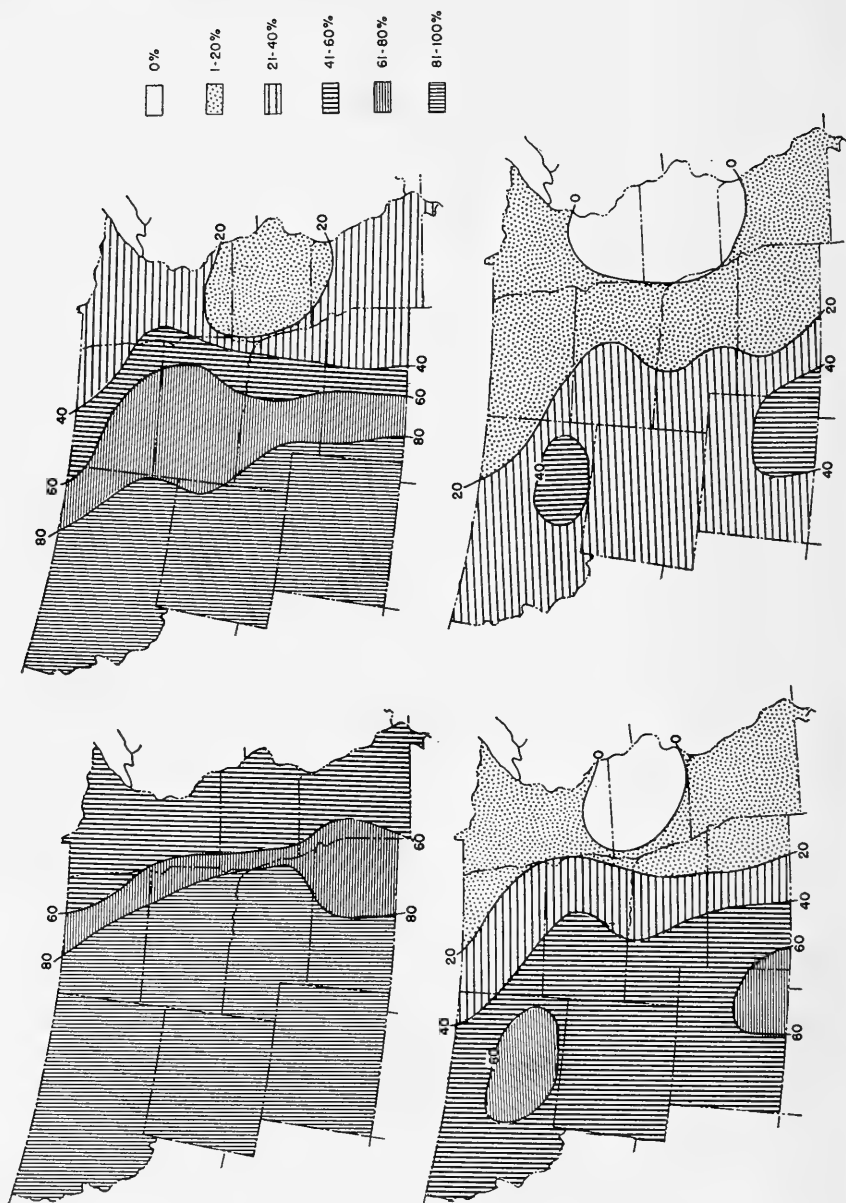


Figure 3. Magnitude of water deficiency in the Missouri Valley, 1920-44; per cent of years with water deficiency more than designated amount. Upper left, deficiency of 4 inches; upper right, deficiency of 8 inches; lower left, deficiency of 12 inches; lower right, deficiency of 16 inches.

The irrigation scheduling procedure which was developed for use in the humid climate of New Jersey will also apply in arid climates; but here the problem is even simpler than in the moister climates because there is little or no need to be concerned over the possibility of rainfall affecting the program (13, 16). Thus, it would not be necessary to provide a "safety factor," and one could schedule irrigation to bring soil moisture just back to field capacity in the desired root zone each time.

Estimating Water Needs

In the arid and semi-arid regions of the world, agriculture is not feasible without recourse to supplemental irrigation. It is therefore of primary importance that reliable information on the magnitude of the water need in these areas be made available. Computations of the water need for the various climatological stations in the states of Utah, Colorado, Arizona, and New Mexico are plotted in Figure 4. It varies from a little over 60 inches in the hot, dry regions of southwestern Arizona to less than 15 inches in the mountainous regions of Colorado. Irrigation engineers have attempted to arrive at figures for water need from the few available measured observations of evaporation from pans. Meyer has presented a map of the evaporation from shallow lakes and reservoirs which indicates values of over 100 inches a year in the southwestern part of Arizona and up to 80 inches a year in New Mexico (7). Horton, analyzing records from Weather Bureau Class A evaporation pans, found values of evaporation of over 120 and 90 inches a year respectively in these same areas (2). Horton's map of evaporation from pans has been reprinted, but it is reprinted as a map of potential evapotranspiration (8).

The high values of evaporation which have been found by Meyer and Horton without due consideration of the effect of the size of the evaporating area on the rate of evaporation have been used to arrive at figures for water need. They have led to false conclusions concerning the water requirements in these arid areas and, in certain cases, have resulted in the excessive use of water with damaging results to the soil. It is time for irrigation engineers and others who are attempting to determine the water needs and requirements of these dry regions to reevaluate the available

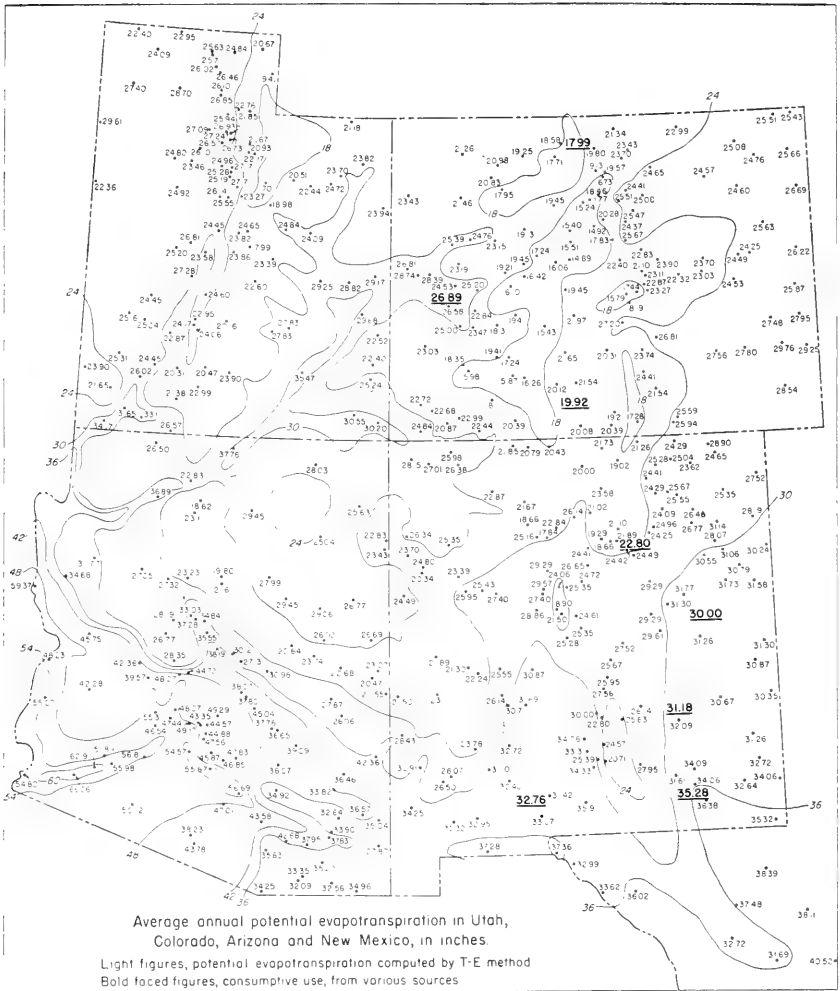


Figure 4. Distribution of average annual potential evapotranspiration in Utah, Colorado, Arizona, and New Mexico.

information on the basis of these known limitations and to readjust their estimates of irrigation requirements and of the water resources of the arid areas.

One of the objects of this paper has been to show the usefulness of the concept of potential evapotranspiration in arid and semi-

arid research. For instance, with this concept it is possible to determine the water needs of an area and to evaluate the utility of the water supply to meet those needs. Through its use in the classification of climates, it becomes basic to any inventory of the arid regions of the world. It is possible to use it to work out a complete and accurate irrigation schedule that will permit the maximum returns with the water available. Thus, it becomes more abundantly clear as studies of the concept of potential evapotranspiration progress that it is a tool of increasing usefulness in the solution of problems not only in humid regions but also in the potentially important arid and semi-arid regions of the world.

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Water Resources in Arid Regions

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In general we consider as arid those regions where water is the usual limiting factor of agricultural production. In North Africa, these regions are approximately those that have an annual rainfall of less than 500 m/m (6). They present extremely varied characteristics. A Tunisian arid area such as the Sahel has a population density of more than 70 inhabitants per square kilometer, although the annual rainfall is well below 400 millimeters. In the south, on the other hand, where the rainfall is less than 100 millimeters, the population density is insignificant, except for the oases.

Arid regions often draw their water resources from humid regions on the outside. This is so, for example, in the Nile Valley, in Mesopotamia, and in the valley of the Indus. This study is limited to the cases of typically arid areas and to the water resources contained within their perimeters.

The hydrology of arid regions naturally obeys the same physical laws as the hydrology of every other region, but also has particular traits to which we shall limit ourselves. We realize that our experience is related especially to the arid areas of North Africa and, to a lesser degree, to the rest of the Mediterranean basin. Accordingly, to that extent this study lacks generality. There will be no discussion of the cold arid zones.

In the study of water resources, it will be impossible to consider individually the agricultural and economic phases since these are inseparable from the hydrology in arid regions.

Effects of Variability of Climate on Economic Life of Arid Regions

Arid zones are characterized by lack of water and variability of climate. This variability entails numerous economic, social, and political consequences. The enumeration of some of these will be useful for they may orient studies of hydrology and climatology.

Nomadism

The rainfall must exceed certain amounts to be usable either for agriculture or for cattle-raising. These amounts are not exceeded everywhere at one time. The population must plant where the rain has fallen and likewise transport their flocks there.

Nomadism is therefore obligatory for complete utilization of very arid areas.

Storing

By storing is meant all the methods of storing resources or products from one year or from one group of years to another.

Storing first has to do with the water supply, and in arid regions it necessitates regulation continuing over several years in the interest of the underground aquifers which alone are capable of resisting loss by evaporation.

Storing should also cover all agricultural products, the principal ones in Tunisia being wheat, vegetables, oil, and fodder. Stocking of these products requires the intervention of the state or of powerful cooperatives, and seed supplies should be furnished by the state in many areas.

In any case, material means for storing are not sufficient and should be supplemented by a system of credit.

Exchanges

Despite all the methods of storing that an arid country can utilize, its possibilities of demographic expansion remain very limited. Beyond these possibilities, and without the importation of water from surrounding humid lands, it is necessary to proceed to exchanges of agricultural products with regions where the climate is temperate or complementary. Such exchanges can be

within the network of the nation itself, of an association of states permitting compensation, or on an international scale.

This raises inevitable political problems, and it can be stated from the record that the prosperity of arid regions has been extremely sensitive to political conditions.

Economic Planning

In arid regions planning should be for long periods. The five-year period, often used in temperate countries, is too short in the arid zones. We give two examples.

Tunisia had established a plan for agricultural development for the years 1949-53, based on statistics for preceding years. The years 1942-48 had been very dry, but the years 1949-53 were extremely humid. Agricultural production increased considerably, but it is very difficult to determine what part of the increase was the result of the measures taken under the plan.

With the same thought (8) Mexico established a six-year plan providing for a 50% increase in wheat production for the period 1953-59, in comparison with the period 1948-51. Argentina aimed at a 27% increase in wheat production before 1958, taking for base the production of 1947-51. Variability in climate can cause as great variations, despite the fact that these countries are larger than Tunisia. When these plans terminate, it will perhaps be difficult to determine whether the objectives have been attained; yet it is necessary to check their efficacy.

A rational procedure should include (a) planning for more than 5 years, depending on the variability of the climate (20 or 30 years, for example), and (b) submitting the economic statistics to climatic corrections resulting from a parallel study by statisticians, agronomists, and hydrologists.

Variability in Rainfall

Rainfall is the most variable element of climate and the one that most conditions the economy of arid regions. Variability in rainfall has repercussions on harvests, where dry culture is used, on the volume of water reaching the water table, and on the volume of runoff.

One might ask whether, in desert areas, the mean annual rainfall is of any interest. If we take a station such as Adrar, where the average annual rainfall is 17.4 millimeters, there is evidently little chance of that amount of rainfall in any one year, the standard deviation being 16.7 millimeters. On the other hand, there is much more chance that 174.0 millimeters will fall in ten years. The annual average value has consequently little bearing on the most probable value, but it gives an idea of the amount of precipitation that is more realistic in less arid regions. Such is the conclusion drawn by Dubief who has specially studied the Sahara (7).

The element which may most easily be considered is the annual rainfall. The yield of crops depends not only on the total annual rainfall, but also on the distribution of the rain by season and even by days.

However, to simplify matters, the discussion in this section will be limited to:

1. What is the probability of having, at a given point, a total annual rainfall greater than a given amount?
2. What is the probability of having a given annual total rainfall over the entire country?
3. Can one forecast variations in the annual rainfall over a period of time?

Rainfall at Given Point

Suppose that it is possible to make observations over a long period of time, say more than 50 years. The variability of the rainfall at a given point can then be represented during the length of observation by the law of Galton Gibrat. If H is the annual amount of rainfall in millimeters, HM the medium amount, and HO the corrective amount, normal distribution will be the logarithm of $(H + HO)$. On a Gausso logarithmic diagram, we obtain a straight line equation:

$$\log (H + HO) = ax + \log (HM + HO)$$

Figure 1 gives the frequencies of the annual rainfall for Tunis, and for the average of five stations scattered over all Tunisia

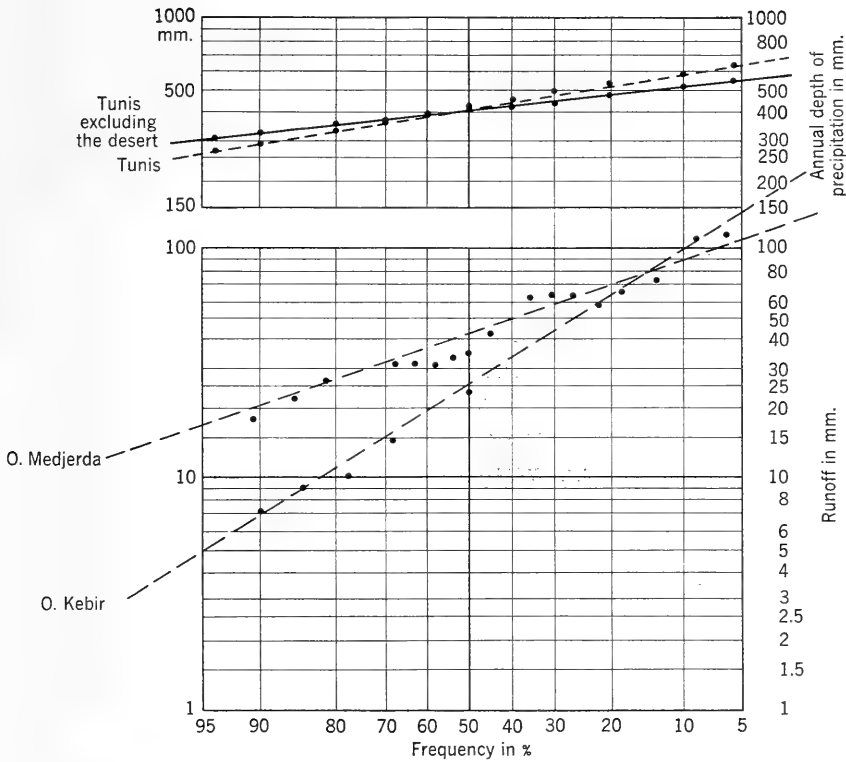


Figure 1. Top, frequencies of annual precipitations, Tunis and average of 5 stations, raised by 200 m/m. Bottom, frequencies of annual runoff of two watercourses in Tunisia.

(the desert zone excepted). This figure also gives the frequencies of the annual average runoff for two watercourses whose basins receive an average of 500 millimeters of rain per year:

Oued Kebir, whose basin surface is 225 square kilometers, and Oued Medjerda, whose basin surface is 16,000 square kilometers.

Rainfall Over Entire Country

As indicated by the curve of Figure 1, relative to the average of the five stations, a deficit of rainfall at one point can be compensated by a surplus at another, and the variability of the total rainfall on a territory is less than in any one locality.

However, the variability of the annual rainfall is still very large, even for a country of the size of Tunisia. It is easy to become aware of this in comparing the distribution of rainfall during two four-year periods, one very dry (1944-47), the other very humid (1931-34) (Figure 2). If we assume that desert begins where there is less than 200 millimeters annual rainfall, we see that the limits of the desert moved some 200 kilometers in the Sahel between these two periods. The four-year period was chosen because it marks the influence of rainfall not only on annual harvests but also on deep-rooted plants such as olive trees. In fact, in the Sfax area, famous for its orchards, the olive trees in 1947 had lost all their leaves and if the drought had lasted longer, great numbers would have died. Sand dunes were developing with great rapidity all the way into the center of Tunisia. Harvests of dry culture were of no account in the center and in the south.

The drought of 1944-1947, moreover, was felt outside Tunisia, in Italy for instance (5). Hence the necessity, when studying the variability of climate, to cover territories of different areas to determine the extent of regions within which there can be an economic compensation for the variability of the climate.

Forecasts on Variability of Rainfall

If the rainfall varies much from one year to another, it varies also in the course of consecutive groups of years. Statistics give some idea of this. For example, the Sfax station gives the data in Table 1. The importance of the difference in the average five-year precipitation illustrates what has been said earlier on the subject of equipment plans. But, the statistics cannot be extrapolated with certainty beyond the period of observations. Beyond that period one must have recourse to other methods of forecasting, which leads one to interrogate witnesses of a more-distant past.

The only methods employed in Tunisia are the examination of tree growth and archaeological studies. The first method bore only on a humid locality but, however, one neighboring to the arid zone. The Meteorological Service of Tunisia has applied it to the study of the climate of Ain Draham since 1736, in examining the growth rings of an old oak knocked down in 1905, and in com-

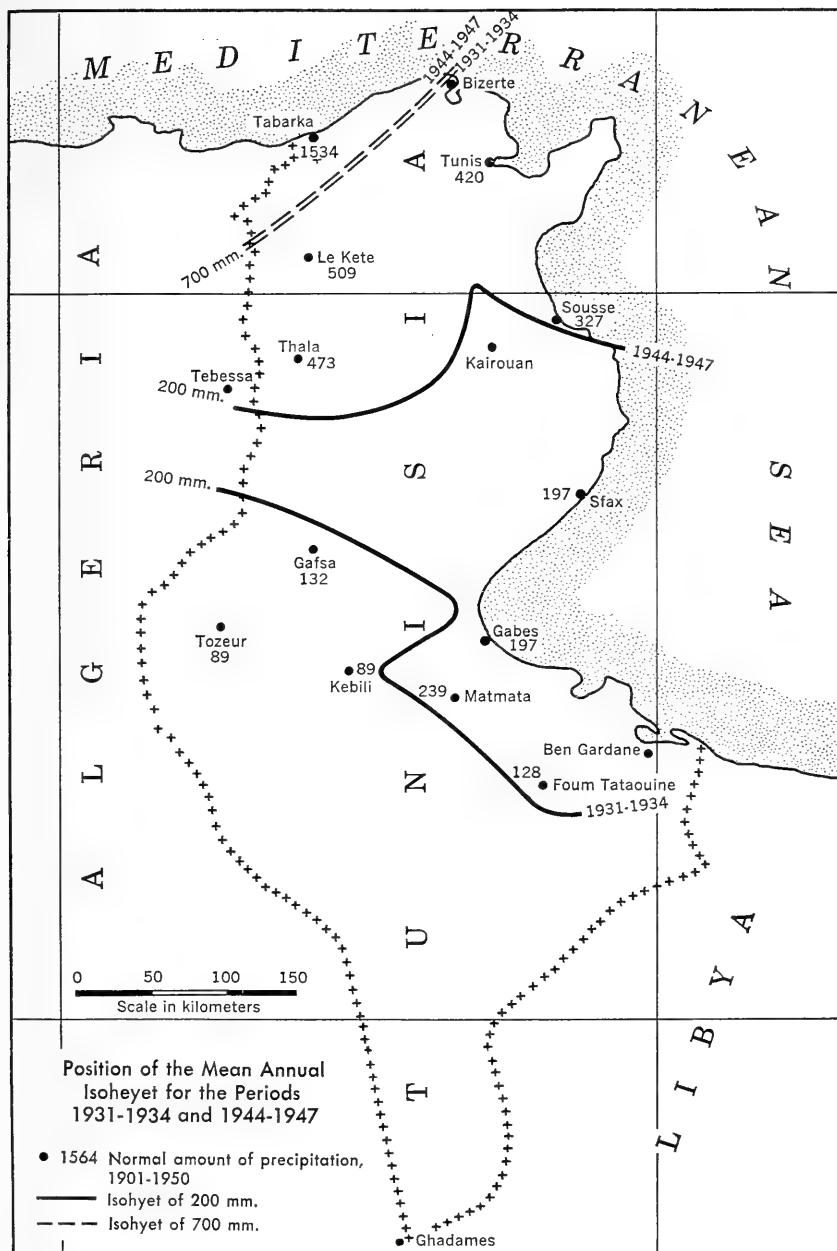


Figure 2. Tunisia, Position of isohyetes in 1931-1934 and in 1944-1947. Annual averages for 4 years.

TABLE I

Sfax Annual Average Rainfall by period	Minimum		Maximum	
	Year	Depth, m/m	Year	Depth, m/m
1 year	1946	62	1921	372
2 consecutive years	1945-46	67	1905-06	333
5 consecutive years	1943-47	115	1918-22	263
10 consecutive years	1938-47	143	1905-14	229
20 consecutive years	1933-52	180	1903-22	224
50 consecutive years	General average 1901-52, 197 m/m.			

paring them with the rainfall during the period 1890-1905 (10). The author of this study has inferred from it that the period 1736-90 was clearly more rainy than the present period. Despite all the reservations that one can have on the methods followed by Ginestous, one is struck by the fact that the historical documents actually make no mention of famines in the eighteenth century (2), but do mention, on the contrary, abundant rains and harvests. One can proceed no farther in Tunisia because there is a lack of trees to observe, but the method may be developed in other countries of the arid zone. Very old trees exist even in the center of the Sahara.

The ensemble of historical and archaeological studies argues in favor of a great stability of climate. For Tunisia, this conclusion was drawn from numerous studies based on the examination of ruins, of Roman and Arab water works, of historical texts, of the constancy of methods of cultivation and types of plants raised, and finally of the exceptional character of the two four-year periods cited above. The same conclusion was arrived at in Israel (18) and in India (16).

So the rainfall seems to have remained the same since antiquity, with the exception of variations of the same kind as those that we noticed at the present time. Can these variations be foreseen?

It must be noted in this respect that a dry year, even an exceptional one, does not result in famine nor does it constitute an economic catastrophe, unless it is one of a group of consecutive dry years extending over a vast territory. It is important to fore-

cast and to evaluate these periods of drought, as well as the periods of abundance that present the same characteristics. Even if the arrival of a given period cannot be predicted, it is useful to know its statistical probability which has evident political and economic consequences: a completely unorganized country will suffer famines which could be avoided by an organization at the provincial level. More and more serious famines could be avoided only by national, federal, or international organization.

There exist, in fact, periods of famine, of long duration, covering more or less extensive territories. They have meteorological causes that should be studied in two phases: (*a*) the meteorological situations which cause the periods of famine, and (*b*) the causes of such meteorological situations.

The statements made regarding the historical permanence of the climate lead to the supposition that variations in climate are the result of causes which themselves fluctuate. Thus one proceeds to a study of the fluctuations in climate and to a study of the fluctuations in all the geophysical or cosmic phenomena capable of varying in a concomitant manner, choosing those phenomena whose fluctuations can be forecast, such as cycles of sunspots.

The simplest method has been to try to deduce periodicities from the analysis of past observations and to suppose that they will continue in the future. This analysis, to be convincing, should be made by dividing the time into two periods for which one possesses information. The first serves for analysis, the second for verification. The conclusions are of value only if they cover a group of stations for which there are available long-term observations.

To my knowledge these attempts have not yet yielded usable conclusions. It is hoped that conclusions may be reached in the future since documentation at hand is constantly increasing and also the field of study of geophysical and cosmic phenomena is widening.

In addition, the study of natural fluctuations in climate has become more and more urgent in the past few years with the appearance of possible causes of artificial man-made variations:

artificial nucleation and atomic processes, whose effects can be considered a part of the first plan. A new field of study of variability is opening. This will become more complicated because the causes of natural variability will be less clear (14).

Since the artificial modification of rainfall is beyond the bounds of this study, we make only one comment. The present studies of the processes of nucleation aim above all at increasing rainfall when the conditions favorable to natural precipitation have already been met. These processes permit the making of one general reservation. If they are effective, they risk, in fact, increasing the variability of the climate, and their application should consequently be considered under such conditions that the processes will contribute not only to an increase of precipitation but also to an increase in water reserves.

Water Resources

The water resources of a region, other than the rain absorbed directly by the soil, are the portion of the rainfall stored in underground aquifers and the portion which runs off and which can be stored in the soil by dispersion or in surface reservoirs. All these fractions are interconnected. For convenience of discussion, however, we shall look at them successively. But first it is necessary to call attention to several fundamental characteristics of the hydrology of arid regions.

General Water Balance

Tunisia receives per year: 32.5 billion cubic meters of rain water and 0.5 billion brought in from neighboring regions, of which 2 billions return to the sea, and less than 1 billion passes by the underground aquifers to be used for irrigation or uselessly evaporated—all this for a population of 3,500,000.

The fraction evaporated and recoverable for dry culture amounts to some 30 billion cubic meters. It represents therefore a much greater volume than that which is recoverable for irrigation. But the importance of irrigation cannot be measured in cubic meters of water. The fractions usable for irrigation are, in fact, put to much better and efficient agricultural use, and, in countries where the variability of the climate is the main obstacle to their

development, they alone may be regulated. The aims of the development plans of Tunisia are: (a) increase of production by seeking better utilization of rainfall by dry-land cultures; (b) among the dry cultures, the development especially of the tree cultures, since the root system of trees permits the exploitation of deep soil layers and consequently maximum utilization of soil water reserves; (c) independently of the economic means enumerated earlier the exploitation of all reserves usable for irrigation whether they be large or small, underground, or surface reservoirs. The demographic expansion of the country being what it is, none should be neglected.

Water Needs: Evapotranspiration

Calculation of the evapotranspiration according to the method of Thornthwaite (20, 21) has been done for Tunisia by Preciozi (17). Because this method permits a more detailed analysis of the climate than others, it is of interest, for we have noted the great variety of conditions in arid regions.

One of its principal applications is, perhaps, the prediction of water needs for irrigation. In Table 2 are the results of the calculation of these needs, after Preciozi, for three Tunisian

TABLE 2

	Stations		
	Tabarca	Gabes	Tozeur
Annual rainfall, m/m	1029	175	89
Climatic indices ^a of Thornthwaite	B ₁ B ₃ ¹ S ₂ a ¹	EB ₃ ¹ d a ¹	EA ¹ d b ₄ ¹
Water insufficiency in July, m/m	150	166	214
Corresponding flow, liter/second/hectare	0.40	0.45	0.58
Water insufficiency through the year, m/m	407	820	1082
Corresponding flow, liter/second/hectare	0.13	0.26	0.34

^a B₁, humid climate; E, arid climate; B₃¹, mesothermal: evapotranspiration between 855 and 997 m/m; A¹, megathermal: evapotranspiration more than 1140 m/m; S₂, important humidity deficit in summer; d, very important humidity deficit; a¹, summer concentration of thermic efficiency, 48%; b₄¹, summer concentration of thermic efficiency, 51.9%.

stations, one in the most humid region, the others in very dry areas.

From our experience, it seems that the water needs thus calculated are too weak for Gabes and especially so for Tozeur. Corrections would be necessary. One is evident: the water at Tozeur is saltier than at Tabarca and the rate of irrigation must therefore be increased. Other corrections would perhaps be necessary if there were at our disposal more observations on the evapotranspiration in arid regions.

Moreover, dry cultures are possible in the arid zone by reducing evaporation surfaces by plant spacing, or by concentrating on only a part of the land the water which falls on more extensive impluvium.

Discontinuity of Procedures for Establishment of Water Resources

In the first part of this report, we stressed the variability of rainfall. We limited our treatment of the topic to annual rainfall. It is now necessary to push the analysis farther by showing the discontinuity of the rainfall and its distribution over the year.

Not only is the rainfall discontinuous, but in general it falls on non-saturated surfaces. The effects of rain on the runoff and on the supply of underground aquifers are felt only after exhaustion of a volume necessary to saturate the soils, or when the rate of rainfall exceeds the rate of absorption by the soil.

Insufficiency of Climatological Information

In order to study the flow of a great river of the humid zone, one can be content with several spaced-out measures, for example, once a week, and thus obtain a sufficiently accurate evaluation of runoff. The discontinuous nature of the flow in arid zones makes much more necessary the continuity of observation. It is very difficult to get an observer to maintain a continuous watch. When he observes a watercourse for months without seeing any flow, his attention is likely to relax, and he may absent himself precisely during the several hours when there is something to observe. This continuity of observation is even more necessary if one wishes to study the silt flow of streams. Available observations are of insufficient duration precisely in those regions in

which observations of much longer duration are more necessary than in humid regions.

As a consequence of the remoteness of the stations, the expenses are very high and cannot easily be borne by the arid regions, which are economically weak, without having recourse to aid by more humid regions. Apparatus runs the risk of being destroyed by nomadic peoples who, with no evil intent, consider a rain gage an object worthy of attention in the desert, interesting to dismount, and useful as a domestic apparatus. Some difficulties would be resolved if cheap and particularly strong automatic devices were used which did not require having observers in each place. Be that as it may, so great are the difficulties that the hydrology of arid regions, now in its infancy, will remain so as long as the network of observations remains largely undeveloped, especially in the mountains where the rains are most abundant.

In Tunisia we have tried to fill the gaps in the pluviometric network by establishing an approximate map of the rainfall, on the following bases.

The reports furnished by the stations of the network serve as reference marks. Between these stations isopluiometric lines have been interpolated by considering the variation in the rainfall according to altitude and exposure, and by complementing these means of evaluation by phytosociological information (9). The advantage of the phytosociological method is that it integrates the rainfall of a long period. It demands much care and time because annual vegetation can have a different appearance according to the year the survey is made. Therefore, perennial plants are of peculiar interest. Anyway one must not neglect any means of cross-checking. We consider, however, the result obtained satisfactory. It completes, at modest cost, the quite insufficient information on annual rainfall given by the climatological stations.

The phytosociological method is not, after all, the only biological method to determine the amount of rainfall. Another method consists of making, in the course of the seasons, evaluations of leaf surfaces and of the evaporating power of the soil and its vegetal cover (15).

Archaeological and Historical Studies

It happens that most of the arid zones were, in the past, seats of very advanced agricultural civilizations, remains of which are well preserved. This is true in North Africa, in all the countries of the Near East, in India, etc.

The disappearance of these civilizations receives two explanations: the first attributes it to variations in the climate; the second, to human factors. We believe that it has been shown that the second is more probable. It is true for North Africa, and the reclamation of Tunisian lands was very much facilitated by using archaeological information. The planting of olive trees in the Sfax region was decided upon because ruins of oil presses lay scattered about the surface. As it has happened, the olive trees have prospered in dry farming when they were planted with the same spacing as that recommended by the Phoenician and Roman agronomists.

At present, every year, many wells or water projects are carried out by using as base the indications given by Roman ruins. For example, in regions where no wells are found, but only ruins of cisterns, cisterns must be constructed or water must be sought at depths greater than those reached by Roman techniques, which, however, took advantage of phreatic water levels by means of wells more than 100 meters deep.

Irrigation, both by perennial or flood waters was practiced also, with techniques that have survived in certain spots up to our epoch and that are always useful of application. It therefore pays to begin research for the development of an arid country by establishing an archaeological survey directed toward water resources. This survey is now made easier by using aerial photos on which appear the limits of the fields, and traces of plantations cultivated even many centuries ago.

Thus we know that in certain steppe regions the population in antiquity was more numerous than it is now and therefore can be increased.

Problems of Salinity

The complete utilization of water means the recovery and reutilization of already used water. This part of the program is

limited by the increase in salinity which accompanies each utilization. Its increase is especially great where evaporation is stronger. Therefore in arid regions one must study the salt cycle as well as the water cycle.

The recovery of water used in towns poses salinity problems. Waters distributed for public use are charged with salt before passing into the sewers by the following process: evaporation in the course of urban utilization, consumption of salt by the inhabitants, industrial waste products, and penetration into the sewers of water coming down from saline water strata, if the sewers are not watertight.

For Tunis, starting with drinking water having a saline content of around 500 m/g per liter, we hope to arrive at sewage water having a salinity of less than 1,500 m/g and usable for irrigation.

Surface Waters

Stream flow in arid regions is subject to evaporation which excludes in many cases any possibility of utilization by surface reservoirs when the annual rainfall is less than 300 m/m. Moreover, these reservoirs would have to operate on interannual regulation over many years because of the irregularity of the runoff. This irregularity is illustrated in Figure 1, where at the bottom is given the distribution of the runoff of two Tunisian water courses whose basins receive an annual rainfall of the order of 500 m/m. and for which thirty years' observations were plotted.

However, the study of runoff in the arid zone is fundamental: (a) because the runoff waters can be stored up in the soil; (b) because they contribute to the recharge of underground aquifers for a more and more important part as one goes toward drier regions.

Recovery of Runoff Waters

We shall return to point (b) when we study the underground reserves. For the moment let us consider point (a). Runoff waters can be recovered in the soil, either by practicing retentive means where the rain falls, i.e., at the origin of runoff, or by letting the

water collect in streams and recovering it downstream on suitable lands. The former method needs no special study of the runoff. It presents only a limited interest because the quantity of water reserved by evapotranspiration for dry farming will be increased rather insignificantly, and also because in the arid zone, the places where rainfall is most abundant are often mountains with poor soil.

The second method is of much greater interest. It permits utilization of soils of good quality, on which the complement of water, as compared with the rainfall per surface unit watered, is important enough to increase the frequency of harvest years. It is the method of water spreading. To be applied scientifically, it requires a study of the soils, in order to choose those which are most likely to give the best agricultural efficiency and the best retaining of the water. It is also obviously necessary to be familiar with the conditions of runoff.

Relationship between Annual Runoff and Annual Rainfall

In humid regions, runoff is mostly dependent on soil saturation. Since, during long periods the rainfall is greater than the potential evapotranspiration, the runoff is characterized by great regularity. It has been studied in numerous countries. Formulas have been established for annual average runoff which in general give satisfaction in the regions for which they were established.

Even more general formulas have been established (19) or the documentation condensed into curves of very wide application (13).

Let us consider a simple formula:

$$R = AH^\alpha$$

where R = annual average runoff in meters,
 H = annual average rainfall in meters,
 α = a coefficient greater than 2.

To apply this formula we must have a map of the precipitation of a given watershed in order to divide it into surfaces of equal depth of precipitation and to arrive at the total of the partial runoffs thus computed.

The coefficients A and α naturally vary with the temperature and the distribution of the rainfall in the course of the year. By referring to the study of the basins of South Africa (24), it can be verified that regions of summer rainfall yield less runoff than regions of winter rainfall.

The available data on runoff are very scanty in arid regions with rainfall less than 400 m/m. For lack of other elements, one can thus try to use a formula of this type which represents rather well the relationship of rainfall to runoff in Tunisia with $\alpha = 3$ and A between 0.25 and 0.4; but this can in no way hide the at present gross insufficiency of the basic data.

The high value of the coefficient α brings out the interest in the mountainous parts of watersheds, which not only are more watered but also have steeper slopes and a lower water retention than the plains.

Runoff Conditions

The very notion of average runoff leaves room for the same observations as the average rainfall. It would be of little use to know an annual average rate of runoff without knowing its distribution and variability. The runoff depends on many other factors besides the annual rainfall.

In humid regions, the runoff is relatively continuous for long periods. In arid regions, the flow presents continuity only if it has been regularized upstream of the measuring point by underground reservoirs. We reserve the study of this last case until the section on underground water. In general, the phenomenon is discontinuous.

If the rain falls on a saturated soil, there will be runoff, but there can be runoff even if the soil is not saturated, if the intensity of the rainfall is fairly great. Thus one can classify floods into saturation floods and intensity floods.

Saturation of the soil by the rainfall becomes rarer in proportion as the aridity of the region increases. However, even in the deserts there can be times when the soil is saturated. This comes from the fact that the rains, while rare, can be abundant, as indicated by Table 3, which gives the annual hundred-year rainfall by extra-

TABLE 3

Stations	Annual Average Rainfall, mm (1)	Daily Rainfall		Length of Observation
		Maximum Observed, (2) mm	100-Year Rainfall, (3) mm	
Ain Draham	1,534	171	230	(1) Normals: 1901-50
Tunis	420	144	200	(2) Totality of the observa- tion from 1890 to 1945
Motmatas	239	160	250	(3) Extrapolation observation period, 1901-45
Gabes	175	103	150	
Tozeur	89	63	58	
Adrar	17	33 (4)		(4) Period, 1926-50

polation according to Galton Gibrat's method from the observations covering the period 1901-45.

On the other hand, there is not sufficient information on the water-retaining capacity of arid soils. There is in Tunisia a great difference in this regard between regions whose rainfall is greater than 200 mm and regions where it is less. In the region of Oued Kebir, the annual rainfall is around 500 mm, the soil is saturated when the rainfall approximately attains 100 mm. In the Sfax region, the annual rainfall reaches 200 mm. The soil depth is sometimes very great, and evaporation can reach a great depth, which can therefore bring an even more important deficit in saturation. On the contrary, in the regions of rainfall of less than 200 mm and especially in the deserts, the retentive capacity can be very weak because of the slowing down, by lack of water, of the processes of soil formation. In fact, over vast areas the rocks are bare. In any event the quantity of rainfall is so reduced that it generally falls on non-saturated terrain and yet rarely do streams remain several years without flow, even in the middle of the desert. So it must be admitted that a flood takes place either because the soil is saturated within limited regions of the basin or because the chief factor in the flow is the intensity of precipitation.

Dubief estimates that in central Sahara there is a flood when the rate of the rainfall exceeds 5 mm with an intensity greater than 0.5 mm. per minute.

It certainly would be too costly to maintain many hydro-metric stations. A rational program of study should be based on the following thoughts:

1. To establish a general pluviometric network much more dense than the present one, chiefly in mountainous areas.

2. To equip for complete observations a small number of basins of limited extent in order to make possible a detailed study.

3. To equip these basins with a sufficiently dense network of self-recording rain gages.

4. To analyze for these basins the elements of the flow of each individual flood.

Thus, for the basins studied, one could obtain increasingly exact correlations between runoff and meteorological conditions. The comparison of these basin prototypes would allow differentiation of the effects of physiographical factors. One could then come to know the rates of flow of other basins from the information furnished by the posts of the general pluviometric network and from the topographical, geological, and pedological elements.

In passing let us call attention to a difficulty peculiar to hydro-metric measurements. Since the water courses are dry for long periods, the devices for taking the water level (floaters or manometric capsules) risk being blocked by sand. Equipment that is well adapted to these conditions should be sought.

Erosion

We will not close the section on surface waters without giving some consideration to erosion and the silt flow of streams in arid regions.

The annual average erosion, calculated in tons of sediment per square kilometer carried away by the waters, reaches important amounts in the arid Mediterranean regions that have the most rainfall (say about 500 mm). It decreases in going toward the desert areas (23), but in all places the great floods carry waters heavily loaded with sediment, which causes all kinds of difficulties.

We have even less information on erosion than on runoff. The program of studies sketched above should be completed by measures of sediment load and salinity of water. It is even more

necessary than for runoff that there be a study of particular and discontinuous phenomena. The intensity of rainfall is an even more determining factor for erosion than for runoff, and statistics of intensity should be established for periods less than or equal to a season, because of the evolution of the vegetation in the course of the year.

The more one moves toward desert regions, the more sediment tends to be at the bottom of the streams and not in suspension. Now everyone knows how difficult it is to evaluate flow at a depth. It would seem that for deserts the topographical method is capable of giving good results. Desert streams flow in general only over a certain length of their course, and a topographical survey would suffice to determine the solid deposit of a flood. For reasons of economy this can be done only in strictly limited cases.

Underground Waters

The rain divides itself after soil saturation into surface and underground waters in a proportion difficult to determine, save in extreme cases: very pervious limestone formations or quite impervious basins, where the excess of rain goes almost entirely to one of these two fractions. Particularly striking examples of these extreme cases can be found in the Hydrological Year Book of Israel. In the course of the hydrological cycle, there are sometimes transfers from one fraction to the other. In general, the individuality of underground water bodies in arid zones is more sharply defined to the degree that the deep aquifers are more important than the shallow ones.

Water-Bearing Formations

The permanent and autochthonous phreatic aquifers yield important resources in semi-arid regions, but increasingly less important ones as one progresses toward drier regions, because these aquifers are subject to a more and more intense evaporation, involving great soil depth. In very dry regions, the existing phreatic water levels are generally fed by the underflow of great streams, or by a resurgence of deep underground water. In

deserts, the hydrology of underground waters is rather a deep hydrology.

Whatever their nature, the study of underground water can begin only by topographical and geological recognition of water-bearing formations, by the survey of springs, their depth (level), flow, and all the hydrological indications on the soil surface. Among these it is particularly useful to observe the deposits left by evaporation of subterranean waters. These deposits are linked with the circulation whose conditions could have been modified in more or less recent times.

Geological, geophysical, and hydrological prospecting does not dispense with boring. At present the system most employed is drilling with rotary equipment, but it consumes a great amount of water, and this increases costs.

For deep drillings with a rotary drill, it is difficult to identify and localize the different layers encountered. Systematic use of electric logging permits the determination of precise correlations between the formations encountered in several borings. It is hoped that this type of process will be more and more improved.

Water Balance

Recharge. Everything that has been said about the irregular and discontinuous supply of runoff is true for the supply of underground waters. The phenomena of saturation of alimentary outcrops over a vast extent are particularly rare. However, we have seen that they could take place, at variable intervals, according to the aridity of the region under consideration, for instance at intervals of the order of a century.

In semi-arid zones, the discontinuity of the supply is already very obvious, as shown in Figure 3, which gives the fluctuations of a well of the Menzel Bou Zelfa aquifer, where average rainfall is 450 mm per year.

This graph allows the identification of two very clear cases of recharge.

In desert regions, rarer still are rains capable of saturating the soil. There is another supply process which can take place at much more frequent intervals. It is the supplying of underground

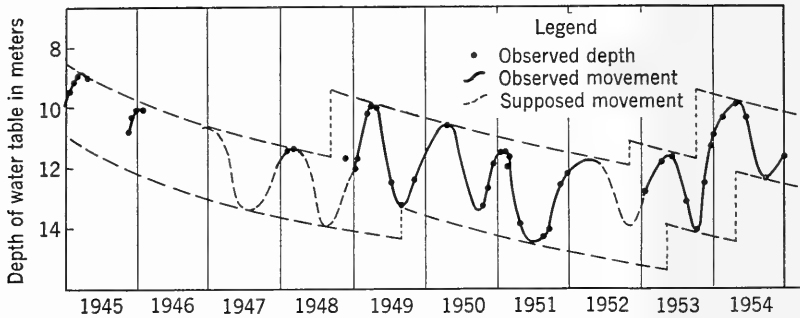


Figure 3. Movement of the water table, Larue Well.

aquifers by stream floods. These can occur several times per year. It is clear that saturation and percolation can frequently occur locally along stream beds and on the flooded adjoining areas.

In Figure 3, we realize that current annual supplies are not sufficient to offset pumping in the dry season. There must be added to these the supply of exceptional sort which coincides with an intense runoff. The efficiency of this supply process is certain (22). The computation of the safe yield of one aquifer cannot therefore be established without observations covering long periods.

It is possible to obtain an idea quite rapidly of the relative participation of these two processes of supply in semi-arid regions, but for the great desert artesian basins one is reduced to mere suppositions.

The methods that can be considered to increase the recharge of aquifers differ according to the process involved. To obtain scientific bases it would be necessary to follow over many years the fluctuations in water levels by sinking piezometric tubes in the zones of recharge, and mainly in the zones of privileged supply which are neighboring to water courses and their alluvial fans.

But the increase of recharge can be faced in a more practical way by utilization of runoff waters. Two processes have been employed: the first consists in stopping the water in infiltration basins, which leads to taking special caution for waters containing sediment to avoid clogging; the second consists in slowing down the runoff in such a way as to increase the time spent in passing over the recharge areas.

Finally there is another source of supply: overflows coming from nearby aquifers. Thus in Tunisia there is a series of aquifers in miocene sand formations whose water naturally springs along watertight faults. The waters are partially used for irrigation. The waters not used, joined with waters strained out and percolated from the irrigations, reinfiltrate and contribute to the supply of a compartment downstream. Water is in this way transferred from compartment to compartment, but each passage to the surface of the soil, or near it, corresponds to an increase in salinity. Sometimes, therefore, it is better to use as well as possible the waters in the upstream compartments, without troubling much about the decrease in supply of downstream compartments.

Hydrological considerations of the salinity of the water have an importance as great as the economic findings for the planning of systems of irrigation. Suppose a cycle of events wherein the water percolated from upstream irrigations is reused for other irrigation. On hydrological grounds the full utilization of underground water requires the construction of watertight irrigation systems as soon as the excess waters come to percolate into water strata which have too much saline content to be recoverable for other irrigation. This is the case for the artesian aquifers of the Tunisian south. As long as downstream water strata which receive percolation from upstream irrigation can be reused without too much salinity, the irrigation ditches need not be lined unless otherwise warranted.

The recharge of an aquifer by another can also take place by underground communication. If the aquifers are of small extent, in regions not very arid, they can be studied by comparing the chemical composition of the waters and by examining the hydrological data (II). In the case of very extensive units such as the miocene and cretaceous basins in the south of the Saharian Atlas, the problem becomes much more difficult and has not yet been solved for lack of sufficient information concerning the geology, the deep hydrology, and the topography of the land (3, 12).

Discharge. Apart from the underground water which returns to the surface in a form rather easily measurable—springs and wells—some is lost to the sea by underwater seepage or evaporates

in regions where the water comes near enough to the soil surface to be evaporated from the soil or transpired by the vegetation. Evaporation, whether from the soil or by plants, results in soil salinity.

In some regions, the ground water bodies lie below closed topographical basins whose bottoms are occupied by salt lakes, without surface water, for the better part of the year. These are the chotts and the sebkhas of the south Mediterranean regions. They are filled by very fine silt. Their flat surface is covered with salt. When soundings are made, water saturated with salt is found under the salty crust, but if deeper soundings are made, it is not uncommon to encounter layers of less salty water. The existence of underground circulations through the silt is proved in Chott Djerid by the existence of little springs and of natural chimneys whose appearance from the air is shown in Figure 4.

A volume of water is also lost by defective catchments and springs more or less choked by sand. These waters feed phreatic aquifers, often salty, and join those evaporated by the halophile plants.

It is a well-known fact that old defective wells, whose casings are corroded, must be sealed off. The sealing operation can generally take place with more or less difficulty. But certain types of leakage are much more difficult to avoid. This is notably true when imprudent operations have caused the collapse of the roof of an artesian aquifer.

The evaluation of all these water losses is quite difficult. It is, however, indispensable for a correct study of underground water resources development.

Circulation Reserves. Underground formations sometimes occur in desert regions, in great basins with huge reserves. The flow of the springs of the Djerid (Tunisia) is so constant that all the measurements taken for 50 years gave results whose differences are comparable to errors of measurement. The same statement has been made in the Mzab (Sahara) (4). Given what we know of the irregularity of the supply of these aquifers, that signifies that the free water table has a very considerable extent. Its position is unfortunately not well known on account of lack



Figure 4. Aerial view of Chott Djerid.

of sufficient explorations and because geological outcrops are often hidden under aeolian formations.

Because of the importance of the reserves, a long period of time is necessary to appreciate the effects produced by new water developments and to determine the moment past which the safe yield of the aquifer will be exceeded.

We saw that for the rainfall and the runoff, it is better to make numerous observations than very precise ones because of the extreme irregularity of these phenomena. For the study of water levels and the flow of aquifers, it is necessary, on the contrary,

to increase as much as possible the precision of the measurements because of the slowness of their variation. Also one should make use of a precise survey system, generally absent in desert regions.

One must not lose sight of the fact that desert oases support an extremely dense population. In the oasis of the Djerid a population of 45,000 lives on 40 square kilometers of irrigated land. One must therefore be very prudent in the execution of work capable of modifying the flow of water.

When working on a virgin or little-used aquifer, it is often possible to obtain spectacular improvements without preparing very precise bases, but beyond a certain degree of use the amelioration of yield requires greater and greater efforts and increasingly precise scientific information.

For good use of the reserves, it is naturally better to take out the water at the lowest possible part of the formations. The usable reserve is thus increased, the losses diminished, and at the same time the instantaneous flow is increased.

But the lowering of the takeoff level by pumping raises difficult social and economic problems. It can lead to the elimination of small owners and the concentration of property. In areas of great population density, divided into small parcels of land, increases in agricultural production should yield priority to drinking needs. These needs satisfied, landowners may lack the resources to pay additional pumping expense. Hence the interest of utilizing local sources of energy and especially wind energy.

Particularly advantageous is the case where it is possible to lower the takeoff level of the water without the expense of pumping. This is the case in Chott Chergui in Algeria (1) where utilization of the waters is projected by taking them below the level of the Chott, situated on a plateau 1,000 meters high, to use them in the valley of Cheliff, several hundred meters below.

From our point of view this experience is of utmost interest. It gives the opportunity for a program of studies now in progress which will not fail to better our knowledge on all the points covered in the present study.

Another advantageous case, because it is relatively easy to study, is that of the very important water-bearing limestone formations in the eastern Mediterranean basin. It is easier in

this case than in that of sandy formations to determine the geometry of the formations. The points of emergence of the water are better localized and observation of them permits easier study of the water balance.

Conclusion

The arid zone is characterized as much by the variability of its climate as by lack of water. To enable a maximum population to live in an arid region, there must be maximum exploitation of all the resources, and compensation for the variations in climate which could not be compensated within that region, by means of exchanges with vaster and vaster territories, according to the degree of compensation necessary. Thus one must study global variations in climate over territories of greater and greater extent.

In order to know the ensemble of the resources, there is need of longer observations than in the humid regions. This gives special interest to archaeological and historical research and increases the importance of international exchanges of information.

The networks of pluviometric and hydrological observations are generally not extensive enough, especially in mountain and desert areas. Instruments of observation need improvement in order to be adapted to arid zone conditions: rain gages capable of functioning automatically and withstanding sand winds; gages fitted for streams which are dry part of the year; devices for measuring sediment flow at the bottom of the streams.

For underground waters, the prolonged time of the observations requires great precision in the measurement of flow and water levels, which presupposes a good leveling survey, providing for quick detection of often slow fluctuations.

It is very important to determine the natural ground water discharge that can be salvaged. In this respect there is a lack of information on the losses from underground aquifers by evaporation in saline soils and by halophyte vegetation.

Hydraulic resources are characterized by the discontinuity of their supply. We believe it necessary to study hydrological phenomena individually: rain, runoff, erosion, recharge and discharge.

Current hearsay is, "In Tunisia, every year is exceptional." Seemingly it should be the same in every arid region. Particular situations demand study as much as and even more than average ones. It is advisable to investigate individual causes and their statistical distribution.

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Data and Understanding

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In the year 1534 when Cabeza de Vaca escaped from the aborigines of southern Texas by whom he had been enslaved for six years, he made his way on foot from the vicinity of Galveston to the west coast of Mexico. Although his *Relación* was not printed until 1542, the verbal report of Cabeza de Vaca gave impetus to the growing interest in exploration of New Spain. Estevanico, the black, one of de Vaca's companions, served as guide to Fray Marcos de Niza on the first Spanish reconnaissance to reach the village of Zuni in New Mexico.

The earliest Spanish exploring parties hoped to find riches, but expected to acquire, at the least, facts. These "gentlemen of high quality," as Castañeda called them, wanted to see for themselves whether the cities of Cibola had streets of silver. Hearsay was not enough. Rumor was to be replaced by first-hand knowledge.

Without discounting the hope for personal gain, these men presumably were fired with some further intellectual and spiritual motivation, among which must have been the desire for facts about these parts where we are assembled. Inscription Rock, only a few miles west of Albuquerque, bears illuminating tidbits of history. Don Diego de Vargas, says the carved inscription of 1692, came here "A su costa"—at his own expense.

We are attempting to survey and correlate some of the facts which people have gained about the nature of semi-arid lands. We are better off than the early Spanish explorers, for in the intervening period data and information have been accumulated in scope and in detail beyond the imagination of our predecessors. We have

available excellent maps, knowledge of the soils and of the rocks, both at the surface and below the ground, measurements of precipitation, descriptions of the vegetation, data on the flow of streams, experience in the use, if not the husbandry, of the land.

It is true that for the purposes of our complex civilization, the need for additional data has far outstripped the programs of fact-finding. But it appears that an indefinite expansion of the collection of routine measurements would still leave something lacking. I draw the distinction between measurement data and understanding; between the collection of facts and knowledge of processes and interrelationships. Although we have a wealth of data, our understanding of the semi-arid environment is poor.

Understanding the physical and biologic processes operating in an environment is important for living in and with the land. As an example, let us look briefly at the interrelation of the water and sediment in ephemeral streams, and the problem of valley trenching or arroyo cutting.

The Problem of Arroyo Cutting

Many of the alluvial valleys of New Mexico are gutted by trenchlike gullies. The rapid growth of arroyos in southwestern valleys in the United States accompanied the livestock boom of the late nineteenth century. It is clear that the pressure of livestock on the vegetation has materially contributed to the growth of arroyos. But the problem is more complicated. The first American reconnaissance teams of the Army of the West traversed New Mexico in the fall of 1846, some 20 years before American settlers and their livestock had any appreciable effect on local vegetation. In August of 1846, Lt. Simpson marched from Santa Fé to the Navajo country. He crossed the Rio Puerco near Cabezon. So deep was the arroyo at that place that he had to cut down the 30-foot banks to get his brass cannon across. There is enough evidence of this kind (1, 5) to indicate that in certain valleys large gullies existed before American settlement, even in places far removed from heavy grazing by Spanish livestock. It must be supposed that these arroyos were the result of natural rather than human causes.

Geologic and archaeologic studies have demonstrated several

post-glacial but pre-Columbian periods of erosion followed by aggradation. The last period of erosion prior to the present one can be dated by pottery buried in the alluvium as occurring approximately in the period A.D. 1200-1400 (2). The concurrent trenching of alluvial valleys in that period appears to have occurred at least as far north as Wyoming (6) and south into Texas (3).

The problem is further complicated by difficulty in assessing the effect of fluctuations in climatic factors on the recent episode of erosion. In the hundred years of rainfall record in central New Mexico, no progressive shifts of annual totals are discernible. But there has been a progressive change in the number of rains of various sizes. The period 1850 to 1880 was characterized by a deficiency in small rains and a relatively great proportion of rain events of large magnitude. This might be interpreted to mean that coincident with the wave of settlement and accompanying pressure of livestock in the nineteenth century, climatic factors were particularly adverse to maintenance of physiographic equilibrium (4):

The upshot of these considerations is that in the last century there has been a repetition of a physiographic episode which had occurred more than once in post-glacial time. But the recent valley trenching was influenced to more or less extent by activities of man and his grazing animals. The presettlement periods of valley erosion and subsequent alluviation presumably resulted from changes in climatic elements.

The arroyos cut during the last century have radically changed the contribution of sediment which the alluvial valleys provide to the master stream. This change of sediment inflow has probably contributed to the fact that the bed of the Rio Grande at Albuquerque has gradually risen in recent decades and now stands only slightly below the level of the flood plain on which the center of this city stands. The gullies have dissected the valley flats which were the best agricultural parts of the hinterland. The cutting of an arroyo trench lowers the local ground water table and cienaga grasses give way to less productive vegetation. Water formerly could be diverted from the shallow

channel by a simple brush dam, or even by felling a single tree. With the water flowing in the bottom of a deep trench, a much more elaborate dam is necessary, even to make diversion possible. The flood peaks increase because of loss of natural valley storage, and for this reason also, any diversion works must be more elaborate.

Not everyone living in an arid region can depend on major irrigation projects. To the subsistence homesteader who depends mostly on his own axe, plow, cow, and horse to make a living off the land, valley trenching, as it occurred in New Mexico, was a major calamity.

For the earth scientist the arroyo problem poses many questions, among which are these: (1) Assuming that grazing use has contributed materially as a causal factor in arroyo cutting, can a change in land use, specifically, a reduction in grazing pressure, slow down arroyo growth or perhaps reverse the trend and lead to valley aggradation? (2) How much can small structures, water spreaders, and other minor works retard gully development? (3) What is the future trend of physiographic development in these alluvial valleys under present conditions of land use? On the answers to these practical questions depend a host of decisions which would affect the welfare of many people.

Practical measures, including gully control, watershed treatment, and grazing management, have been applied locally in various degrees over a period of two decades. Additional data have been collected to describe the vegetation, the soils, the streamflow, and the sediment yield. Yet it appears that the answer to these questions is not much closer than it was in 1933.

Need for Fundamental Research

What is lacking is a satisfactory understanding of the hydrologic, physiographic, and biologic mechanisms on which depend the stability or instability of the alluvial valley. In the hope of achieving practical answers, no provision for long-term research in fundamental mechanisms has been made. Although some excellent research was started at Mexican Springs in 1933, lack of continuity of funds forced a curtailment of those efforts and

finally their discontinuance. Individual investigations such as the study of Polacca Wash (8) have not been followed up.

First it seems necessary to improve our understanding of the hydrologic relationships between intensity and amount of precipitation, infiltration, and surface runoff, for combinations of soils and vegetation in semi-arid areas. The small experimental watersheds maintained by the Soil Conservation Service and Forest Service in New Mexico and Arizona are a step in this direction, but lack of adequate funds keeps this effort pitifully small relative to the need for such information.

A second field of needed research is in the hydraulics of flow of sediment-laden water. Particularly deficient is our understanding of the nature of bed and bank roughness and the manner in which sediment in transport affects hydraulic resistance. In most ephemeral channels bed roughness is determined primarily by the dunes or ripples formed by moving sediment. We have few observations and no theoretical concepts on which to build an understanding of this phenomenon.

A third broad field is in the mechanics of gully formation, including hydraulic forces, phenomena in the realm of soil mechanics, and physiographic principles.

Our own recent work has been concerned with these problems, and at least indicates some of the possible approaches which appear fruitful. The work began as a study of interrelations of discharge, width, depth, velocity, slope, and sediment in natural channels. On some of these parameters a plethora of data exists in the records of the regular stream-gaging stations. But in the existing network of measuring stations few measurements have been made on water and sediment flows in ephemeral streams draining 1 to 10 square miles. To obtain measurements for analysis, during three summers of work in Wyoming and New Mexico we chased thunderstorms, trying to reach a storm center in time to observe arroyos in flood. When flow was found we waded out into the arroyo and measured the depth, velocity, and width, and sampled the sediment load. Successive sets of measurements were made during the falling stage of the flow. Later, measurements of channel slope and bed material were made.

This investigation led to results which added something to our knowledge of interrelations of sediment and hydraulic factors in ephemeral channels (7). It emphasized an unexpected similarity between perennial channels in humid areas and the ephemeral channels of semi-arid areas. Certain differences, however, were demonstrated, particularly in sediment load characteristics. These differences appear to be reflected in hydraulic factors, particularly in flow velocity.

The current problems of sediment deposition, of arroyo cutting, land management, and water supply emphasize a present deficiency in our understanding of basic physical mechanisms in this environment. Basic data are necessary for, but do not substitute for, basic research.

We have not extracted all the knowledge it is possible to gain even from records and data already collected. Rainfall measurements must be interpreted with an eye to topography, vegetation, and land use. The arroyo problem presents so complex an interrelation between soils, geology, vegetation, hydraulics, and history, that no single discipline can take precedence over others if understanding is to be achieved. These are only two examples of unsolved problems.

If we are to achieve understanding and not merely content ourselves with the collection of facts, we must bring to the task the zeal implied by the words on Inscription Rock, "A su costa."

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Variability and Predictability of Water Supply

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This paper is concerned essentially with the variability and predictability of water supply in the drier parts of certain of the British Overseas Territories and Commonwealth countries, mainly in Africa. A great deal of experience in these matters has been gained in these territories, and in recent years much coordinated investigation and development of water supplies has been achieved.

Common Features

The drier parts of these territories are not all strictly arid in the sense of the definition adopted by UNESCO (17). The basis for the division employed in this definition is the system developed by Thornthwaite (26), which uses an index based upon the adequacy of precipitation in relation to the needs of plants, so that precipitation and temperature data and various other factors are employed. This is described on pages 74-80.

Data for the application of Thornthwaite's system are not ordinarily available, although in some territories, as in Tanganyika, attempts have recently been made to obtain them locally. Consequently, the territories to be discussed may be described in general terms as arid or semi-arid, corresponding respectively to the desert and steppe of many authors. Culturally, the arid areas are those in which the rainfall on a given piece of land is not adequate for crop production; in the semi-arid lands, rainfall

is sufficient for certain types of crops, and grass is an important element of the natural vegetation unless overgrazing has replaced it by brush. In the absence of other data these criteria are often of considerable value. Where rainfall data are available, even if only from scanty records, arid areas are sometimes taken to include those with less than 350 millimeters (13.8 in.) and the semi-arid those with less than 750 millimeters (29.5 in.). In North Africa Tixeront and Drouhin consider as arid lands those with an annual rainfall of less than 500 millimeters (see page 85). An area is classified as "extreme arid" if in a given locality at least twelve consecutive months without rainfall have been recorded, and if there is not a regular seasonal rhythm of rainfall.

Some of the territories, e.g., Northern Kenya, Aden, parts of Bechuanaland, are known to have an average annual rainfall of less than 12 inches, while in most of them the average annual rainfall is less than 30 inches. Moreover, in most of these territories the annual precipitation occurs within a period of four months or less, so that for the remainder of the year the conditions are often truly arid. Some account of the water supply conditions in these territories and of the water supply investigation and development programs carried out in them in recent years has already been given (5, 6, 7, 8, 10). But whether arid, semi-arid, or humid, the principles involved in the hydrogeological investigation of these territories are the same, and the lessons gained in any one of them relating to the location, occurrence, or movement of ground waters are very largely applicable to the others. Moreover, the question of drought, a relative term, affects all of them, although in the drier areas droughts are of fairly frequent, but irregular, occurrence.

There are certain other features which are common to all the drier territories to be described, namely, their isolation, poor communications, the general lack of basic hydrological data relating to precipitation, runoff, evapotranspiration and percolation, the high cost of labor, transport, and material required to ameliorate the unsatisfactory water supply conditions, and the inability of the sparse population to pay for such amelioration except where there is an economic outlet for their stock or for

hides and skins. These conditions, mainly sparse population and low economic prospects, have in the past afforded but little incentive toward the acquisition of basic hydrological data, and still do to a large extent.

Arid regions are, as a rule, better adapted for quantitative hydrological studies than humid regions, and many of the available methods of estimating ground water supplies have been developed in arid regions. A wider range of methods is none the less available in developed than in underdeveloped areas. A number of methods, however, do not depend at all on development, and much successful quantitative work has been done in areas that were virtually undeveloped (19). The Chott Chergui scheme of northern Algeria provides a good example of this (12).

There is one important difference between arid and semi-arid areas which has been emphasized by Shotton (25). In those fringe areas—southern Palestine and parts of Jordan are good examples, as well as the semi-arid parts of Africa—where nature has provided at some period of the year an adequate rainfall and yet turns the countries to arid desert at other times, there is every incentive to search for underground water and to use it to balance the irregularities of the rainfall. The search may even be long and difficult and the results must always conform to the law that more water cannot be taken from the ground than soaks into it; but, subject to these limitations, there is a future for parts of the semi-desert earth which most of the true desert cannot hope to share.

Climatic Variations

The question of variations of climate in respect to arid lands often arises, particularly as to whether a given territory is drying up or not. There are, of course, cycles or variations of widely different amplitude, whether of 11, 30, several hundreds, or many thousands of years, and, over a given period of a few years, it is usually not possible to say whether an increasing aridity is part of a progressive change in that direction or merely the downward curve of a lesser cycle. In the levels of certain of the great lakes of central Africa a periodic rise and fall has been observed which

shows a measure of correlation with the eleven-year sunspot cycle (9). In this region also within the past forty years or more the levels of certain lakes have shown a progressive fall, and ice caps have shrunk, indicating a climatic change. Wayland believes that the Kalahari climate is slowly reverting to a more arid phase, but at the same time he says, "It is unthinkable that the change will be an entirely one-way process; moreover, these climatic mergings take time—geological time" (28).

In southern Africa an increasing aridity since European occupation began is generally admitted, although opinions still differ as to the extent to which this is due to climatic change or to man's interference with vegetation and other natural conditions. Bosazza *et al.* (2) expressed the view that the desert encroachment of South Africa is the result of the activities of man and his companion animals, although others have seen in meteorological records and in the altered regime of rivers evidence of late climatic change.

Gevers (13), for example, described drying rivers in the north-eastern Transvaal. He recorded that Dr. Schumann, Chief Government Meteorologist, in 1934 showed that there had been a noticeable decrease in rainfall over great parts of the Union since the eighteen nineties, and he quoted figures showing a steadily declining rainfall from 1906-07 to 1946-47 at the Duivel-skloof and Ravenshill stations, in the vicinity of the rivers described. He stated that there was no question of the widespread desiccation in the area referred to, and that there was also little doubt that the marked decrease in rainfall since 1926 was the predominant cause. There is equally little doubt that the effects of the incidence of rainfall have been greatly modified by man-made agencies, such as despoliation of the vegetal cover (forests, bush, scrub, and grasslands) with consequent removal of long-conditioned absorptive topsoil and increase in runoff. It is quite clear by comparison with former conditions and ocular evidence of the present day that all streams not rising in protected or comparatively well preserved catchment areas have lost their staying and recuperative powers and that many of them have been turned into stormwater drains. Gevers considered also that the

area was ideal for prolonged research on the lines of the Jonkers Hoek and Cathkin Peak Forestry Research Stations. The effects of gum and other plantations as against indigenous tree and bush cover, and again of tree cover in general as against grasslands, could be studied with great profit in this region.

This question of rainfall is highly pertinent, too, to the outlook of the Sahara; some writers believe it to be decreasing, but the evidence is not conclusive. Probably there has been no significant change in the northern Sahara since Roman times. Apparent desiccation can be traced to human rather than climatic causes, particularly overuse of the native vegetation, overdraft of ground water, and past raiding. There is widespread belief that the southern Sahara is advancing, but here again the evidence as to climatic change is conflicting (18).

Tixeront (pages 90-92) ascribes the disappearance of the ancient agricultural civilization of the arid lands of northern Africa, comparable with that of the arid lands of the Near East and of India, to human rather than to climatic factors. He records that in the recent development of Tunisia full use has been made of archaeological and historic records relating to Roman and Arab cisterns, wells, and other works which when reconstructed and restored appear to function much as originally, and certain springs in this region also seem to be flowing as well as in Roman days.

The Search for Water

On the question of the search for water in arid lands, one must pay tribute to the extreme efficiency and thoroughness with which the earlier inhabitants sought out and exploited temporary surface supplies in scarcely perceptible hollows and at the foot of rock catchments, as well as ground waters in shallow well fields. It is amazing to see the great herds of the larger and smaller stock that can be maintained from these sources. Even with the aid of modern techniques it is often very difficult to find such occurrences of water which are not already being exploited or have been used in the past, and frequently the only advance we can make is to prove, by drilling, deeper supplies that were

beyond the reach of those early people. The modern inhabitants, like the Masai of Tanganyika, or the Somali of northern Kenya, merely use, often without even troubling to maintain, the wells, hafirs, and catchments that were discovered and constructed by their long-vanished predecessors.

In the present-day search for water it is necessary to use every modern aid. A thorough study of the geology is required, with special reference to the absorption, retention, and transmission of ground water, together with an investigation of all aspects of the hydrogeological cycle, even though studied under more humid conditions. In addition, the application of geophysical methods is needed to determine the presence of dykes, faults, shears, fissures, and other structures, and the depth to solid or impervious rocks, and of aerial photography to assist in the determination of geological, topographical, hydrogeological and vegetational features. A study must also be made of the vegetation itself.

Where highlands of higher rainfall rise out of the deserts, the runoff on the windward side often increases the deeper ground water flow even at a considerable distance from the foot of the mountains.

Accumulated local geological experience becomes of special importance in these circumstances and sometimes leads to an almost intuitive appreciation of the possible presence of ground water. Experience shows that in any program of development of water supplies in arid regions it is most important, and far more economical, that water should be sought in places where it is most likely to occur rather than where it would be most convenient, and drilling merely on a grid or interval basis is likely to be very wasteful of boreholes. In some territories, as in much of eastern Africa, this is already leading to an increasing difficulty in finding good supplies, in that the more promising sites are being taken up to an increasing extent.

Well Yields

The question of the maintenance of yield of boreholes in arid places is a very important one, for even when the pumping proceeds at only 50 or 60% of the tested yield, the yields sometimes

gradually diminish. For this reason some observers, such as Wayland (28), in the Kalahari, consider that such boreholes are dependent upon "fossil" water, which accumulated in a past humid period; others, such as Bosazza (1), consider that small reservoirs underground in the Orange Free State and the southern Kalahari are undoubtedly recharged over a matter of years but can be depleted in a few months with excessive pumping. Martin has expressed the view that in southwest Africa the recharge of aquifers on any large scale takes place only during periods of exceptional precipitation which occur approximately every ten years.

By means of lysimeters it has been shown that in some cases in arid countries only 2% of precipitation has penetrated more than 4 feet below the surface. In southern Africa it has been recorded that borehole water supplies are less difficult in relatively dry areas with little vegetation than in moister areas with denser vegetation (22).

The United States Geological Survey has recently completed a paper on the qualitative aspects of the relation of soil structure to infiltration and unsaturated flow of water above the water table, and quantitative studies of this important subject are in hand.

Infiltration is much affected by salts, including the nitrate and ammonium fertilizers; low permeability is common in regions where alkaline salts are present in soil or irrigation water, and is due to base exchange taking place during infiltration. The acidification of waters tends to increase the rate of infiltration (21).

Water Quality

The ground waters of arid lands are normally highly mineralized. Frequently the clay fraction in wells and rocks seems to be a principal factor in inducing salinity; in southern Mozambique, for example, saline waters have been found to be almost invariably associated with beds of clay and very clayey sands, whereas fresh waters were almost invariably associated with sandstone or grit (1). Experience with the deep alluvia of the Nyasa-Shire

rift shows that in the saline areas the beds of sand and gravel interbedded with thick clays also yield saline water (14).

In some countries, as in northern Africa, bodies of shallow saline water are sometimes due to the evaporation of ground waters of usable quality, and there is room for further investigation into the occurrence and use of such ground waters.

For these and other reasons related to the nature and structure of rocks and the relative freedom of movement of waters in them, usable and unusable waters are frequently found only short distances apart, so that an area yielding unusable supplies should not be given up too hurriedly before the possibilities of finding local fresh waters have been exhausted.

A recent survey carried out by Bosazza (1) in the low rainfall and former desert area of the Sul Do Save in Mozambique shows that over an area of about 2,500 square kilometers, out of all the boreholes drilled to 30 to 40 meters, 24% are of low enough salinity for human consumption and a further 24% good enough for stock. Thus 48% of the boreholes are usable, a percentage that is very high for southern Africa; and these conclusions are drawn from work on boreholes which have been drilled at intervals throughout the area without any geophysical work to assist.

Shotton (25) has recorded that ideas on the standard of water acceptable to man for drinking have changed considerably in recent years. It may now be taken as a fact that water with a salinity of 3,000 parts by weight of sodium chloride per million of water can be drunk regularly by human beings in a desert climate, that a figure of 4,000 unaccompanied by important quantities of other salts is acceptable, and that for short periods even a figure of 5,000 is endurable. Domestic animals are often more tolerant of dissolved constituents than man though there is no close agreement on the worst limits of quality. Much investigation on this question has been carried out in Australia. Jack (15) in South Australia states that horses will thrive on water with 1 ounce of sodium chloride per gallon (6,260 parts per million) and sets upper limits for living as 7,800 for horses, 9,400 for cattle, and 15,600 for sheep—unless magnesium sulfate is present, when the figures must be lowered. Edgeworth-David and Browne

(II) giving figures expressed as total solids have set limits even beyond those of Jack. It is clear that both man and his stock can drink water which is of a quality not infrequently obtainable in deserts.

To obtain water of a quality suitable for crop irrigation is a far more difficult matter, for there are certain salts—the alkali carbonates and bicarbonates (black alkali)—which are only acceptable to plants in very small concentration. A practical limit of only 700 parts per million has been given for the total solids permissible in irrigation water, and unless man finds such water in quantity, he can neither grow regular crops for their own sake nor as fodder for his horses. Shotton's experience in northern Egypt and Libya during World War II convinced him that a water table could be found almost everywhere in this desert, but usually of such high salinity that a random well had small chance of finding drinking water and next to no chance of water of irrigation quality. He considers it a fair assumption that irrigation quality water is not to be expected in a desert from its own local and limited rainfall unless exceptional conditions exist. Of a number of such conditions two are mentioned. The first occurs when newly percolated rain, making its way to the water table, finds difficulty in mixing with the general body of saline water. In the Western Desert during the war many water points were established through this cause, with salinities from 200 to 2,000 parts per million in a vast area where normally the salinity stood at 5,000 or 6,000 (i.e., unpotable) and exceptionally went up to 60,000. Characteristic of such wells were the thin depth of good water (typically only a few feet), the very sporadic distribution of these patches (undrinkable water could exist only 100 yards away), the gradual tendency to become more saline with pumping, and the small yield which rarely exceeded a few hundred gallons an hour. Indeed, the smallness of yield is an inevitable corollary of the fresh water—a fissure or pore system open enough to give a large yield would not permit the fresh water to remain unmixed with the salt in the first place. Such wells, therefore, have no importance in irrigation prospects.

The second possibility is that of perched water, where geological

structure causes the holding up of water above and quite separate from the main table. The controlling factor is often a bed of shale or clay occurring as a lens or fold between the aquifers. Several examples of this type were developed in the Western Desert during World War II.

Wartime experience in the eastern Egyptian Desert (Red Sea Hills), where rainfall is extremely small and sporadic, showed that by careful attention to geology, aided by geophysical measurements, underground reservoirs of drinkable waters could be found (23); of ten wells with drinkable water, five were of irrigation quality, but the yields were only a few hundred gallons an hour with a limited life, and therefore useless for irrigation schemes.

As in a number of well-known cases in northern Africa, the geological structure of some deserts is such that deep boreholes in them tap artesian supplies of fresh water derived from humid regions far beyond the desert margins.

In general, the overpumping of ground water supplies in arid lands, where it does not lead to exhaustion, gives rise to increasing salinity; rare exceptions to this are known, as where the abstracted saline water is replaced by a new acquisition of infiltrated rain water. Shaw (24) has shown that at Ma'an in Trans-Jordan, over a period of eight years, while the effect of pumping in certain wells was to increase salinity either at once or after a time lag, a complete recovery could take place even after considerable periods of heavy pumping have raised the salinity to very high figures.

Apart from the development of rare surface and shallow ground water supplies, the indispensable tool in the investigation and development of the water supplies of arid lands is the water-boring machine, used with proper regard to the prevailing geological and hydrogeological factors. In the British Overseas and Commonwealth Territories, for example, large sums have been spent on these operations in recent years for the benefit of the local inhabitants and for ranching and other projects, and in every territory active teams are now busily engaged on extended programs of amelioration and development (5-8). As far as the local inhabitants are concerned, the beneficial use of the new

water supplies is intimately bound up with the question of grazing control, without which overgrazing and its attendant evils would occur and the final state of the territory would be worse than the first.

Use of Surface Waters

In arid lands generally the question often arises of the possibility of making use of the storm water flows of the "dry" sandy river and stream beds which normally run to waste, or ultimately spread out over flats from which they are evaporated with little benefit to ground water sources below. Temporary or even permanent local supplies are sometimes found in them, and in some territories, as in Tanganyika, it has been found that in the dry season the water in sandy river beds tends to be concentrated in lenticular, but not necessarily connected, sand reservoirs, and that the individual sand lenses are slowly draining downstream (4).

Sub-surface dams are frequently proposed with a view to holding up the sub-surface flow in sandy river beds. They sometimes meet with marked success, but the common obstacle to greater development of such supplies is the difficulty of finding sections of stream channels that are sufficiently impervious along both floor and sides, together with the difficulty of finding low-cost materials and methods of construction in isolated places.

There is usually great scope for the construction of dams and tanks of various kinds to take the runoff from natural rock and other catchments and from artificial catchments, but the high evaporation losses, which may amount to as much as 8 feet in a dry season, have usually acted as a deterrent to such schemes, since they tend to make it impracticable or unduly costly to preserve water until late in the dry season. The recent investigations in Australia, Kenya, and elsewhere on the reduction of evaporation losses by the use of cetyl alcohol, and related compounds, which form a thin film on a water surface and thereby substantially reduce evaporation, raise new hopes for the conservation of water supplies in arid lands. Experiments to date have proved highly successful, and large scale trials are now in hand. The chemicals used are harmless to animals and plants.

Small-scale out-of-door tests of cetyl alcohol by C.S.I.R.O. in Australia have now been in progress in Victoria for about eighteen months, and the results show an average of 50% reduction in evaporation. A large-scale test was conducted in the summer of 1954 on a town reservoir at Woomerland, Victoria. Two acres of water were treated, and, although the results were complicated by seepage, it seems likely that evaporation was reduced by 30%. Additional larger-scale tests are in progress.

Recharge of Aquifers

Finally, there is the question of the recharge of aquifers which normally takes place under natural conditions but can also be effected artificially. Of any given rainfall the residue, after runoff, evaporation, and transpiration by plants have been accounted for, percolates downward through the soil and ultimately augments the ground water. In arid regions the proportion of rainfall that reaches the ground water is small, say 4 or 5%, and in extreme cases, as in parts of the Kalahari, recharge is considered to be nil. In the drier parts of Tanganyika, for example, the precipitation is considered to be accounted for as follows: runoff 4 to 6%, evapotranspiration minimum 72%, average 85%, maximum 90%, and percolation the remainder, say about 10% (4). But the losses by runoff and evapotranspiration can to some extent be controlled by manipulation of the vegetation and surface conditions with a view to increasing the recharge of ground water. Grass sometimes reduces runoff as compared with natural vegetation, and sometimes evapotranspiration can be reduced if the natural vegetation is replaced by grass or cultivated crops. In Tanganyika a considerable rise of shallow ground water has been observed in some areas as a result of the clearing of the bush for cultivation. Soil erosion not infrequently develops at a later stage, and then runoff is increased to such an extent that very little percolation takes place and the shallow ground water reserves are destroyed.

An important natural recharge takes place by influent streams in arid areas, and this can be increased by the building of dams and weirs which increase the opportunity for infiltration along the stream channel; this is sometimes employed for improving the supplies to wells and boreholes along stream courses.

In arid regions the losses of rain water as a result of runoff and evaporation in pans are enormous, and the question of the possibility of conserving these supplies for dry season use by means of storage or recharge frequently arises. If the methods of artificial recharge now commonly applied in humid and semi-humid countries could be employed in arid regions they would be of untold benefit, but so far there has been only limited scope for such application. In the first place, water intended for artificial recharge is generally pretreated so that it will not clog the pores of the recharge basins, and this would ordinarily not be practicable in arid countries. Secondly, the form and capacity of the recharge aquifer and its suitability for retaining and yielding up the water can generally be determined, whereas this would also be difficult with the limited resources and data of the arid regions. Again, in humid countries, it is often found that under certain conditions of natural vegetation and soil a rapid absorption of water spread over a surface can be effected. In general, therefore, recharge in arid areas is possible only if the water can be applied in its untreated form, if a suitable absorption surface can be found, and if a suitable aquifer is readily available.

So far, little if any application of these methods has been practicable in the more arid parts of Africa, but some successful attempts in this direction have been made in southern California, where the exhaustion of aquifers used for the irrigation of crops has been prevented by the storing of flood waters of mountain streams in the ground for later use. This was done mainly by surface flooding or by infiltrating water from ditches or basins into the fans of gravel, sand, and silt which extend from the mouths of canyons to the lower cultivated areas, as has been described by Lane (16) and by Michelson and Muckel (20).

In the flood method, water is allowed to pass over the ground as a thin sheet controlled by ditches and embankments. Experiments and field observations have shown that the highest percolation rates are obtained where the natural vegetation and soil are least disturbed.

Where ditches are used, they are flat bottomed, 3 feet to 12 feet wide and 9 inches deep. They are constructed in a variety of ways so as to disperse the water over a large area, usually with a recep-

tion ditch to return the silt and surplus water to the main channel. The flow is controlled by sluices. This method is easily operated and maintained, but the percentage of actual infiltration area is relatively small.

For recharge by basins, water is impounded in areas of some 400 feet to 100 feet by earth dams or banks some 3 feet high, built along the contours. The basins are arranged so that the water can overflow from one to the other, silt being deposited mainly in the highest one. The level of the water is generally maintained at a depth of about 6 inches. Where silting occurs, the surface is repeatedly broken by scraping or harrowing, as on the spreading grounds of Los Angeles, where this is done after each 10 to 14 days (3).

Where in a limited unit area, as defined by geological or geographical conditions, data are available or could be acquired for a complete study of the hydrogeological cycle, it is sometimes possible to make full use of the total water resources of the area. In Tunisia, for example, Tixeront (27) has studied the water supply resources of three limestone masses on which the towns of Tunis and Bizerta depend. The masses are individually of limited but known extent, and they are cut off by faults and impermeable beds. The rainfall, evaporation, and outflow of streams are all well known, and the movements of the water table are checked by observation wells, boreholes, and other works. The annual volume of the additions of water to the ground water reservoirs as observed and calculated accord satisfactorily. The results obtained enabled the authorities to follow the fluctuations of the reservoirs in the aquifers studied, to regulate their exploitation, and to predict the importance to the township supplies of any new additions of water.

In British African territories much interchange of information and coordination of effort has been achieved by Inter-Territorial Hydrological Conferences which it is proposed to hold periodically. One such conference took place at Nairobi in 1950 and another in Southern Rhodesia in 1954. The papers presented at these conferences, as well as the publications of the Water and Meteorological Departments, clearly indicate the wide range of

hydrological research and development now in hand in these territories.

Outline of Situation in British Overseas and Commonwealth Territories

The points suggested for discussion comprise the following:

1. How predictable is precipitation in an arid region?
2. Are there distinct drought cycles?
3. What are the prospects for usable ground water occurrence in arid areas?
4. What is the practicability of locating and estimating volume and rate of natural recharge of underground water supplies?
5. Within a given watershed, to what degree can the water sources and water yield be determined?

I have considered these points in turn in relation to investigation and development now proceeding in various British Overseas and Commonwealth Territories. Very brief, general answers are given in this paper, detailed answers for each area in a paper published separately in *Colonial Geology and Mineral Resources*. I wish here to express my great indebtedness to all those officers mentioned in the text who have supplied me with the information on which this account is based.

1. *How Predictable is Precipitation in an Arid Region?* In the territories considered precipitation is not ordinarily predictable owing to the absence of adequate long-term data on which to base statistical investigations.

2. *Are There Distinct Drought Cycles?* In the British Overseas Territories considered droughts are of common occurrence, but they do not recur in regular cycles.

3. *What Are the Prospects for Usable Ground Water Occurrence in Arid Areas?* In the territories considered, in the most arid areas, such as Somaliland, northern Kenya, parts of Tanganyika, and Bechuanaland, usable ground waters are found only with difficulty, and the percentage of successful boreholes is low, 50%, or less; waters are frequently too saline for use, and in parts of Tanganyika and Kenya the fluorine content is also high. The waters occur at depths of 300 to 400 feet, or even more. In the less arid

areas, such as Karamoja District of Uganda, parts of Kenya and Tanganyika, and Northern Rhodesia and Nyasaland, the ground waters are usually potable, and are met commonly at depths of 100 to 200 feet. The proportion of successful boreholes, yielding 135 to 1,000 gallons or more per hour, commonly ranges between 80 and 90%.

4. *What Is the Practicability of Locating and Estimating Volume and Rate of Natural Recharge of Underground Water Supplies?* As regards the locating of ground waters, in all the territories considered, sites are selected on the basis of geological, topographical, and geophysical investigations, but in the end the actual locating or proving is effected by means of the drill. Water-boring operations accordingly take pride of place in all schemes for the investigation and development of ground waters. In the less developed countries Government has to take the initiative in providing drillers and drilling equipment, but in other countries private contractors are also available. Governments carry out water boring for the indigenous peoples as part of programs of development, but they drill also for European settlers on payment.

As an example of Government drilling for the benefit of settlers may be quoted the following arrangements current in the Union of South Africa, where, however, the operations are more highly subsidized than in most other territories.

Boring for water, on application by individual farmers, is carried on by the Irrigation Department throughout the Union, while Government subsidies are also payable on boreholes drilled by private contractors, where the water supplies are required for domestic and stock-drinking purposes. These measures have undoubtedly contributed greatly to the utilization of semi-arid stockfarming areas and have also been a potent factor in the fight against soil erosion, by reducing the distance stock have to travel to water. There are at present 217 Government drills in operation and the work is heavily subsidized.

In 1946, in order to assist stock farmers in certain parts of the country where arid conditions prevailed, it was decided to proclaim certain areas as drilling zones, and the gradual extension of the areas so proclaimed has resulted in the Union being divided

into two areas for water-boring purposes. The difference in the two areas is concerned chiefly with the charges levied for holes drilled by government machines, drilling in proclaimed areas being on a "no water—no payment" basis, and when water is found the rate payable is based on a sliding scale calculated on the quantity of water obtained and the footage drilled. In non-proclaimed areas drilling is charged for at a fixed daily rate, but rebates are allowed which in practice make the actual charges very reasonable.

As regards estimates of volume and rate of natural recharge of ground waters, none of the territories considered is sufficiently well developed to have acquired the necessary detailed geological and hydrological data to enable general estimates of this nature to be made; locally, however, the requisite data have been built up for particular limited projects, and on the basis of these data estimates of volume and rate of recharge have been prepared and put to practical use in the development of various schemes for township and other water supplies.

5. *Within a Given Watershed, to What Extent Can the Water Sources and Water Yield Be Determined?* In the better developed territories the necessary data have been acquired regarding water sources and water yield for particular projects, such as town water supplies and hydroelectric and irrigation works. In the less well-developed territories the information of this nature available is almost nil, and is confined to minor local projects and scanty short-term records. In general, in relation to the vast areas and potential involved, the amount of hydrological data at present available is small indeed. Within the last few years the British east and central African territories have greatly augmented their hydrological staffs and have provided for the collection of standard data on a scale never before attempted. This essential step has been taken because of the rapid development of these territories and of the urgent realization of the need for such data for many purposes. The necessity to provide water supplies for the larger townships, and to prepare the great hydroelectric projects associated with Victoria, Albert, and Nyasa lakes, and the Zambezi and Kafue rivers has proved an immense incentive to the develop-

ment of plans for large-scale hydrological investigation and for the acquisition of the requisite basic data.

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Fluctuations and Variability in Mexican Rainfall

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The need for climatological research in arid and semi-arid regions to the benefit of agriculture has been stressed very clearly by Thornthwaite (pp. 67-84), especially as regards the study of the water balance. There are other meteorological branches, however, the study of which seem to be of similar importance to the arid regions as practically all problems of such areas emanate from atmospheric conditions.

In Table 1 are summarized the most essential meteorological research problems to be studied in the arid zones. These might be separated into two principal groups: general meteorological and synoptic climatological studies related to the circulation conditions on the one side, and studies of the water balance on the other.

It is obvious that in applying to agriculture in arid and semi-arid regions both direct precipitation and ground water it is necessary to know in detail, "Why it rains, when it rains, where it rains," which therefore always must involve the basic problem of all climatic research in such areas. In investigating the direct water supply for vegetation and agriculture as well as in trying to discover ground water resources, it is necessary to have a basic knowledge of the precipitation mechanisms and circulation conditions that give or prevent rainfall and also to know the actual amount of precipitation, its frequency of occurrence, its variability, and long-term fluctuations. It is therefore as important to study, for example, the classification of circulation

TABLE 1
Climatic Research in Arid Lands

I General and synoptic meteorology, dynamic climatology	II Water balance
<i>Basic investigations</i>	Macroclimatic investigations
	<i>Basic</i>
General circulation conditions	Humidity conditions of air masses involved
Particular circulation problems as "easterly waves"	Causes for humidity distribution
Hurricanes	Cloud physics
Influence of westerlies, as for instance how "jet stream" position effects winter rain	Distribution of precipitation; relation of distribution to circulation
Dynamics of cumulus clouds	Variability of precipitation
Radiation from sun and sky	Chemical content of precipitation
<i>Applied</i>	Heaviness of precipitation
Research on use of wind energy	Max. temp. in relation to sunshine; in cases frost studies
Research on use of solar energy	<i>Applied</i>
Soil conservation studies	Artificial rainfall
Long-range forecasting of precipitation	Irrigation
	Use of chemical content in precipitation
	Ground water and precipitation
	Soil conservation
	Microclimatic investigations
	<i>Basic</i>
	Exchange of heat, humidity, and momentum at the ground
	Calculation of evaporation from heat balance
	Measurements of evapotranspiration
	Water supply in the soil
	Soil and ground temperature
	Dew studies
	Microclimate in forests
	<i>Applied</i>
	Prevention of evaporation
	Use of dew for different plants
	Influence of deforestation
	Reforestation
	Soil conservation
	Plant ecology
	Seeding days and harvest days
	Phenology

types, hurricanes, perturbations in the airflow, convective instability in cumulus clouds, winter rainfall related to the "jet-stream" position and the statistics of fluctuations of rainfall created by these mechanisms as to find out in which strata of rocks the ground water exists or how to irrigate dry lands by surface water coming from surrounding areas of higher precipitation or from rivers coming from such regions.

The second type of investigation cannot be successfully carried out without the first one. Furthermore, careful investigations of

rainfall and of which circulation conditions create convection and heavy showers are extraordinarily important in relation to soil erosion, which is a serious danger in these regions. It should finally be kept in mind that inducing rainfall by artificial means never could be successful unless one has a thorough knowledge of the circulation mechanism that creates the necessary cloud types in the areas concerned.

An ultimate goal of the statistical and synoptic climatological studies mentioned in the first group in Table I should also be to give methods for long-range forecasting (monthly, seasonal, or longer) of rainfall. This is of particular importance to agriculture and water supply in arid and semi-arid lands.

The suggested studies of the water balance (*group II*) in itself may be separated into a macroclimatological and a microclimatological type. The former type often serves as a bridge between the investigations in general meteorology and synoptic climatology of the first-mentioned group (I) and the detailed studies included in the microclimatic type. These investigations, in other words, should give more detailed information of rainfall mechanisms and cloud physics as well as of temperature conditions than might be obtained by the general investigations of the first group.

The aim of the microclimatic studies of heat and water balance discussed by Thornthwaite is to understand how economically to apply irrigation for the reduction of evaporation, soil conservation, reforestation, etc., with due regard for results given by the general investigations. It is not advisable to take up such microclimatic studies of the water balance without having laid a solid foundation by investigating the first-mentioned general problems.

As an example of a basic statistical and synoptic-climatic study of a partly semi-arid or arid country I shall discuss briefly a study of fluctuations and variability of Mexican rainfall which was performed during my work as UNESCO advisor in economic climatology to the Mexican Government in 1954 (6).

Precipitation in Mexico

Detailed studies of more delicate characteristics of precipitation in Mexico are still lacking, mainly because the scattered network

of stations makes detailed studies difficult to conduct. Nevertheless it was possible to make some studies of fluctuations and variability of rainfall, these characteristics being of special interest to agriculture.

From the scattered network of stations, with often not too accurate measurements, it was possible to select 52 stations having in most cases reliable records for more than 20 years. Tacubaya, D.F., with records since 1878, has also been used.

It was generally assumed that only small errors can be involved in records from a certain area which all show the same general interannual fluctuations. When the records showed doubtful deviations from the general trends of fluctuation, the stations were not accepted.

The northern and northwestern parts of Mexico show semi-arid or desert conditions with an annual rainfall ranging from 200 millimeters in Sonora to about 500 in Durango and Coahuila (Figure 1). On the other hand, rainfall reaches 3,000-4,000 millimeters in the southeastern parts of the country. Except for these extremes the rainfall map shows a large triangular area of dryness extending through the country southward and having its base at the U. S. border.

Mexico is a country of seasonal rainfall with summer and autumn the rainy seasons in all parts of the country except for a small area in the northwest where the Mediterranean rainfall regime of winter rain prevails. The May-October season gives generally more than 80% of the annual precipitation. This figure is somewhat smaller along the Gulf Coast and higher in the southwest (4).

The following circulation factors regulate the Mexican rainfall as far as we know them:

1. Seasonal fluctuations in the position of the intertropical convergence zone.
2. Location, extension, and intensity of the subtropical high-pressure cells, directing the influence of the trades.
3. Perturbations in the summer easterlies ("easterly waves").
4. Hurricanes, generally created in connection with the "easterly waves."

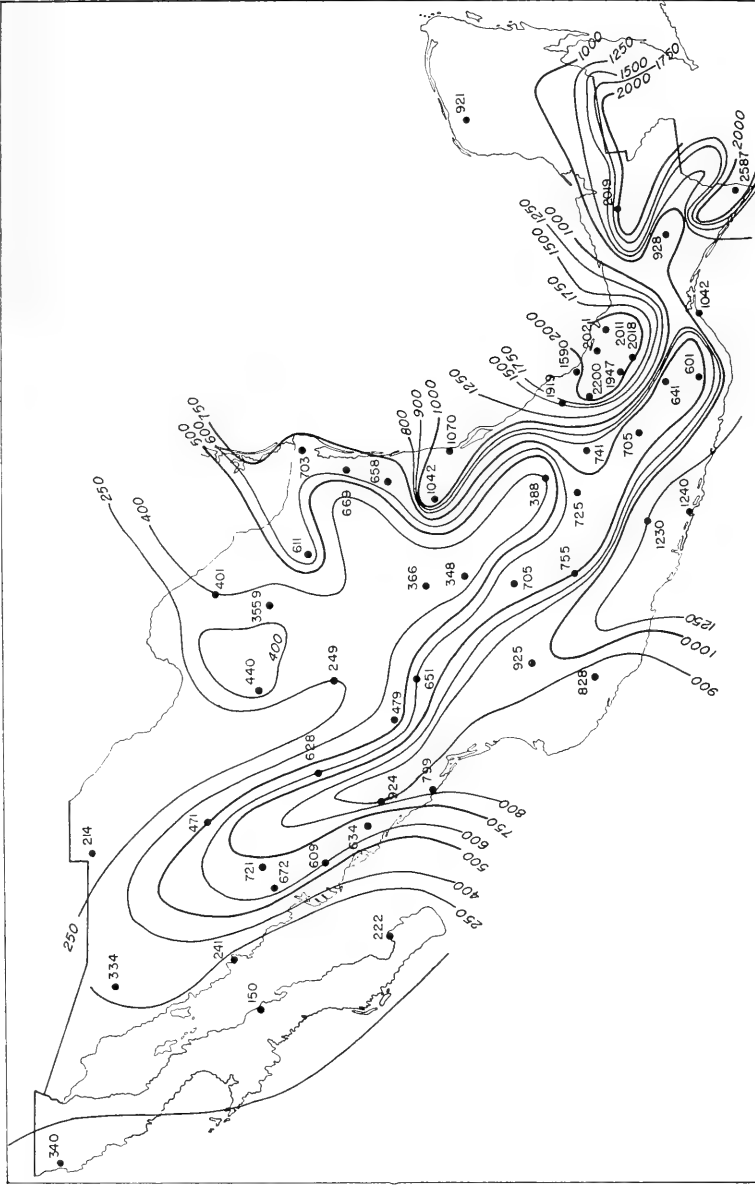


Figure 1. Mean annual precipitation (1919-1953).

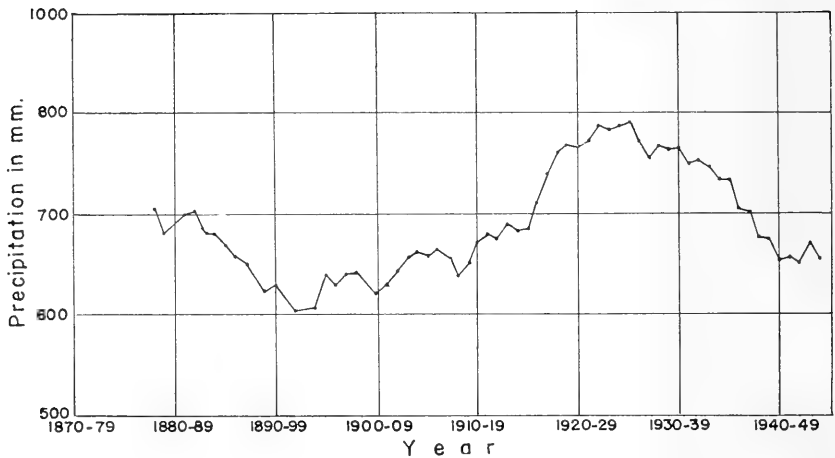


Figure 2. Ten-year overlapping means of annual precipitation in Tacubaya, D.F. (1878-1953).

5. Middle latitude westerly troughs passing over the northern part of the country in winter.

In winter when the intertropical convergence zone is far to the south, the easterlies influence only the southernmost part of the land area while the northern parts are under the influence of the middle latitude westerlies, which give very little precipitation except for the Gulf Coast area in connection with the so-called nortes. In summer the whole country, except for the northwestern very dry regions, is under the influence of the tropical easterlies, and rainfall is frequent owing to convectional instability and even more to perturbations in the easterlies and to hurricanes.

Long-Term Fluctuations in Mexican Rainfall

Smoothing of the fluctuations in annual and monthly precipitation was made by calculating 10-year overlapping means. Figure 2 shows the 10-year overlapping means curve for annual rainfall in Tacubaya, D.F. The curve indicates that there was a decrease of rainfall in central Mexico from the period of 1878-87 to the period of 1892-1901 and then an increase up to around 1935. Since then there has been a decrease again up to recent years. The fluctuations are rather great and the maximum amount of

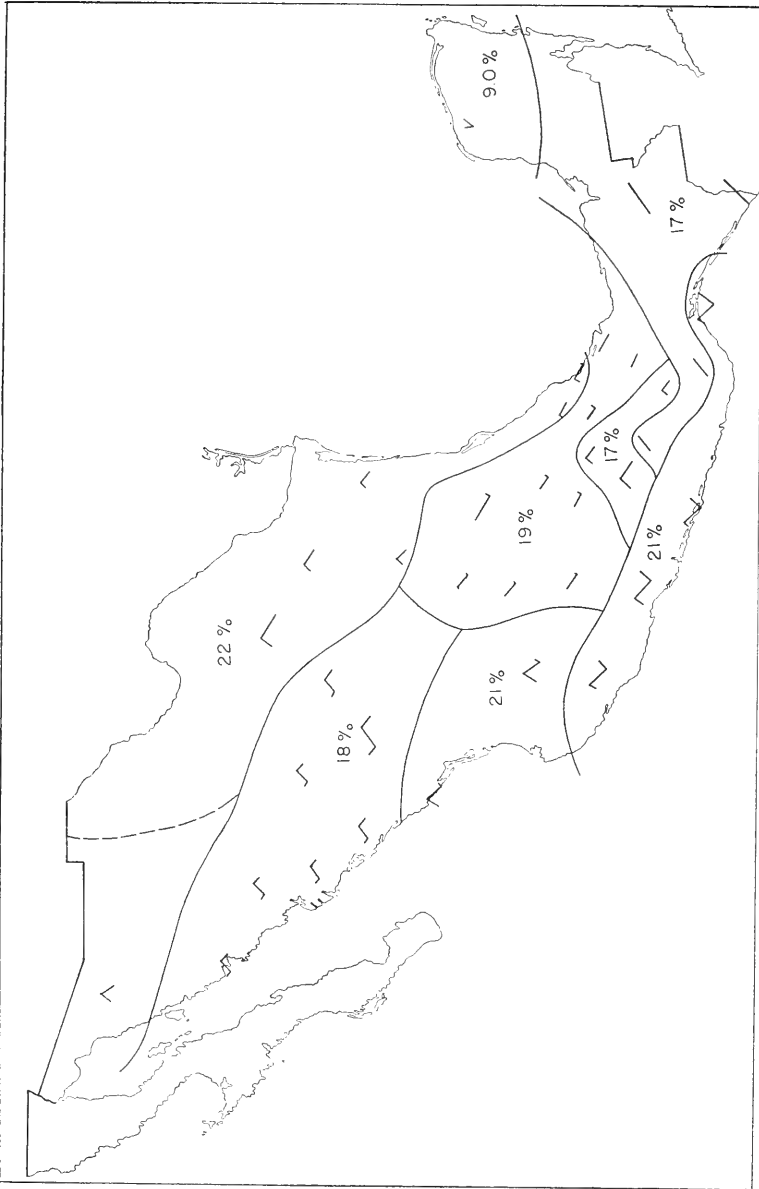


Figure 3. Long-period fluctuations in annual precipitation. Per cent variation from maximum to minimum.

rainfall, 958 millimeters, was reached in 1925, the minimum value, 440 millimeters occurred in 1894.

Studies of the fluctuations of monthly precipitations have revealed that the increase from 1900 until around 1920 was caused by an increase of both summer and winter precipitation, counterbalanced by a decrease in fall precipitation. The rapid increase from 1920 until 1935 was caused by an increase of precipitation in both summer and fall. The decrease thereafter has been accounted for by a decrease in rainfall of both summer and fall.

It is likely that the considerable increase of summer rainfall from the turn of the century until the middle of the 30's must have been associated with a strengthening of the summer easterlies over Mexico. This in turn was caused by a general shifting northward of the subtropical high-pressure cells and particularly by a transition to the west of the summer cell in the Caribbean Sea. Such a northward shift goes very well with the well-known warming up of the winters of northern latitudes during the same period.

The decrease of annual precipitation since the middle of the 30's suggests that a gradual regression of the subtropical high-pressure cells has taken place. This has also been suggested by evidences in northern latitudes of a cooling off in recent years and particularly since the end of the 30's (5).

Figure 3 shows the fluctuations of annual rainfall since 1920 in different areas of Mexico. There is an overall tendency in all regions, except for the southernmost one, to show first an upward trend and later a decrease of rainfall. The turning points of the curves from an upward to a downward trend occur at different times so that they generally appear earlier in the south than in the north. This is even more obvious on the western side than on the eastern side. This gradual displacement of the maximum, as we proceed northward, fits in very well with the idea of a gradual shifting northward of the subtropical high-pressure cells and a gradual moving back.

Variability of Rainfall in Mexico

In our study of the variability of rainfall in Mexico we have used several measures. Of most interest were the studies of the

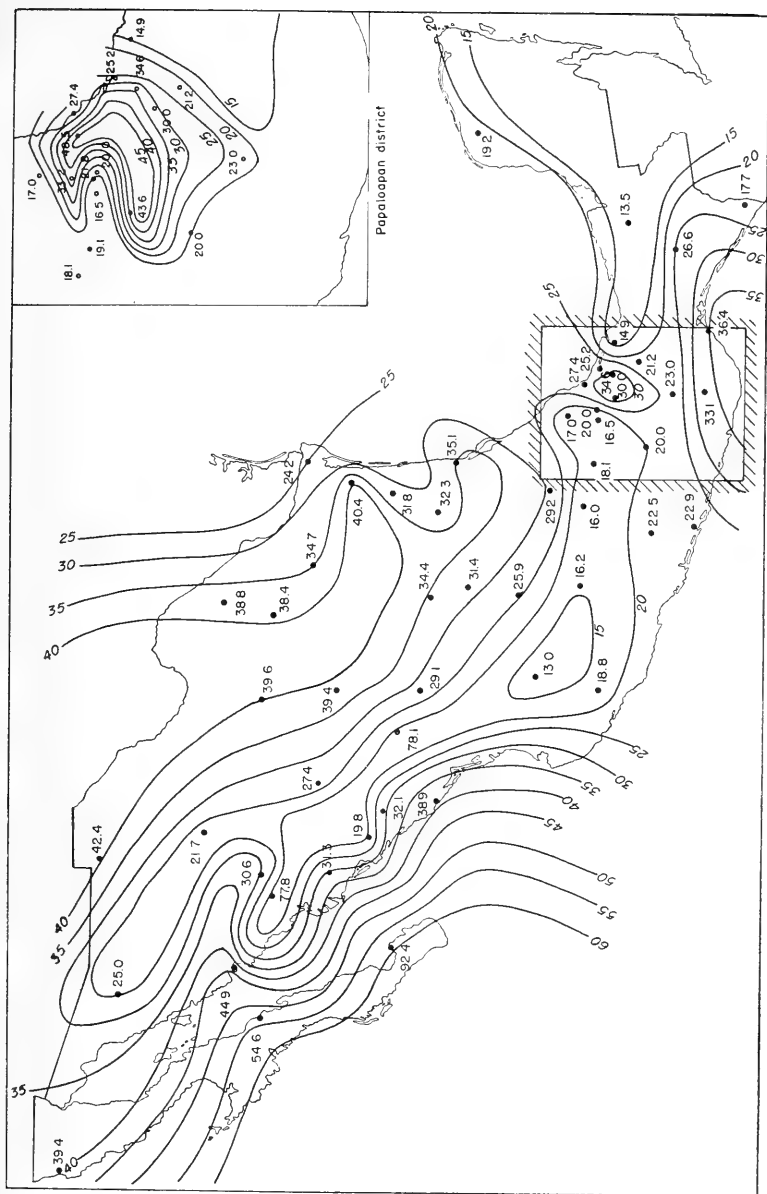


Figure 4. Relative interannual variability of annual precipitation (1919-1953).

relative interannual variability (IaV)* and the anomalies of the relative variability (RV)† in comparison with the Conrad's standard curve showing the interrelation between amount of precipitation and variability for the world as a whole (1). Such anomalies are much better to study than the (RV) in itself as they are no longer influenced by the actual amount of rainfall as is the value of (RV). The relative interannual variability is shown in Figure 4 and the anomalies in Figure 5.

The highest variability is found in the areas of low precipitation in the northern and northwestern parts of Mexico with a maximum of around 50% in the extreme dry areas. A secondary maximum of around 40% is found in the northeast, where rainfall is greater but the water supply conditions are difficult for agriculture. Third maximas of some 30% are found in the Papaloapán district of comparatively high precipitation. The lowest values are found on the central plateau and along Sierra Madre Occidental, reaching 15-20%.

Looking at the anomalies of Figure 5 we note that the area of Baja California shows high positive anomalies, indicating that the variability is even larger than normal. The same is true in northeastern Mexico, southern Sinaloa, Nayarit, and parts of the Gulf Coast area. On the other hand, it is interesting to note that the inner part of the dry state of Sonora has variability values much *lower* than the normal conditions would give.

It is to be expected that current investigations of the relationship between the general circulation and precipitation in Mexico will explain the reasons for these extreme areas of anomalies, but some ideas may be expressed now.

Thus, it seems likely that the reason for the abnormal variability in Baja California, Sinaloa, Tamaulipas, and the Gulf of Tehuantepec are the hurricanes which frequently hit these coasts in fall. Studies of the variability of October precipitation suggest this

$$* (IaV) = [(p_1 - p_2) + (p_2 - p_3) + \dots + (p_{n-1} - p_n)]/p_{n-1}; (IaV)_{rel} = 100 \frac{(IaV)}{p}$$

p = mean annual precipitation; n = number of years on record.

$$\dagger [RV] = 100 \cdot \frac{\sigma}{p} \text{ where } \sigma = \sqrt{\frac{\sum d_i^2}{n}}, \text{ where } d_i = p_i - p.$$

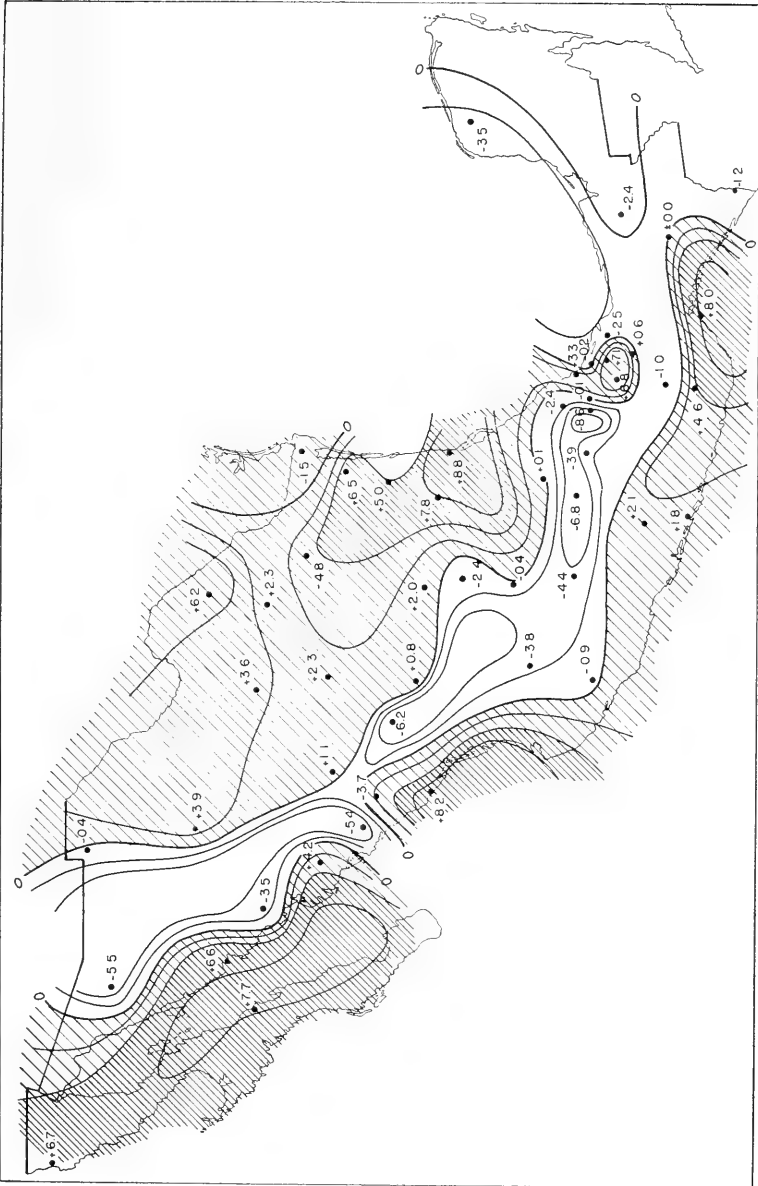


Figure 5. Isanomalies of relative variability of annual precipitation anomalies with regard to world normal distribution of relative variability of precipitation, according to Conrad.

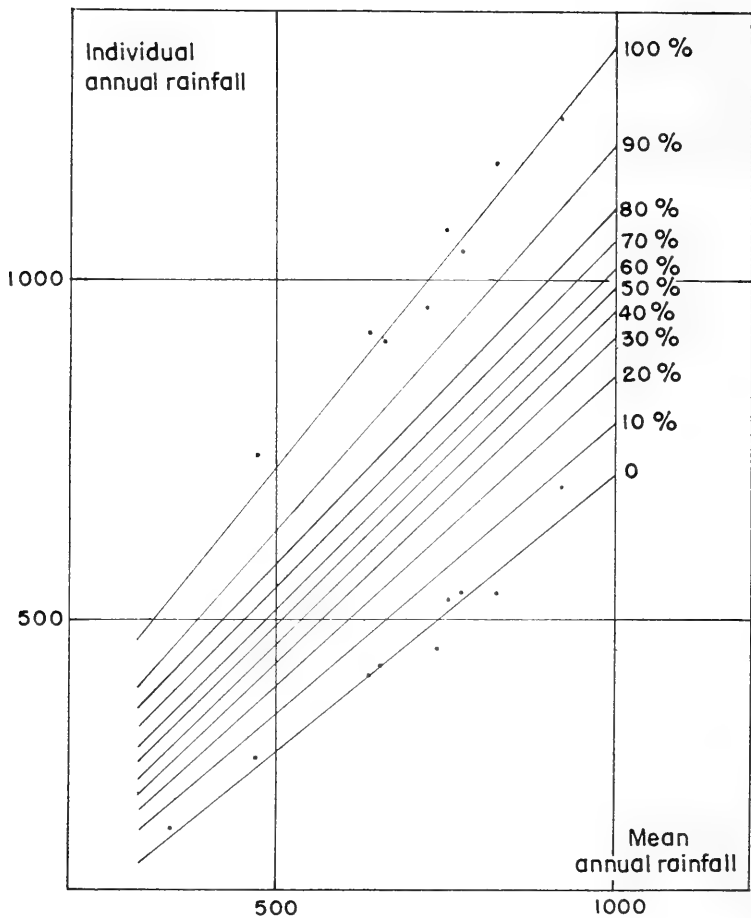


Figure 6. Probabilities of having individual rainfall amounts (ordinates) in the central plateau of Mexico as a function of mean annual rainfall (abscissas).

idea. In the areas of rather large precipitation, as in the Papaloapán district, local topographical conditions must be decisive in explaining the variability, especially in connection with fluctuations in the general direction of the rain-giving easterlies.

Frequency Distribution of Rainfall Amounts

In studying the frequency distribution of annual rainfall a special risk diagram suggested by Landsberg (3) was applied.

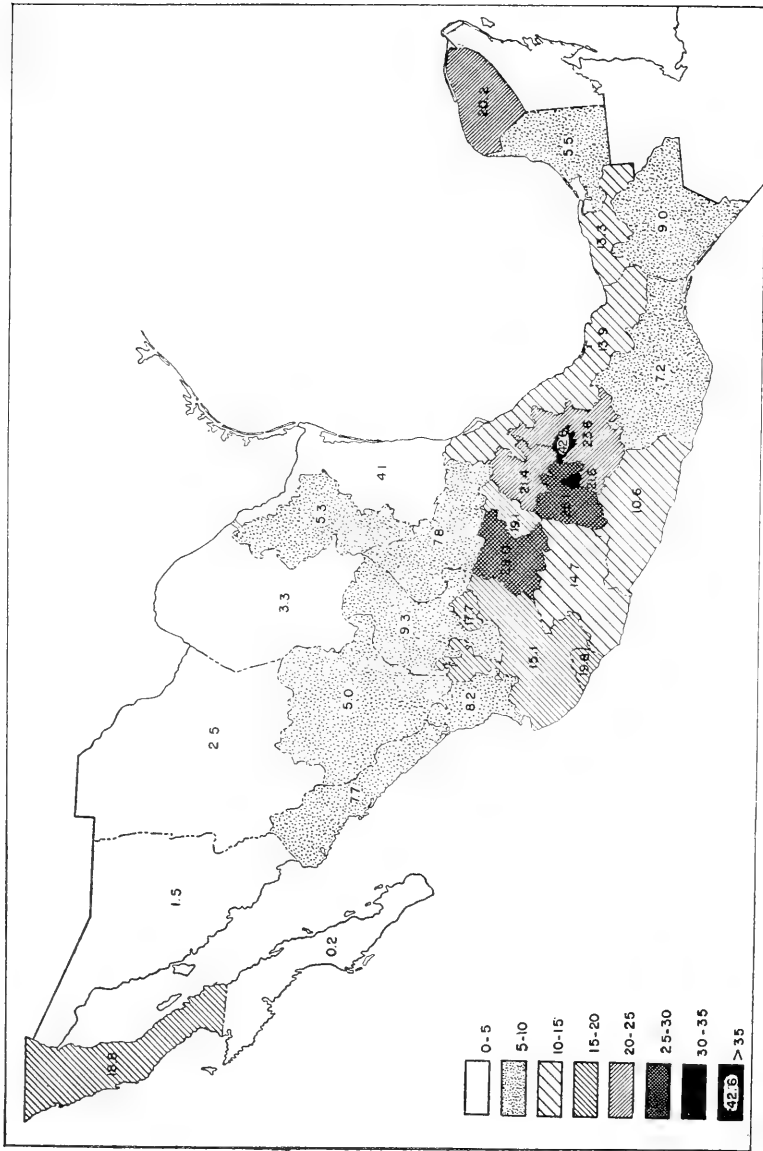


Figure 7. Distribution of cultivated area in relation to area of states in Mexico (1940).

Figure 6 shows the probability of having individual annual rainfall amounts (ordinates) in the central parts of Mexico as a function of mean annual rainfall (abscissas). To show how to use this sort of diagram, which seems particularly useful in arid regions of high variability, we assume, for instance, that a particular agricultural plant requires on the latitudes in question at least 750 millimeters of annual rainfall in 80% of the years in order to be profitable on a long-term basis. The diagram shows, from finding the intersection between the 750-millimeter value on the ordinate and the 20% probability line, that only areas having an average annual precipitation of more than 880 millimeters meet the requirements. It could be mentioned as a comparison that a similar diagram for the Papaloapán district shows that only areas having more than 1,040 millimeters annually meet the same requirements.

Diagrams of this kind should be prepared for more limited districts in Mexico as soon as enough data are available.

Agriculture and Variability of Rainfall

It is evident from the maps of rainfall variability that the areas in Mexico with high variability coincide with those where it is known that agriculture is difficult. One of the best known examples is the northeastern area where, even if precipitation sometimes is sufficient, it is so unreliable that agriculture is very hazardous.

It is also clear that the central plateau area which long has been known as the best for agriculture in Mexico is the region of lowest variability in all the country. The relation between agriculture and variability is shown from a comparison between the maps in Figures 1, 4, and 7. The last one shows the percentage relation of cultivated land to the area of states in Mexico in 1940. Little relation is found between the amount of rainfall in itself and the distribution of cultivated land, but a rather good interrelation exists between cultivation and variability. A good relation could also be found between the distribution of cultivated land and climatic provinces of Mexico based upon the classification of climate according to Thornthwaite, in which evapotranspiration is the essential factor. It seems, however, that in applying climatic

indices to show the usefulness of land areas for agricultural purposes the variability of precipitation should be introduced besides the evapotranspiration factor.

Work to Follow

In the recently established Institute of Applied Science in the University of Mexico work is now going on to investigate the precipitation mechanisms that create the above-mentioned conditions of fluctuation and variability. A classification of weather types has been made for surface and upper air circulation over Mexico and frequencies of the different types in various parts of the year have been calculated. The next step will be to study the correlation between these circulation types and precipitation in various parts of the country. It is our hope that these investigations will become a solid basis for continued work on methods for long-range forecasting of precipitation as well as for extensive studies of the possibilities for inducing artificial rainfall and of the water balance of the country.

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Beneficial Use of Water in Arid Lands

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During the past several years the Soil Conservation Service has studied the characteristic precipitation and water yields of Arizona, Colorado, New Mexico, and Utah in an attempt to determine: (1) what the average annual precipitation is; (2) what part of this original supply is available for irrigation, domestic, and other uses; (3) what watershed or climatic factors are predominant in the production of water yields; and (4) what may be done to reduce losses of water to non-beneficial use.

During the course of the study, isohyetal and water yield maps of the four states were developed on a scale of 1:500,000 to permit reasonable delineations of usual amounts of precipitation and subsequent water yields throughout the four-state area. Weighted amounts of precipitation and the apparent total yield of water to downstream users were then determined. The annual precipitation varied from less than 4 to about 60 inches, and water yields from less than one-tenth inch to more than 30 inches. The figures for water yield do not take into account flow into or out of the four-state area; they are merely map measurements. However, they are considered representative of existing conditions.

Although the four states were covered in their entirety, the following discussion will be confined to those portions with an annual precipitation of 18 inches or less. These, we believe, encompass the arid zones.

Our studies developed the following facts with regard to the four questions we asked:

What Is the Average Annual Precipitation?

The 18-inch-maximum zones comprise some 335,600 square miles or 80% of the total surface area of the four states. The average annual precipitation over this zone is about 13 inches. This represents some 225,800,000 acre-feet of water and is the total water supply or precipitation occurring over the arid zone of these states.

What Part of Original Supply Is Available for Irrigation, Domestic, and Other Uses?

Map measurements of the various water yield zones indicate that some 5,200,000 acre-feet of water subsequently becomes available for other than natural watershed uses. Conversely, about 220,600,000 acre-feet, or 98%, of the water that falls in the form of precipitation is either consumed where it falls or is lost in transit to points of downstream use. In checking other information and data concerning water yields of the various states, it appears that the yields shown on the maps are, if anything, generous. Therefore, the estimates of water available from arid zones for downstream use are probably high.

What Watershed or Climatic Factors Are Predominant in Production of Water Yields?

During the course of our studies, notes were made of the physiographic, vegetational, and other watershed characteristics that might influence the relation between precipitation, the runoff in surface streams, and ground water accretions. Extensive tables were prepared showing the soils, vegetation, topography, geologic conditions, and numerous other factors for each watershed that had been gaged. An analysis of these data was then made to attempt to delineate the factors or combinations of factors that profoundly influence water supplies. In certain instances the presence or absence of deep soils with high water holding capacities was found to exert a strong influence on water yields. Other watershed characteristics, such as topography (which may or may

not encourage natural water spreading) and vegetation (which can modify infiltration rates), were also found to be influential. However, no single watershed characteristic that consistently correlated with high or low water yields could be found. This may be due in part to the fact that each watershed had a different combination of soils, vegetation, physiography, and other factors, any of which might play a greater or lesser part in one watershed than in another.

Soon after the study was started, however, it became apparent that precipitation, in combination with evapotranspiration potentials, consistently correlated with watershed yields throughout a wide range of watershed conditions. True, it was found that, all other things being equal, such watershed conditions as have been mentioned heretofore could materially influence the yield of water; nevertheless, the apparent influence of the precipitation-evapotranspiration factor far overshadowed watershed influences. For example, it was found that with low precipitation and high evapotranspiration perhaps 1% of the annual precipitation might be expected to appear as water yield. On the other hand, and considering *all zones covered by the study*, with high precipitation and low evapotranspiration, perhaps 50% of the precipitation might appear as water yield. It became obvious, therefore, that these two factors were predominant in the yield of water to the extent that watershed characteristics, as such, "fell out of the picture."

As mentioned by Thornthwaite (1) there has been published a generalized map of the evapotranspiration potentials of the four states considered in this study. Although the map is not of such a scale as to permit a high degree of accuracy, it was possible to develop approximate evapotranspiration potentials from the map for comparative purposes.

Considering only the arid zone, the weighted evapotranspiration potential was found to be about 29 inches on the average, annually. This can be compared with the weighted precipitation of 13 inches. To phrase this another way: on the average, there exists a potential for evaporation or transpiration of some 220% of the average annual precipitation. Although this comparison disregards seasonal fluctuations in evapotranspiration or precipi-

tation during those times of year when precipitation may be high and evapotranspiration low, or vice versa, the situation in the arid zone would undergo no major change were this factor considered. Recognizing this normal preponderance of evapotranspiration potentials over precipitation, it is self-evident that any precipitated water that does not leave an area through surface runoff or through infiltration to ground water will ultimately be consumed.

This fact brings to light a popular misconception concerning the importance of the relative evapotranspiration potentials of various types of vegetation in the yield of water from arid zones. It has been commonly believed that if one plant uses more water than another then there will be less water available for downstream use. It is not usually recognized, however, that whenever *evapotranspiration potentials exceed the supply*, or precipitation, it makes no difference what *type* of plant occupies an area, the water will be removed. Such being the case, the replacement of non-beneficial plants with forage producing plants may be accomplished with little or no loss of water.

Another result of the normally high evapotranspiration potentials in arid zones is the tremendous amount of water evaporated or transpired before reaching a point of downstream use. In the San Simon Valley of Arizona, for example, only some 20% of the indicated water yield from small experimental watersheds ever reaches the mouth of the valley; the remainder, for the most part, is consumed by evaporation or transpiration.

What Might Be Done to Reduce Losses of Water to Non-beneficial Use?

At this point it might be well to review several facts brought out in the previous discussion. (1) There are some 220,600,000 acre-feet of water, or about 98% of the total precipitation, being consumed naturally on our arid watersheds before reaching a point of downstream use. (2) In the arid portions of our four-state area, evapotranspiration potentials are usually sufficient to consume any water not flowing out of a watershed. This is without regard to the particular type or amount of vegetation that may be present on the area. (3) Tremendous water losses occur through

evaporation or transpiration between the points of origin and downstream use.

Disregarding the relatively small additional amount of water that we might, with diligent effort, cause to flow out of our natural watersheds, we still have millions of acre-feet remaining there. It may be well to ask: What forage is this water now producing, compared with its potential productivity? Also, what needed commodities are produced by the water now being lost in transit between the point of origin and the point of downstream use?

If we accept the premise that evaporation and transpiration potentials are such that normally any precipitation not leaving a watershed will ultimately be consumed by whatever type of vegetation that may be present or by evaporation alone, then is it unreasonable to assume that we could, through replacement of undesirable plants with desirable plants, develop a forage production that we do not have today?

If we are correct also in assuming that large quantities of water are consumed by non-beneficial vegetation in stream channels, is there not reason to believe that we can effect large savings of water by the removal of such vegetation?

In summary, is there not every reason to believe that the part of the 220,600,000 acre-feet of water which is not now reaching points of downstream use and which is not now being put to beneficial use on natural watersheds, represents the real potential for increased production of needed commodities in our particular arid area?

If the answer to these questions is yes, it appears that we should direct our attention, action, and our research toward ways and means of changing the use of water on our natural watersheds from non-beneficial to beneficial use.

Although this discussion has been directed toward a particular segment of a particular country, reasoning applied here probably is applicable to other arid areas.

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Geochronology as an Aid to Study of Arid Lands

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Researches into past climate have yielded information which illustrates that local climate is ever changing. The degree to which this change occurs varies in time and in area. First attempts to define climatic areas, or areas wherein the climate is essentially homogeneous, met with about as much success as first attempts to define the size and shape of an amoeba, both being equally fluid and equally alive, appearing never to repeat themselves in exactly the same pattern or shape. Additional research brought to light the fact that in both studies there is more than meets the eye, there is cause and effect which has to be determined and understood. Geochronology can aid in understanding the effects of climate although it cannot help in determining the cause.

Geochronology is operationally defined as a field of study encompassing all scientific methods which can be applied to the dating of terrestrial events. Climatic change is an event which falls within this category. These methods are used to date changes which have occurred over long periods of time to determine the duration of change, the length of visible climatic patterns, and the recurring climatic cyclics so we may view them in their proper perspective and weigh them accordingly. No evidence of what might be called a true cycle has been discovered even with recently refined dating techniques. All evidence indicates a variable (in time and in intensity) cyclic-like pattern of change which can only be interpreted on a relative scale. One specific approach, i.e.,

palynology, pedology, or dendrochronology, gives information along a prescribed line, whereas another approach gives different data. Through correlating and, or, superimposing one over the other(s), the climatic picture begins to evolve.

Tree Rings and Relative Rainfall

The first method I should like to discuss is dendrochronology. This method yields absolute dates on specific tree rings according to the growth year, and it yields relative rainfall patterns. There is, at present, no technique known in which tree-ring data can give information along the lines of absolute quantities. For example, we can establish departures from a running mean which in itself is the average of the data in hand; we can determine if a year, or a period of years, is below average, average, or above average in growth, but no method is yet known that will allow us to determine the absolute amount of rainfall represented by that average. Because many factors influence the growth of a tree, it is impossible to isolate completely one physiological or environmental factor from all the others. Thus we are not positive that we have a true or absolute representation of the rainfall patterns in contrast to patterns representative of other growth factors.

In the course of our tree-ring studies, thousands of samples from living trees as well as historic and prehistoric specimens from over the southwestern United States have been analyzed. Working with the archaeological material supplied in quantity by southwestern excavators, we have developed regional tree-ring indices for the major river drainages and their related geographic regions in this general climatic area. These local chronologies extend into prehistoric times. They are limited by the material available; consequently their individual lengths of time vary from one region to another. The study of these regional indices is profitable because they indicate the less pronounced variability that has existed from one region to another within the larger and relatively homogeneous climatic area. The tree-ring "droughts," or periods of deficient rainfall as exhibited in tree growth, can be considered as "droughts" only inasmuch as they fall below the average.

Aside from the relative quality of these deficient periods, there

is also the variable intensity of deficiency from one region to another. For example, what might be exhibited as an extremely deficient period in the Rio Grande region will be less severe (at least the trees will have much more relative growth) in the Mesa Verde region of southwestern Colorado, and the actual dates on the two respective periods will agree only in a general way. The evidence indicates that we should have a separate ring series for each area because there is no single period of equal intensity and duration over the entire Southwest.

It is impossible to determine the major overall trend for either the individual region or the entire area at the present time, although future studies may allow a partial solution of this problem. In other words, we cannot predict what will happen next year, or the following year, or during any future year. As long as there is enough moisture to support tree growth, we can determine the departures from the average, but this average may be at a minimum or a maximum or any point in between, although it must be within the prescribed amount of rainfall within which a particular species of tree can grow. *Pinus ponderosa* can grow, for example, in areas where the average rainfall is around 14 inches, and it also grows where there is as much as 35 or more inches, wherein it begins to be crowded out by other species. One area, near Bend, Oregon, has a good stand of ponderosa where the average annual rainfall is but 12 inches; this growth is possible because the moisture comes at the right time of the year and the tree is able to utilize all that does fall. From these figures, we can say that the average yearly indices can vary from 12 to 40 inches at least. Other factors, biotic, edaphic, etc., can influence both the maxima and the minima to the extent that these figures must be considered as approximations.

The subjective diagrammatic deficiency period chart, Figure 1, gives what I believe to be the best representation of the periods of deficiency for five major areas in the Southwest. Two of these areas, Durango and northeastern Arizona, are incomplete. From this chart, one can see that there is a period from ca. 50 B.C. to ca. A.D. 320 during which there were very few of these so-called droughts. Beginning with a deficient period around A.D. 320,

however, such periods were common and more intense until the late 1200's when a long deficient period occurred. The 1300's were mostly good, as were the 1400's. Several periods occurred during the 1500's, with a severe one at the close of the century. From 1600 to the present, conditions have been favorable, and a short interval during the turn of the twentieth century is about the only really deficient period. The horizontal line in the deficiency curve at the bottom of the figure has no quantitative meaning; it could represent 12 inches, or 40 inches, or any point in between, and it could, in itself, be a fluctuating average or curve which it probably should be.

Possible changes in the average annual rainfall are indicated, I believe, by the following bits of information. Samples obtained from living trees growing on the higher mountain ranges of southern Arizona rarely have chronologies extending to before A.D. 1600. Detailed studies now beginning on species identification of woods found in archaeological sites scattered over the Southwest indicate that a high percentage of specimens from a site, say dating around A.D. 500, are *Pinus edulis*, yet today the area is well covered with *Pinus ponderosa*. Tentative studies indicate that the presence of *prosopis* in archaeological sites located on the Sonoran Desert, seems to be confined to only those sites which are fairly recent in time, say the last 300 or 400 years. Charred hickory (*Carya* sp.) was found in the Double Adobe site located about 12 miles northwest of Douglas, Arizona. Antevs has placed an age of about 9,000 to 10,000 years on this site. The presence of hickory indicates a far more moist climate prevailed than there is at the present time. The closest hickory, today, is found in eastern Texas, about 800 to 1,000 miles to the east.

It is interesting to note, although it is beyond the scope of our purpose here to go into detailed analysis, that Figure 1 has much meaning archaeologically speaking. Studies concerning the correlation of shifting populations during times of deficient periods of rainfall, as expressed in tree rings, are now being inaugurated. Evidence based on past studies indicates that there was, during such times of stress, considerable shifting of the population centers from one region to another.

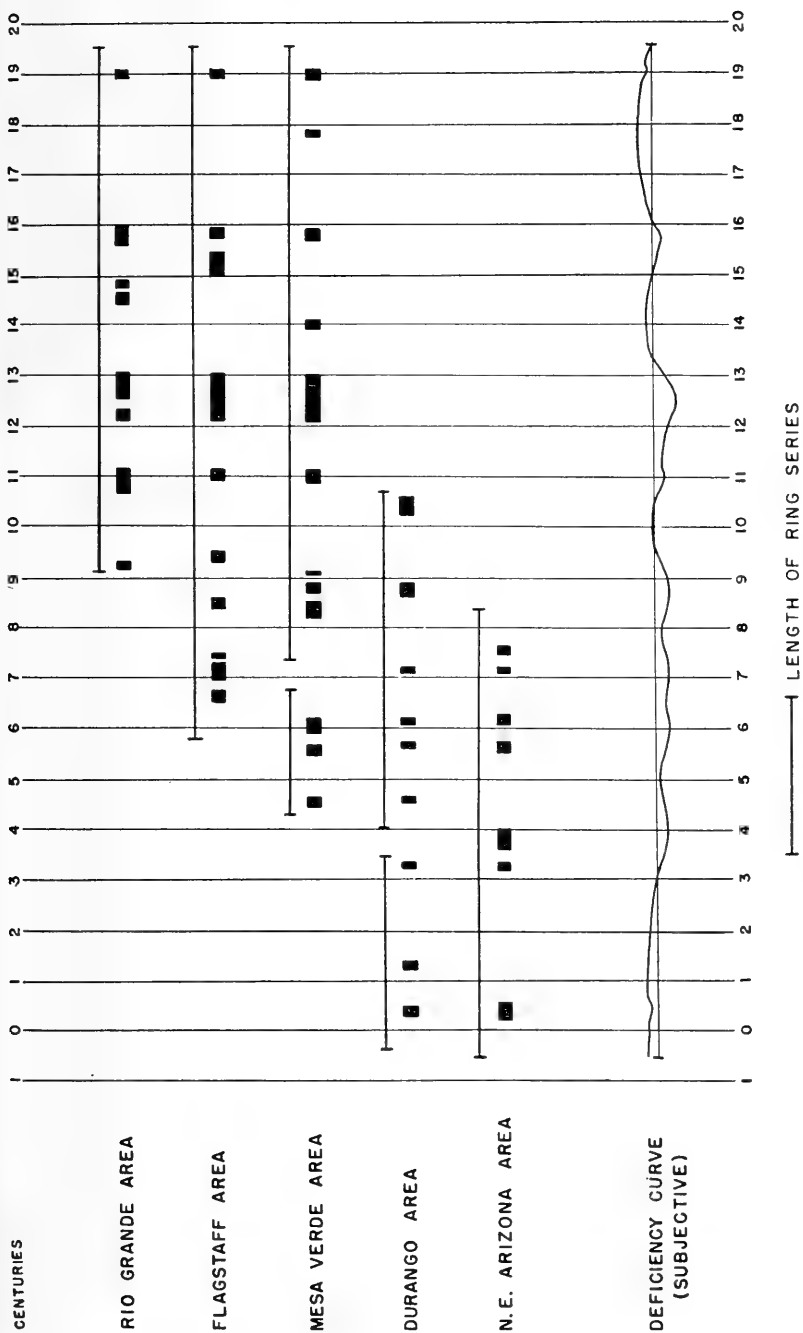


Figure 1. Deficient periods of tree growth in the Southwest.

Geochronological Approach

Antevs has done much work in determining the paleoclimatic story in the Southwest. His researches, based on geologic-climatic observation and study, are the basis for much of our interpretation of paleoclimate during the pre-Christian eras. Much of his work was conducted in conjunction with archaeological problems concerning "early man" discoveries in the area. Thus we have some spotty knowledge of climate and man for the last 12,000 years, although there are large gaps in this period for which we have no information. The data derived by Antevs are based on the rise and fall of lake levels, arroyo cutting and filling, the formation of caliche, the deposition of laminated beds, and other geologic and climatic features.

The detailed study of archaeological chronology in the Southwest is now being started at the University of Arizona through the use of tree-ring dating and carbon-14 analysis. Many dates on various stratigraphical correlations will be necessary for minute analysis of this problem.

Identification of the flora and fauna found associated with such archaeological sites will also be one of the major problems in this study. Studies in palynology have been recently started for this area, and preliminary runs indicate far better results than had been expected. These runs indicate that "caves may be to the arid regions what peat bogs are to the glaciated areas." In caves which have been occupied by man, and many have been say for 10,000 years, we have found not only wind-blown pollen but also pollen from plants which were insect pollinated and which may have been brought in by man for preparation of food. Other caves, not occupied by man, give good wind-blown series plus grains from plants which were probably carried in by animals. The open clay deposits, or cienegas, in the valley bottoms also yield pollen although not as much as do the caves.

It is hoped that the pollen spectra associated with archaeological sites in which specific identification of plant and animal remains can be made will give a more accurate understanding of detailed climatic indices for such things as rainfall and temperatures. The dating of these sites would enable us to locate them along the time

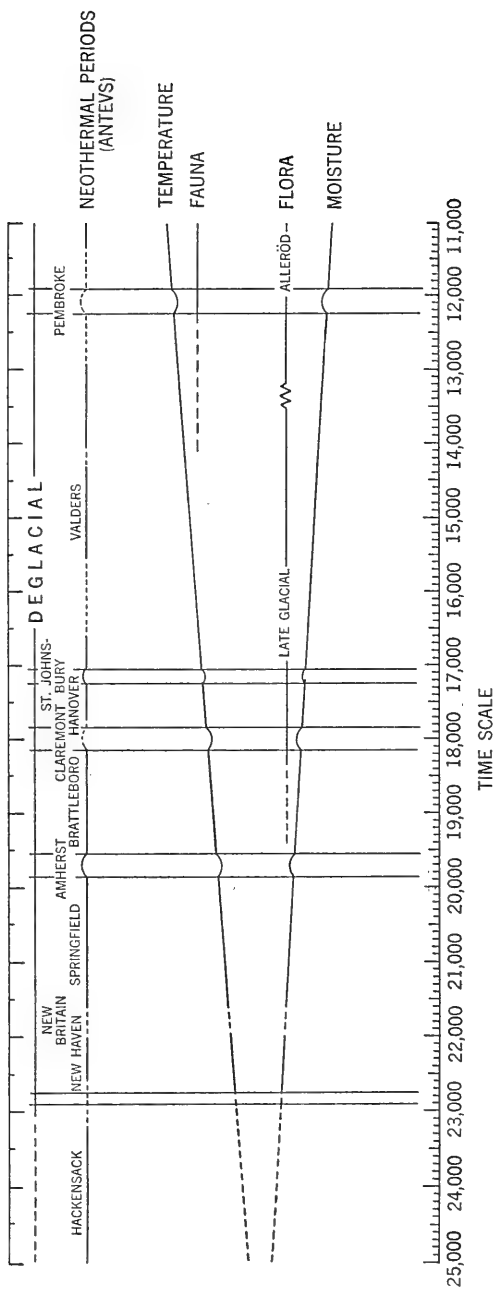
scale so that our compilation of the paleoclimatic history for the area can then be continued.

The detailed study of geomorphological conditions to determine the aridity of the land and its associated plant cover is also important to our work. Such periods as those of arroyo cutting and filling are normally marked, or located nearby, by archaeological sites. Thus we have some method of determining their age.

The study of the migrations of small modern mammals, as well as fossil remains, will greatly enhance our knowledge of the local conditions which prevailed at the time the animals lived in the area. This, coupled with the study of other types of fossils, should throw some light on the question as to why certain species of animals have either migrated or become extinct in this area.

Several preliminary tests made in the playa lake beds in the Southwest indicate that detailed studies in paleolimnology and associated fields of micropaleontology, paleobotany, palynology, paleoecology, and non-glacial varve analysis would be most useful. From such studies we should be able to deduce specific climatic indices which could then be fitted to a time scale through the use of either carbon-14 analysis, or tree-ring dating, or some other method of dating. It is hoped that such studies can be extended into the third interglacial times so that an understanding of true interglacial conditions which prevailed in this area could be had. It is also essential that the so-called thermal maximum period (ca. 5500-2000 B.C.) be carefully studied for its detailed effects.

Figure 2 is a tentative summary of the past climatic conditions, on a generalized basis, that have existed in the Southwest for the last 10,000 years; beyond this is an extrapolated period extending to the climax of the Wisconsin glaciation at ca. 25,000 B.C. This diagram has been compiled from many sources, mainly Antevs, Fries, Bryan, Ahlmann, and others. It is not intended that it be considered accurate. Rather it is intended to represent a working model to guide our future research. The weakest portion is that of the flora for which there is but little local information. It is hoped that with the study of palynology accelerating as it is, we soon can have a more accurate picture of this aspect. Our intentions are that, as we work on a locality and we incorporate the specific data



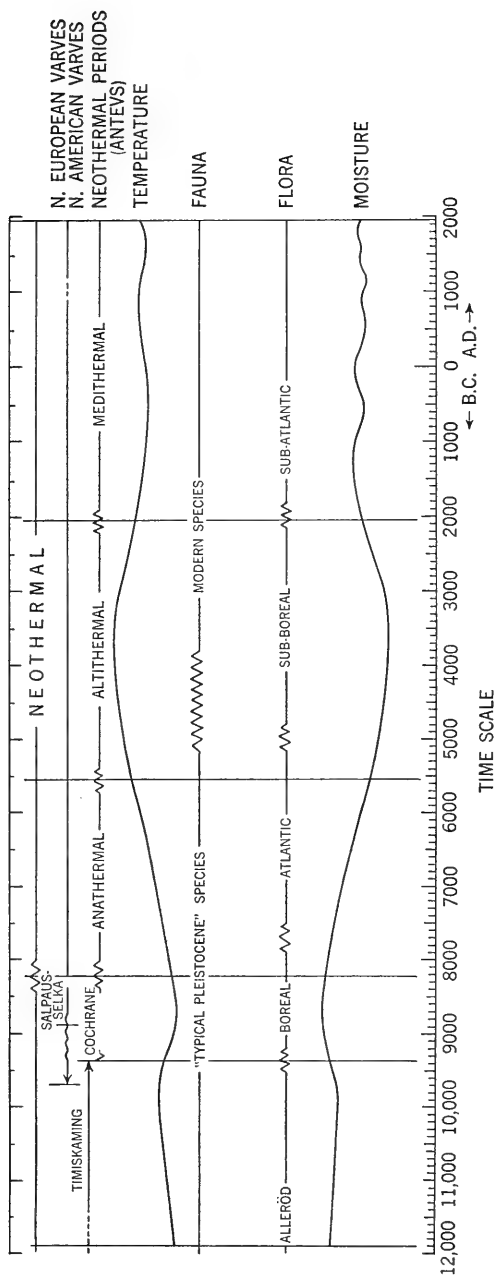


Figure 2. A tentative diagrammatic model for the last 27,000 years. See text for explanation. (A similar model appears in Smiley (23).)

in its proper time position, we will be able to correct this model as we go along. One of the eventual aims of this program in geochronology is to determine the specific climatic history of the Southwest for the last 50,000 or so years in as detailed a fashion as possible.

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Summary Statement

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Not only have variability and predictability of water supply been discussed but also the broader subject of water supply in general. The major overall problem of arid lands is the need for more water. Lack of water has limited occupancy and development of arid lands since the beginning of history. It is important to understand the sources of water available to arid lands, the amounts, quality, variability, and predictability.

Arid land economies must rely on three sources of water: precipitation on the arid lands themselves, ground water, and stream flow from more humid areas. Each of these water supplies has distinct characteristics and presents different problems.

Precipitation on Arid Lands

Starting first with arid land precipitation, we can make several general observations. The precipitation on these areas is meager—usually much less than the evapotranspiration potential. The amount of precipitation varies greatly from year to year and from place to place in the same year. Droughts are common and sometimes extend over several years at a time. Forage and crop production is highly uncertain.

We are agreed, I think, that the major obstacle to greater and more efficient use of this limited and variable water supply is the lack of a reliable method of predicting the occurrence of favorable and unfavorable moisture conditions. Though much has been learned about the probable recurrence interval of wet and dry

years over a period of time, we have yet to learn how to predict conditions for specific years and seasons. Solution of this problem calls for further knowledge about the causes of climatic fluctuations. More research on the physics of the air, and especially on air-mass movements, is needed if we are to obtain that knowledge.

What runoff there is from arid lands occurs mainly as overland flow during brief but torrential rains. These storm flows commonly are of short duration. They sometimes develop into violent floods and almost always carry great quantities of sediment. It has been pointed out that the water in these discharges is therefore of limited usefulness unless it can be impounded and desilted. Furthermore, though the arid lands yield very little runoff, they are a major source of damaging sediment. I should like to underline this point with some figures of my own. About 85% of the lands in the Upper Colorado River drainage basin are arid. They contribute less than 10% of the water to the flow of the river, but they are the source of more than 85% of the sediment that is being deposited in Lake Mead behind Hoover Dam.

We may conclude from what has been said that the prospects are not very promising for increasing usable amounts of runoff from our arid lands. The main problems are to get better control of the runoff, reduce erosion and sedimentation rates, and to conserve the meager supplies that are available.

Ground Water

The second source of water in arid regions is ground water. Springs and wells have been one of the more important sources of water supplies in arid regions down through the ages. They have been the principal and the most reliable source of water for domestic needs, for irrigation, and for stock-watering purposes. The big question seems to be what are the possibilities of getting more sustained and usable yield from ground water sources?

It seems to be agreed that virtually all the readily accessible ground water supplies have already been located and put to use. New supplies must therefore come from new discoveries. The consensus is also that we are not likely greatly to increase the water supply by new discoveries of underground sources. I might go

one step farther and say that in some localities underground water is being used at a much more rapid rate than it is being replenished.

We now have at our disposal highly efficient sounding devices for locating ground water supplies. We also have drills that can tap those sources and pumps to extract the water. However, there are three obstacles standing in the way of utilizing new water supplies: (1) a lack of information about ground water origin; (2) inadequate knowledge of ground water recharge rates; (3) lack of knowledge about the usability of impure water and economical ways of making it more usable. Research in these fields is already under way, but there is need for more.

Water from Humid Areas

A third source of water for arid lands is from streams that originate elsewhere. Like most of the ground water of great consequence, this inflow is from more humid areas. The origins of the streams in some places are humid islands within the arid zone and in others they are situated at great distances.

The streams that flow from these humid areas in many arid areas are the principal source of water for irrigation, power, and manufacturing. The Rio Grande Valley is truly arid, and the scale of occupancy and development as we find it today would not have been possible except for the water—both ground and surface—that comes to it from the humid mountains in the headwaters of the Rio Grande. The highly productive Imperial Valley in Southern California would still be a desert if it were not for the availability of water from the Colorado River.

There has been a great expansion in the development of mountain-born waters for use in arid zones in recent years. Great storage dams, diversion works, and canals are being constructed on most of the great rivers of the world and still more are planned. Therein lies the big opportunity of more water for developing the arid regions.

Several ideas presented in the discussion are worth repeating. This outside or inflow water supply has some important limitations. It is subject to annual and seasonal fluctuations. Periods of flow

do not always coincide with periods of need for water. Many streams carry objectionable quantities of sediment. Moreover, the normal regime of flow can be altered and its sediment load greatly increased by unwise use of the watershed lands.

Inasmuch as most of the comments about inflowing water came out of the discussion, rather than from the papers, I would like to develop this aspect of the subject a little more fully.

Dams and reservoirs are a well-known means of regulating the availability of water from streams. They do not, however, control water on the land or maintain the soil in place on watershed slopes. The greatest threats to the usefulness of streamflow as a source of water for arid lands are sedimentation in downstream water storage structures and floods. The control of these menaces and the increasing of water yields pose many problems in the field of upstream watershed management. Among them are:

1. Inadequate understanding of the source of sediment and of soil formation and erosion processes.
2. The necessity of distinguishing between normal and accelerated erosion, for which adequate criteria have not been developed in many places.
3. The need for controlling accelerated erosion on slopes and in channels for which effective measures are not yet known in many places.
4. Prevention of watershed deterioration under the impact of increasing demands for use of the timber and forage resources, for which guides are also lacking.
5. Inadequate information about the quantitative effects of watershed treatments on sediment production and streamflow characteristics.



BETTER USE OF PRESENT RESOURCES

Questions

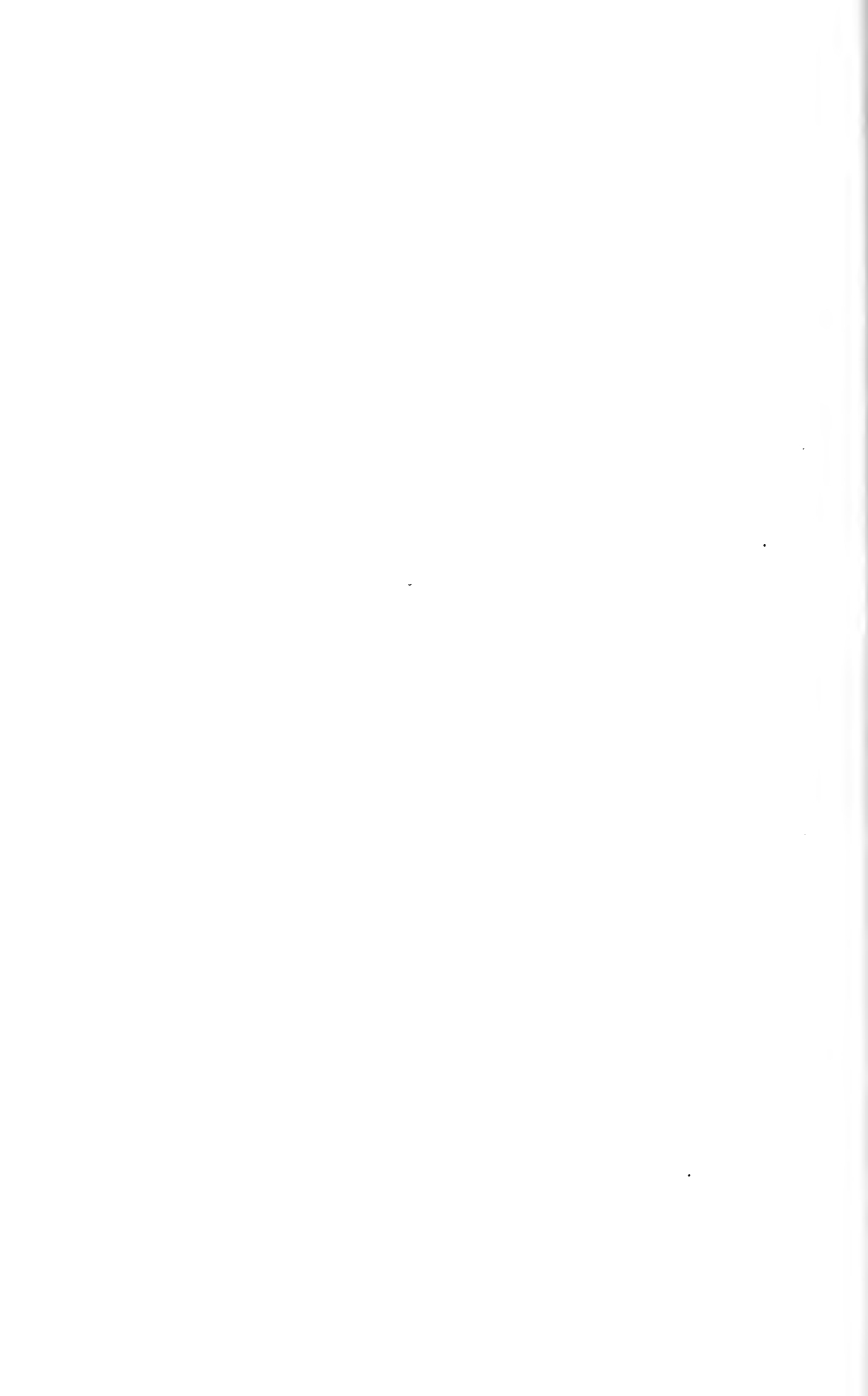
What are the possibilities of increasing and maintaining sustained production from grass and forest lands without accelerating erosion?

What are the consequences of utilizing arid lands beyond their capabilities?

What constitutes wise allocation of available water supplies among the various needs in arid land drainage areas?

How can production be increased from existing water supplies?

Can irrigated lands be occupied permanently?



Grazing Resources

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In order to avoid generalizations on this very extensive subject which may be applicable to one area and not to others, the discussion will be limited to countries in regions in which experience has been gained under current FAO activities. These include the Working Party on Mediterranean Pasture and Fodder Development, the Working Party on the Development of the Grazing and Fodder Resources of the Near East, and the Co-ordinated Grassland and Fodder Research Scheme of the Indian Council of Agricultural Research. These three activities cover a belt from Portugal to East Pakistan, characterized by lands which have been used and misused for centuries, by several different types of climate, and by a wide range of social and land-use systems. Throughout all of them aridity is a dominant factor.

Grazing Lands from Portugal to East Pakistan

The Mediterranean climate is primarily one of winter rainfall and summer droughts, increasing in intensity from the west to the south and the east as one proceeds farther away from the ameliorating influences of the Atlantic and comes nearer to the Sahara and Arabian Desert. Certain regions of Spain and Turkey differ in having a continental type of climate resembling that in parts of North America. The degree of aridity in this region is related primarily to the duration and intensity of the summer drought; the problems are greatest in the countries of North Africa lying along the desert fringe of the Sahara. Most of the countries

covered by the Working Party on the Development of the Grazing and Fodder Resources of the Near East are also the winter-rainfall type, and here the aridity of the summers is intensified in relation to their proximity to the Arabian Desert. The winter rainfall is generally lower than in much of the Mediterranean area and is more erratic and unreliable in annual total and in geographical distribution.

Passing eastward through Pakistan to India one enters a monsoonal environment in which, in the semi-arid regions of the west, a low, erratic, wet monsoon occurs between mid-July and mid-September and almost complete drought for the rest of the year, combined first with low and later with high temperatures.

The history of land use in these regions extends far beyond the time of scientific observation and control, when early civilizations were destroying the original vegetative cover for grazing, cultivation, fuel, house and ship construction and by the waging of wars. By a study of early writings and of the many fragments of evidence which are becoming available, an attempt is being made to recreate a picture of the vegetation of that time and to trace its use, misuse, and deterioration through man's employment of the axe, firestick, the plough, and the grazing animal.

Although there certainly were in the region under consideration extensive areas of true desert or semi-desert, these have been gradually extended by misuse of land and vegetation. There has thus been a great increase in the total area of land affected by aridity and desiccation; these conditions, so unfavorable for plant growth and agriculture, have extended into areas not truly semi-arid in type and have seriously affected natural reforestation or regeneration of vegetative cover on grazing lands, as well as the cultivation of crops. We must therefore attempt to distinguish between the true deserts and the man-made semi-arid lands which are those most susceptible of improvement.

In this connection it should be noted that there is little evidence of climatic change in these areas, at least within the period during which the major part of the de-vegetation has taken place, nor is there any indication that regeneration of the vegetative cover of forest, grass, or semi-desert scrub is likely to change the overall

climatic pattern of today. The efficiency of the rainfall has, however, been greatly reduced owing to the deterioration of the vegetative cover and the increased evaporation from the soil surface, unprotected from the sun's rays; the temperature, velocity, and sandload of the searing desert winds which blow over these denuded areas have a serious effect on the remaining vegetation, crops and trees, and effectively inhibit or retard regeneration.

Although it may be a desirable objective to attempt to regenerate some type of vegetation on all semi-arid lands, attention must obviously be directed first to those regions in which it is possible to carry out practical, and, as far as possible, economic measures within a reasonable period of time. The delineation of such areas would have to bear some relation to the amount and seasonal distribution of rainfall, the incidence of drought years, the present stage of deterioration, and other factors. In defining the area for immediate operations, it will be necessary to consider current forms of land use, the grazing systems on the desert and semi-desert lands, the extent of the practice of the cereal-fallow rotation in systems of shifting and settled agriculture, and the lower limits of rainfall efficiency at which simple systems of rotations of crops or reforestation are practicable.

Throughout the semi-arid lands of the Mediterranean, the Near East, and India are to be found many types of rural sociology, village or tribal structure, religious belief and prejudice, and methods of crop and animal husbandry, but perhaps the outstanding factor which has to be considered, and which has played a more important part in the destruction of the vegetation, the prevention of its regeneration, and the increase of desiccation, is the sociological distinction between the shepherd and the cultivator. One writer in another part of the world has related this distinction to the patrilineal and matrilineal types of family structure and inheritance. The shepherd has for centuries been a freedom-loving nomadic type, owning no land and having no interest in the practice of proper land use for the sake of his village, tribe, or nation. The cultivator is the sedentary type, satisfied with the land around his home. Both have destroyed the vegetative cover for their separate purposes. As populations and livestock numbers have

increased, so has also the conflict between shepherd and cultivator in the struggle for dwindling land resources in an environment of increasing desiccation which is their common inheritance.

Possible Measures for Improvement

The present picture indicates the consequences of using arid and semi-arid lands beyond their capabilities and of inducing aridity in regions not actually arid or semi-arid climatically. What are the possibilities of increasing and maintaining sustained production from grazing, cultivated and forest lands in these climatic zones, while at the same time ensuring optimal conservation of soil and water and reducing desiccation?

Basic Surveys

It is considered to be essential in the first place to survey and map the existing plant cover on the uncultivated land, and also to map the cultivated lands in relation to their farming systems and the crops grown thereon. This information, combined with our present knowledge of the possible extent of improvement, will contribute materially, as far as the arid and semi-arid lands are concerned, to correct land classification and so to the resources survey upon which FAO is likely to be engaged in the coming years.

There is, in the regions under review, considerable activity at the moment in the survey, analysis, and mapping of the natural vegetation. Teams of ecologists trained in France are working in French Morocco, Algeria, and Tunisia. Work is in progress in Portugal, an FAO botanist-ecologist is working in the countries covered by the Near East Working Party, and a grassland survey team of the Indian Council of Agricultural Research is studying the grass vegetation of that country with reference to botanical composition, yield, and carrying capacity and the relation of the existing grass vegetation to the potential grass sub-climaxes, to soil type, and to the climax type of forest in each vegetation zone. The data which are becoming available from these plant sociological and ecological studies will be of great practical value in the optimal development of land resources, by the use of vegetation-

cum-soil indicators in the limitation of livestock carrying capacity, the selection of areas for reseeded, cultivation, reforestation, and other forms of land development.

It is well known that there are many different methods of analyzing vegetation in current use, as well as different standards for nomenclature in plant associations, and different techniques of mapping. A survey of the grassland and grazing resources of the world as a whole or of any particular part or region of it will be most difficult to conduct if some agreement on the methods of analysis and presentation of results is not achieved. It is the objective of FAO to call together a group of specialists in this field in order to obtain the desired uniformity, at least as far as the vegetation on grazing lands is concerned.

Reducing Pressure of Livestock

Since the natural vegetation in this belt from Portugal to Pakistan is primarily a grazing resource, attention must be devoted in the first place to reducing the pressure of livestock on the land. These livestock are mostly maintained under various systems of free-range grazing, based on different forms of nomadism. The types of domestic animals are those which can exist on precarious supplies of fodder and water and under conditions of wide climatic extremes. A change from more destructive to less destructive types and an improvement in the general quality and productivity of livestock both depend primarily on improved amounts and quality of fodders and the elimination of excessive losses in critical seasons or years.

The pressure of people and livestock on the natural vegetation of arid and semi-arid grazing lands, in which the plant cover is held at a very low ecological stage due to excessive grazing or cutting for fuel, can be reduced by the settlement of nomadic people in selected and especially favorable areas. Although such action may be possible in restricted areas and with certain types of social structure, it must be questioned whether it is possible and in fact even desirable for, for example, the desert Arabs of the Sahara (la zone steppienne pré-saharienne), the Bedouins of

the lands bordering the Arabian Desert, and the graziers of the semi-arid lands of Baluchistan and Rajasthan.

The measures being adopted in Algeria under the Secteurs d'Amélioration Rurale are probably more realistic under present conditions and might with advantage be extended to many other parts of the region. The centers set up by this organization provide specialized advice and attention to animal health; breeding flocks are maintained from which the shepherding community can obtain improved rams to replace the low-quality ones in their own flocks. Reserves of fodder are built up at these centers from crops grown locally or imported from other parts of the country more favorable for crop production. Through a system of insurance at so much per sheep per year, the livestock owners may draw upon these reserves and so avoid the catastrophic losses which occur in years of extreme drought. In the severe winter of 1953-54, losses among flocks not associated with these centers amounted to up to 40% of adult sheep and 80% of the lambs, whereas losses where such centers existed were not more than 15% for the private owners and 3% for the flocks belonging to the centers.

Such measures, combined with appropriate facilities for marketing and distribution of the produce, can be of permanent value only if livestock owners realize the necessity of maintaining the same or even a lower number of livestock of improved quality than before. They should not attempt to keep even greater numbers of livestock because of the greater security which these centers and fodder reserves provide. The whole program would in such a case defeat its own ends and the destruction of the vegetative cover would proceed even more rapidly.

Better Use of Water

There are, in the regions under consideration, possibilities for the development and better utilization of water resources. Where these exist in regions primarily devoted to livestock husbandry, it would obviously be desirable to utilize some or most of the water for the cultivation of fodder crops and for the provision of stock watering points. The fodder so produced might be used to build up reserves for desert flocks or might be the basis of a more

settled form of animal husbandry combined with the cultivation of food crops.

Regeneration of Vegetation

The main objective in pushing back the desert from those regions in which aridity is primarily man-induced and limiting it to the areas with a true desert climate must again be the regeneration of vegetation by natural and artificial means. This work must be carried out in regions with ancient forms of land use and against a background of increasing human and livestock populations which must continue to obtain their livelihood and sustenance from the land, while the improvement is going on. If the biotic factor could be limited for some 5 or 10 years, it would be possible to make full use of the remarkable capacity of degraded types of vegetation to revive, to climb again up the ecological ladder, and to provide a superior type of vegetation. It would then be possible to evolve new controlled systems of land use, to provide better sources and types of food, fodder, or fuel, without again causing the degeneration of the plant cover back to its present condition. There are many examples within the area of excellent regeneration of vegetation, even after a few years' protection and sometimes under very low rainfalls. Many more areas protected against grazing, browsing, and cutting are required to provide the ecologist with his field laboratory in which he can obtain the data on botanical composition and succession required by the improver of land use practices.

Many specialists trained in range work in the western United States have been posted in the countries of North Africa and the Near East in particular. It is natural that they should attempt to apply in these new environments the outlook and techniques found to be successful in their home states. In particular, they have attempted the reseeding of semi-desert rangelands, with or without water spreading. With a few exceptions can it be said that any success has so far been obtained by the reseeding technique. The difficulties which have arisen are associated chiefly with the methods adopted and the availability of seeds of adapted species.

It appears that more experimentation is needed with regard to methods of reseeding in the semi-arid lands under review. The method is likely to be applicable only in limited areas. The Foreign Operations Administration expert in Iran, Laurence R. Short, states that reseeding is possible in only about 10% of the rangeland in that country. In the Desert Range Project in the Western Desert of Egypt, it has been suggested that wholesale clearance of desert scrub prior to ploughing and reseeding is not advisable. The existing vegetation may be cleared in strips and ploughing, or preferably light disking, and reseeding carried out, producing the alternation of scrub strip-grass strip rather like the cereal-fallow strip system adopted in parts of Western Canada and sited across the prevailing wind. Such a system does not entail so drastic a change in the microclimate at plant level, the grass stands are protected to some extent from the searing effects of desert winds and a reservoir of seed plants of adapted vegetation remains should the reseeding fail.

In French Morocco, where artificial reseeding has failed in many places, it has been found appropriate to grow seed mother plants in a nursery and to transplant these in the area to be revegetated. If protected from grazing, these plants will produce seed for the establishment of young plants around their bases and in the protection they themselves provide what might be called the "hen and chicken" method of reseeding.

Seeds of the adapted species of the semi-arid lands in these regions are not available in any quantity. Indigenous species which might well be collected and multiplied include: *Dactylis hispanica*, *Stipa lagascae*, *Cynodon dactylon*, *Aristida ciliata*, *Hyparrhenia hirta*, *Avena barbata*, and *Lolium rigidum* in the Western Desert of Egypt, species of *Agropyron* and low-rainfall ecotypes of *Dactylis hispanica* and *Phalaris tuberosa* on the Arabian desert fringe, and *Cenchrus ciliaris* in the Rajasthan semi-arid lands. A number of the Foreign Operations Administration Missions are beginning to collect and employ these adapted species and ecotypes. Israel has a large scheme under way and has established a special seed multiplication nursery at Migdal Askalon. FAO in 1954 in association with the Commonwealth Scientific and Industrial Research Organization of Aus-

tralia carried out a collection of grasses and legumes in the Mediterranean countries, particularly in North Africa; these 600 species and ecotypes are now being multiplied at Rome through the cooperation of the Italian government and Professor U. de Cillis, with a view to introducing them in due course into the observation trial grounds throughout the Mediterranean, the so-called Uniform Mediterranean Nurseries. It is hoped to adopt a similar approach in the Near East in 1956 and so in due course to have available ample supplies of seed of species adapted to the conditions of the environments in which reseeding work is considered to be practicable.

Water spreading is another American practice which is being tried with varying success in several semi-arid regions of the Near East. Although it is obviously desirable to attempt to hold the water from the torrential winter rainstorms on the land on which it falls for the production of fodder and grazing, the technique is still open to criticism in relation to the expense of construction of the diversion and retention dams, and the erratic geographical distribution of these rainstorms from one season to another.

Forestry

The forester also has an important role to play in these arid and semi-arid regions. Cutting of relict tree and scrub vegetation for fuel leads to widespread destruction of fuel and ecological regression. There is great scope for the planting of fuel lots, shelter belts to provide protection for crop areas or livestock concentrations, and fodder trees for supplementary feed during periods of emergency. The grazier and cultivator must also realize the ameliorative influence of a forest stand on extremes of climate and in relation to soil and water conservation. The forester is still losing ground rapidly on account of encroachment of grazing in forest areas, the cutting of trees for fuel or building purposes, the insatiable demand for land for the production of food and cash crops. An intelligent plan of land utilization based on land classification must allow for an adequate percentage of forest cover, in the right places, which must be composed of the most desirable species for economic utilization.

Social Change and Needs

In this brief review it has been possible to say little about the cultivated land in the arid and semi-arid regions under review. Much of this land is marginal for crop cultivation, some is farmed on a semi-desert type of shifting cultivation, and the remainder can be regarded as suitable for crop cultivation with the adoption of modern methods of husbandry, the application of fertilizers, and the use of adapted species. Again we have to accept the fact that peoples are living in these areas and have to produce their own requirements locally.

And that is the note upon which this review may be concluded. The technicians know in many cases what may theoretically be done to maintain and even increase the production of resources under semi-arid conditions or how to reduce the severity of these conditions. But this is like trying to rebuild the highway while the traffic is still moving on it. Throughout these regions are to be found graziers and farmers with long experience of maintaining themselves and their crops and animals under some of the most difficult and rigorous conditions to be found anywhere. They know fairly well the systems of animal husbandry and migration to adopt under the circumstances, they know the relative value and availability of their semi-desert fodder plants, they know the best grazing areas and go there as soon as news comes along the desert grapevine that a rain has fallen and growth is beginning. The technicians must at all times consider them and their knowledge, customs, and needs, and adopt measures of improvement which fit in with their social and land use systems and appear practicable to them. The people on their part must lose their mistrust and suspicion of the technician, whether he be sociologist, ecologist, animal husbandman, forester, or irrigation engineer. They must realize that what is being attempted, always difficult and sometimes impossible, is for their own ultimate good. If they cooperate and offer friendly advice and criticism when they see the technicians going wrong, there is no doubt that great progress can be made in the rehabilitation of these semi-arid lands.

Water Resources

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A century ago, Daniel Webster said: "What do we want with this vast worthless area—this region of savages and wild beasts, of shifting sands and whirlwinds of dust, of cactus and prairie dogs? To what use could we ever hope to put these great deserts and those endless mountain ranges?"

Daniel Webster was a great national leader. I repeat his familiar quotation concerning the arid western United States not to disparage his memory but to emphasize a point. A wise man was unable in his day to foresee the wonderful developments that human progress can bring. Here in the arid west, cactus has given way to citrus. Potatoes grow where there were prairie dog towns. Shifting sands and whirlwinds of dust have not prevented the development of an economy that supports a population of 38 million people. Crop, livestock, and industrial wealth, undreamed of a hundred years ago, has been created by the energies of man and his skills in science.

This empire, which last year contributed many billions of dollars to the national wealth, has been made possible largely by the development of its water resources. Time will tell whether this generation has better vision than did Mr. Webster's generation, and whether we will be able to develop properly water that is still unused. At least we recognize our duty to try to plan for best use of the resources given us.

The theme of this symposium, the better use of present resources, obviously could include a variety of resources. This paper is confined, however, to the water resource. More particularly,

it will bear on the place of irrigation in "wise allocation of available water." It also will touch upon a few of the many opportunities to increase use of existing water and thereby to increase production.

I should like to preface my remarks on these subjects by recognizing the impressive magnitude and difficulty of the tasks ahead of us. While noting the great things accomplished, we must realize that our future endeavor becomes ever larger and more difficult in direct proportion to the increasingly severe demands on our water resources. New research tools are needed, and we must make better use of the old ones to meet the challenges of the future. Sociologic and economic research and engineering and scientific research must advance rapidly and keep pace with each other if we are to plan properly for the complex conditions of the future.

Major Water Uses

There can be no challenge to the ultimate goal, in any arid realm on the globe, to achieve maximum beneficial use of all available water supplies. There is little latitude in the allocation of such limited water resources—direct use of water by man for his direct benefit is the highest possible beneficial use and comes first. Municipal and domestic uses therefore usually assume the first claim on available water supplies.

The second claim may be for industrial and agricultural use. All these uses should be considered in the planning for utilization of any water supply. At the time the engineering works are constructed to retain water through storage or to divert it to immediate use, the irrigation allocation may be paramount. As time passes, the municipal use may increase and this future possibility should be recognized in planning water utilization projects.

Agricultural purposes are the largest single consumer of water in the water-deficient areas of this country and of the world. Irrigation is a principal use of land in the 17 western states in this country, where the land area totals 1.1 billion acres. Of these acres, some 42 million are considered susceptible to irrigation, and some 25 million are already under irrigation. The total water supply averages about 392 million acre-feet annually. Of this water, only

about 128 million acre-feet can be ultimately used for irrigation. Presently about 78 million acre-feet have been put to use. In many western streams, the entire water supply is fully used except for infrequent years of high flood runoff.

In other words, about one-third of the total stream runoff can be used for irrigation, and we are now using only one-fifth of the total. But for the sake of progress toward the goal, it is essential that all efforts be made to irrigate the remaining 17 million acres, putting to work much of the remaining 50 million acre-feet of available water. In many cases this will necessitate diversions of water between major waterbeds.

For streams such as the Columbia and Missouri Rivers, there is a large foreseeable flow that cannot be used for irrigation purposes. In such areas, plans are being formulated for the controlled and coordinated use of water for non-consumptive purposes such as navigation and power development.

Problems of Long-Term Planning

Whatever allocation of the water resource is made to whatever purposes, the greatest final benefit to all interests will necessitate adequate storage. Increasingly as years pass greater use will be made of both surface and ground water storage. I am not seeking an argument when I say that surface storage developed to its maximum is the prime means of developing and utilizing our surface water supplies. Some water should and will be put to work where it falls—head water, small dam storage has a proper place in planning full beneficial water development. The fact remains, however, that reservoirs, whether main stream or tributary, must be the principal basis for conserving the waters of our surface streams.

Certain benefits of surface storage are so obvious as to need no recitation here. One benefit that I would like to bring out is that storage is a necessity to correct the variable characteristic of stream flow. Such variability is of a cyclic nature. It is marked by a tendency for high stream flow to occur in periods of from five to ten years, and for low flow to extend over periods of from five to twenty years. Capacities must be provided to retain water from

high flows to and through droughts. Otherwise we cannot accomplish more complete utilization of our limited water. Such facilities must be planned with care so as to afford greatest yields. They must also be planned and built well in advance of their actual need to ensure full reservoirs prior to the droughts of the future.

We are considering broad-scale water development, which essentially is planning for the future. The length of time required for orderly planning and construction of water conservation works should be stressed. On the Columbia Basin Project in the State of Washington, for example, water was first available for irrigation in 1952. The first report envisioning future development of this project was made by the Corps of Engineers in 1879—76 years ago. The Reclamation Service launched its first studies of this project in 1904. The Columbia Basin Project is one of the world's largest and most expensive, but it is typical of large projects. It illustrates the inevitable passage of time from dreams to reality in matters of this sort.

Probably every country of the world is experiencing an increase in population because of many factors, especially including improved medical progress and higher levels of living. The increases in the United States during recent decades have consistently exceeded advance estimates. As recently as 1950 the Bureau of the Census was forecasting that the national population in the year 1975 would be 190 million. Currently this Bureau is cautiously making its estimate for the year 1975 with a maximum and a minimum—a range of 198 million to 221 million persons. Whatever figure proves to be correct, the point is inescapable—water requirements will continue to rise.

Population increase is a greater problem in the western states where water is scarcer than it is in the rest of the country. The rate of growth during the decade that ended in 1950 was 25.8% in the 17 western states, and was 14.5% for the nation as a whole. The disparity in population growth between the western one-third of the nation and the other two-thirds has become greater since 1950.

Allocation of Water Supplies

Man's domestic requirements inevitably will be satisfied first and finally, up to the point at which consumption of all available water sets a limit on expansion of a community. (This is the situation numerous American cities are approaching today, in the east as well as in the west.)

In assessing "wise allocation" for types of use other than domestic, more latitude in judgment and planning exists. For example, irrigation may be criticized as an extravagant use of water. Nevertheless, the construction of irrigation works that are efficiently planned and soundly financed is justified by the increase in food and fiber which this kind of agriculture produces.

One major justification for irrigation is the contribution it makes to the wealth of the nation. Besides the farm families themselves, whole communities derive their support from irrigated agriculture. For each individual living on a farm, there are two more individuals in a nearby community whose support is directly or indirectly due to irrigated agriculture.

The dramatic examples of the new farms and of one-to-two ratio are in America's scattered "last frontier." This frontier is a source of inspiration to those who visit the plateau above the Columbia River, the previously empty desert lying between Phoenix and the Colorado River, or the prairies and benchlands in the Missouri Basin receiving irrigation water for the first time.

To measure in dollars part of the value of irrigated agriculture, I mention that the value of crops irrigated on 69 Bureau of Reclamation projects was \$786,000,000 during 1953 and \$935,000,000 in 1952. Income of such dimensions came from about 6 million acres, or only about one-fourth of the land in the United States which is irrigated through various organizations.

The same storage structures which make irrigation possible in many instances bring about other important benefits. The power that helps to finance the irrigation also contributes to the economic base of the west, and the flood control features prevent destruction of wealth.

Incidentally, the total of values, over and above the direct

values of crops, livestock, and power, far exceed the portion of construction that is reimbursable under law.

There are those who advocate reduction of irrigation's share of limited water resources because the United States as a nation produces a surplus of some crops. To these, I say that crop surpluses should not be considered to be a serious liability so long as there are human beings on the edge of starvation anywhere in the world.

The crop surpluses of recent years in this country are transient. Without unceasing efforts in the direction of expansion, by 1975 our surpluses as we know them today will disappear simply under the impact of increasing population in the United States itself. Per capita consumption of food also is rising. The quality of our diet has steadily improved for decades and will continue to improve under the impetus of our rising level of living.

The limitation on tillable acres is real and recognizable. We know that through simple multiplication of cultivated acreage we cannot meet the requirements of the future, even under the concept of 100% utilization of the water that is available for irrigation. We must count, however, on continued scientific improvement in agricultural methods, which have yielded such spectacular successes especially during the last decade.

Irrigation is in the west where the population is growing at the fastest rate, and efficient distribution methods demand maximum production close to points of consumption. A final point is that irrigated land in the west is the source of many specialty off-season crops which are not competitive with production elsewhere.

Irrigation, then, must have equal consideration in any allocation of our limited water supplies. Although my references have sometimes applied specifically to the western part of the United States, the principles apply equally to any part of the world's arid realm.

Increasing Production from Existing Supplies

Many of the world's rivers, including major ones flowing to the sea through dry and underdeveloped areas, are not yet put fully to beneficial use. Such use must be the legacy of science and

engineering to the well-being of the present and future generations. We must try to do several things—put to use water not now used, make better use of water now used, and improve the quality of water.

Many possibilities now are being explored to make better use of water and to improve its quality. I cannot hope to discuss these in any detail, and therefore will content myself with a quick sketching of some of the areas of research which hold promise.

Tremendous quantities of water diverted from streams or reservoirs are not actually used. Tens of thousands of miles of irrigation canals, for example, suffer seepage and other losses up to as much as one-half the amount of water diverted. A variety of impervious linings are being placed in these canals in an endeavor to reduce these losses. In the six years ending in 1952, about 25 million square yards of linings were placed in more than 750 miles of canals and laterals on Federal Reclamation projects, saving an estimated 700,000 acre-feet of water annually. The cost of these linings is justified by the value of the water saved.

Excessive weed growth in canals increases losses from seepage and transpiration. Experiments with miscible oils led to the development of a plant poison that is toxic in canals but not toxic on land. The problem is to kill weeds without killing beneficial plants. An aromatic oil that comes out of suspension and evaporates before the water is diverted to the fields is a partial solution.

As the cost of water increases, western industry is finding it advantageous to plan for maximum practical reuse of water, even though the action requires expensive equipment or plant additions.

Planners in the field of agricultural irrigation are ever more taking into account the potentialities of reuse—sometimes repeated reuse of return flows. Water subject to reuse often requires improvement in quality. The techniques for improvement vary according to whether the purposes are urban, industrial, or agricultural.

The Department of the Interior is engaged in a pioneer saline water research program. Although the greater public attention has been given to conversion of sea water to produce a quality acceptable for industrial or even domestic use, the research en-

compasses also saline waters in interior portions of the west. Improvement of these interior waters will enable not only certain new uses but also certain reuses. At present, costs of sea water conversion run upward from \$450 per acre-foot of usable water yielded. It would of course be desirable to reduce this unit cost if possible to do so. At the same time the present cost is not too much above the sum needy communities are willing to pay; the city of Colorado Springs recently offered \$350 an acre-foot for water presently being used for agricultural purposes.

Many cities are learning they no longer can be profligate in their consumption of limited water resources, even in times of normal precipitation and storage. They are encouraging or even requiring their residents to be more economical in water use and are becoming more rigid in enforcement of regulations governing the water use by industrial plants. States are inclining more and more toward requiring treatment of industrial waste and sewage so as to improve waters that are subject to reuse.

In the field of agriculture, great promise lies in research to discover the minimum quantities of water required to produce maximum crops. The Department of Agriculture and the Land Grant Colleges have made rather substantial progress in this field. I for one will be pleased when the laboratory experiments and limited field tests have been expanded into general application of the principles, and the results are known. Our irrigation districts and public authorities can do much to educate farmers along the lines of voluntary water conservation which is in their own interest.

A somewhat related thought is that by persuasion, and perhaps ultimately by law, farmers must become convinced that paralleling canals, competing irrigation districts, and excessive individual water applications are luxuries the nation cannot afford.

Operators of storage reservoirs, among whom the Bureau of Reclamation is the largest in the United States, have only scratched the surface of the subject of reservoir evaporation. Means of reducing evaporation are in the experimental stage. We are actively interested in the principle of using polar compounds which have the effect of a film on water surfaces. Household

detergents, not oil, are familiar polar compounds. A monomolecular layer, if it could be maintained, would have the effect of greatly reducing reservoir evaporation, but its harmful effects, if any, are unknown, and must be carefully studied before seriously considered for use.

Reforestation, controlled livestock grazing, regulated recreation, and other accepted practices to avert land erosion have the additional main purpose of conserving water. The saving of valuable land and water resources is a goal in itself, but an attendant benefit is the reduction in the volume of sediment poured into stream beds. Sediment is a tremendous nuisance, as it reduces water quality, aggrades channels, makes deposits on cultivated fields during irrigation, and shortens the life of reservoirs. In planning projects in areas where sediment is a serious problem, adequate consideration, from the physical and financial viewpoints, must be given to sediment problems.

One of the important measures needed for putting our water supplies to most beneficial use is improved hydrological techniques and more comprehensive hydrological and meteorological data. The installation of additional observation and recording stations during recent years and the accumulation of records covering longer periods will pay off in terms of more accurate planning of engineering structures. Recent improvements in methods for computing maximum probable large and small floods, together with more precise hydrological data, provide a firmer basis for saving water.

More accurate estimates of water yield from snow cover will result in improved operation of irrigation projects. The precision of flood control operations can be enhanced by better estimates of the rate of runoff from snow melt. An illustration of the benefits of better data lies in the research completed and underway at Lake Hefner, Lake Mead, and the Bruning Air Base which is providing more precise methods for estimating evaporation and transpiration. These are aids toward more exact use of reservoir capacity, irrigation, and operating methods.

Evaporation is a major waster of water, but is not first in this unenviable distinction. Evaporation consumes an estimated 15

million acre-feet a year in the 17 arid western states. A greater waster is the class of plants known as phreatophytes. Tamarisk or salt cedar is one of the better known of these water-loving useless plants. It has been estimated that in the west these consume more than 20 million acre-feet of water a year. The importance of the loss is illustrated by the fact that water developments in California, which have cost hundreds of millions of dollars to provide for a population of 12 million, assure a water supply totaling only 21 million acre-feet. The previously used chemical spraying and mechanical methods of controlling phreatophytes in reservoir deltas and elsewhere undoubtedly can be improved upon.

Ground water pumping in too many places has been overdeveloped. Improved state laws, or in some states the passage of ground water codes, and better enforcement of laws certainly are needed to improve control of ground water use. Beyond law, however, we need also additional engineering information about ground water. Water development planning is giving constantly greater attention to combined development of surface and ground water resources.

Important principles are involved not only in the technological problems sketched above, but lie also in the broader considerations of comprehensive resource development. Such planning is intended and I am sure will be accomplished by the joint efforts of local, state, and federal agencies. Beyond local or state boundaries there is need for regional research, for analysis of regional needs properly related to national needs, for analysis of economical development, and for balanced area development.

The days of quick and inexpensive exploitation of any natural resource are in the past. Our situation today is such that important progress can be made only through the unified effort of the many interests involved and the planning for any given area.

There can be no room for jealousies or enmities between developmental groups, public or private. We cannot afford competition between sciences; teamwork is essential between chemists, geologists, engineers, economists, hydrologists, and agricultural specialists.

Ill-conceived development is an extravagance no nation in the

world is wealthy enough to afford. Yet water is a renewable resource, but it has a value measurable in dollars, and each usable gallon that flows unused to the sea is an unforgivable waste.

The arid areas of the west and of other parts of the world have water resources to develop as a foundation for urban centers, for industry and for the agricultural hinterlands. Research, planning, and construction should proceed at an increasing rate to make the promise of today the actuality of tomorrow. There is much to be done, and we should set ourselves to the task of doing it promptly, cooperatively, and vigorously.

Geography's Contribution to the Better Use of Resources

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This paper has a twofold purpose. In the first place, it attempts to furnish a few instances of how the work of geographers can contribute to the better use of present resources. But, since the geographical approach can best be understood by references to a specific example, the paper also highlights some aspects of the dry section of the Nordeste, or northeastern Brazil, afflicted with recurring periods of drought.

The Nordeste

The region we are concerned with consists essentially of an extensive, but not very elevated, plateau (200–300 meters, or 650–1,000 feet), where most of the moderately upwarped pre-Cambrian basement, a maturely eroded surface, has been stripped of its sedimentary covering. Along a considerable section of the eastern seaboard, the crystallines—under the regional designation of Borborema plateau—terminate in a much dissected front, which rises from the 40- to 60-kilometer (roughly 25- to 40-mile) wide coastal belt and is particularly prominent in the states of Pernambuco and Paraíba. On the west, approximately at the state boundary between Ceará and Piauí, the oldland plunges under an extensive pile of westward-dipping strata. These break off in an imposing escarpment, the Ibiapaba, which dominates the exhumed plain by as much as 800 meters (2,600 feet). Exten-



Figure 1. The Serra do Pereiro, rising abruptly out of the crystalline plain, eastern Ceará. Partially destroyed mature landscape of upland gives way to steep flanks of serra.

sive patches of the once widespread sedimentary blanket have been left behind as tablelands on the resurrected erosion surface of the basement complex. More or less isolated massifs of resistant igneous and metamorphic rock also rise abruptly as mountains (*serras*) above the undulating plain (Figure 1). They represent remnants of a higher, even older, erosion surface or, in some cases, fault blocks.

Broadly speaking, moisture decreases rapidly from east to west, hence the threefold, longitudinal division of the Nordeste in climato-botanical bands, recognizable when striking inland from, say, Recife or João Pessoa: (1) the so-called *zona de mata*, or forest zone, a humid coastal region; (2) a transition belt known as the *agreste*; and (3) the vast, drier backlands, or *sertão*, where precipitation, after reaching minimum values, picks up again toward the west. The area of more abundant and dependable rainfall, which parallels the eastern coastline, will not be of immediate interest in this discussion.

In the section with which we are concerned, seasons are sharply defined by precipitation, not temperature: winter, so-called,



Figure 2. The Jaguaribe River by the town of the same name, in Ceará. Notice the square, board-lined water hole dug in the dry river bed.

roughly the first six months of the year, is wet; summer, the second semester, is dry. Thus, for example, data from the ten meteorological stations maintained in Ceará state by the *Serviço de Meteorologia* indicate that 91% of the aggregate annual precipitation normally falls in the winter months. The 3,000 kilometer (2,000 mile) long São Francisco River, rising in the humid mountains of Minas Gerais, flows through the southern section of the region under consideration. All other streams, fed directly by surface runoff, are subject to violent floods and, in the dry season, are sectioned into isolated pools. The Jaguaribe River basin, in Ceará, is typical. Although it drains an area one and a half times that of the Rio Grande upstream of Elephant Butte, it is an intermittent stream, often facetiously referred to as the largest dry river in the world (Figure 2). At intervals, the rainy season sets in late and/or shows a marked downward deviation from normal. When acute moisture deficiencies occur two or more years in succession, all economic activities are disrupted—the *sêca* (drought) has struck once more.

The fact that the island-like eminences rising above the level of the old basement—be they crystalline ranges or sedimentary tablelands—as well as the dissected eastern slopes of the Borborema, and the Ibiapaba escarpment to the west, are all favored by

much more abundant and reliable precipitation influences the population pattern to no little extent. But it is highly relevant to point out that the drier *sertão*, although more sparsely settled, is by no means uninhabited and commonly sustains a major part of the total population. Unlike the peoples of more permanently aggressive environments, who face uninterrupted water deficiencies, the *sertanejos*, who need no special ability to graze their herds and plant certain crops on this land during normal years, time and again are taken unawares by the *sêca*. It is hard enough to develop a system of land use which fully considers ordinary conditions; to contend with unusual circumstances really calls for additional determination, organization, skills—and capital. The region is certainly not organized to make full use of available water supplies. It would appear, in fact, that the water resource problems of the Nordeste, are man-made to a larger degree than is commonly assumed (II).

Delimitation of Drought Area

Accelerated erosion, the signs of which are obvious throughout the region, signifies not merely soil lost for agriculture, but reduction in water storage capacity (Figure 3). That outright desert landscapes may be created by man, even in warm temperate rainy climates, is a well-known fact, which may be illustrated



Figure 3. Wilted cornfield on gullied lands of western Ceará. Poti River Valley.



Figure 4. A quarter century of misuse created this desert landscape out of forest-covered lands in Município of Cerqueira Cesar, São Paulo State.

with a recent example from the pioneer coffee lands of southern Brazil (Figure 4). Incorrect agricultural practices that aggravate floods and droughts are certainly not restricted to the northeastern section of Brazil, but are the rule throughout the country (9, 10). It is not surprising, therefore, that much confusion exists concerning the true extent of the lands afflicted by recurrent droughts. The problem of defining their area is no mere point of academic interest, for the Brazilian Constitution establishes that:

In implementing plans to provide for protection from the effects of the so-called *sêca* of the Nordeste, the Union shall expend yearly, on works and services of economic and social assistance, a sum equivalent to not less than three per cent of the tributary income.

Paragraph one. One-third of this amount shall be set up as a special fund with which to succor the populations stricken by the calamity; this reserve, or part of it, may be applied at moderate interest rates, according to law, in loans to farmers and industrialists established within the area subject to the drought.

Paragraph two. The states lying within the "area of the drought" shall apply three per cent of their tax income in the construction, on a cooperative basis, of reservoirs, and in other services which may be necessary to their populations.*

* Law 1005, sanctioned December 24, 1949, establishes rules for the application of the constitutional provision.

Now better use of present resources undoubtedly involves wise allocation of such funds as are available for the rehabilitation and development of the semi-arid lands. An overextension of the bounds drawn for such purpose is contrary to the spirit and to the letter of the Constitution. By spreading financial resources thin, it seriously impairs the solution of the specific problems envisaged. Here then we have a field of inquiry for the geographer—and the task of drawing boundaries is one of his least challenged attributions.

The record shows several attempts to delimit the semi-arid Nordeste, but I am afraid none of them is very convincing.

The area at present receiving official recognition as water-deficient is called the "Drought-Polygon." The formula by which it was delineated derives its origin from a report by the head of the federal agency dealing with droughts. Published some twenty years ago, immediately after a sequence of years with diminished rainfall, it is based on the assumption that "observations carried out during the dry years 1930, 1931, and 1932 permit a scrupulous and sufficiently exact delimitation . . . of the area subject to the great periodic droughts, that is to say, the area defined as dry (*sêca*)" (14). The following procedure was recommended:

After drawing the isohyets corresponding to this triennium, the dry zone may be circumscribed by a polygonal line which accompanies the 600 mm [23.62 in.] isohyet in such a fashion that [advancing] from the periphery towards the center, the 300 mm line is always found.

This, the report explains, excludes the semi-arid zone of southern Bahia, where rainfall did not fall below the 300 mm [11.81 in.] limit in 1932 (14).

The ensuing geometric boundary, with minor variations, was subsequently written into law.* The same law provides that:

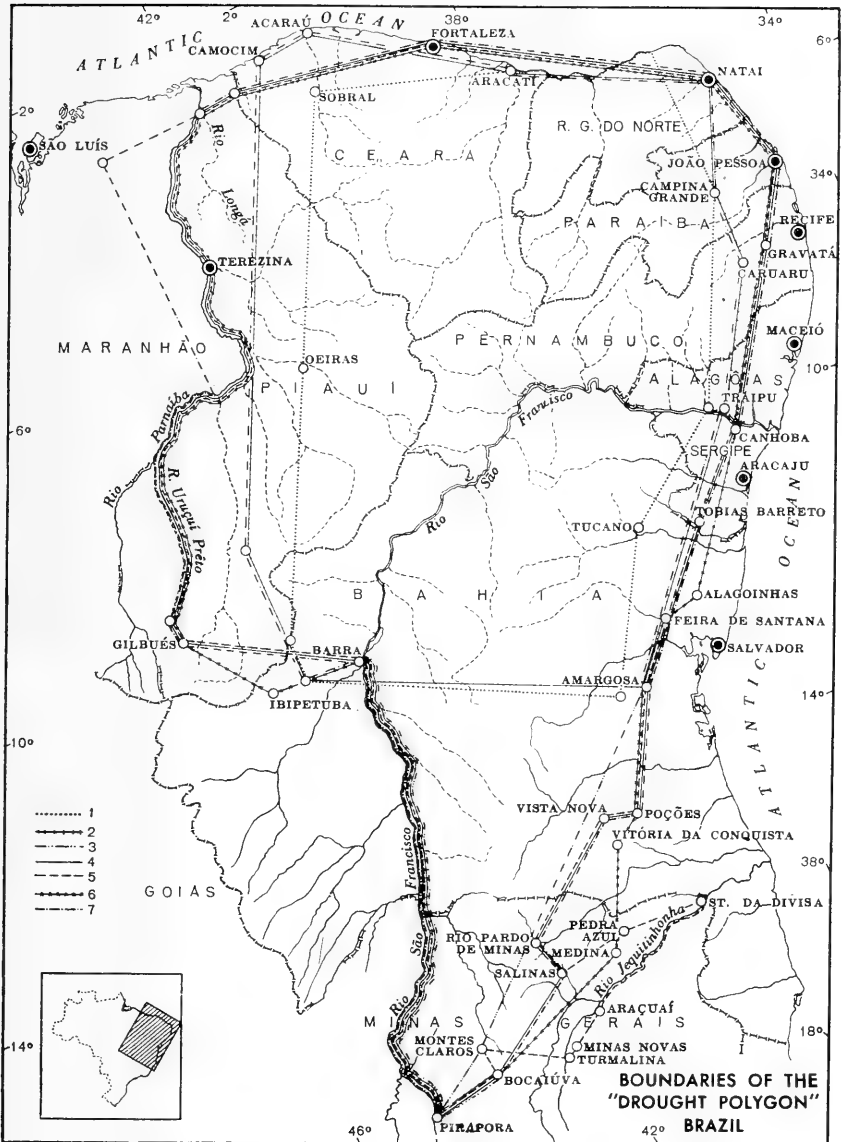
The established boundaries may be altered by law if further observations should reveal the occurrence of the *sêcas* in other zones of the northern states with the same characteristics already observed in the area delimited in the present article.

* Lei No. 175 de 7 de janeiro de 1936, Regula o disposto no artigo 177 da Constituição.

It is immaterial to speculate whether these "characteristics" refer to the zones or landscapes where the droughts obtain or to the *sêcas* themselves: neither one nor the other has been characterized with any degree of precision. This perhaps may be one reason why there has been relatively little opposition to subsequent amendments, which have enlarged the "legal" (but obviously arbitrary) drought area to the point, for instance, where the boundary has advanced some 700 kilometers (more than 400 miles) in a southwesterly direction (Figure 5).

The way in which a single element was considered in setting up this operational region may be contrasted with the attention commonly dispensed by geographers to the interrelation of all pertinent phenomena occurring in a certain area. Whereas the amount of precipitation is unquestionably a basic control, it is not clear why the 600-millimeter isohyet was invested with the significance of a critical limit. Furthermore, the knowledge that rainfall operates in the presence of other factors should caution against the facile acceptance of the simplified sequence of cause and effect which the adopted criterion implies. Not only must other climatic components be considered, but it is necessary to take into account additional influences, such as slope and water-holding capacity of soils. Field work appears thus as an indispensable ally (not to say part) of climatological studies.

Even supposing agreement had been reached concerning the value of precipitation to be considered critical in defining the area, the wisdom of drawing boundaries on the strength of rainfall measured during one single, exceptional period, such as 1930-32, remains open to question. The more customary procedure, of course, would utilize mean or normal conditions, on the basis of records extending back through the greatest possible number of years. One might, however, challenge the advisability of obscuring the unusual experiences in long averages, since, especially in the Northeast, it is the unusual conditions which are the greatest cause for concern. How then can one attempt to sharpen the technical meaning of the expression "*área da sêca*," current in non-technical usage? A simple and apparently satisfactory approach might be based on the frequency of the occurrence of drought-producing



conditions, somewhat along the lines suggested by Russell's climatic year concept (7).

It seems evident from the foregoing that the establishment of boundary lines implies an investigation of the internal structure of the area to be delimited. The interpretation of regional differences and local patterns brought to light in the course of such an investigation, a routine task for the geographer, prepares a valuable framework for regional planning. Having an area comparable in size to that of France or Spain, the Nordeste could be expected to include several greatly contrasted natural landscapes. As already indicated, the region does indeed present considerable topographic and climatic diversity. There can be no single development scheme here, and any long-range program should aim to extract all possible advantages from the variety of existing conditions. This calls for optimum use of every single tract of land and a combined development of all resources. The required inventory and appraisal of the possibilities offered by the environment furnishes the planner with a basis to judge the claims of competing uses. It also enables him to obtain a better perspective in the appraisal (or reappraisal) of the significance of what may be no more than one-sided solutions for the problems of the region.

Water Storage

The traditional approach to the question of insuring a permanent provision of water in the Northeast rests essentially on the construction of large surface storage reservoirs. Elsewhere, I have indicated some of the limitations of this solution as applied to the region (11). However, since it is customary to point to the benefits which the establishment of large reservoirs have brought to lands of even more acute moisture deficiencies, I should like to refer to yet another phase of the geographers' work, the comparative study of widely separated geographical regions. Although the Nordeste, in respect to certain elements or element complexes, may be bracketed in the same general type as other arid and semi-arid lands, an examination of some notable differences shows the region to be unique in many respects. One example will suffice here. With a single exception, all its streams rise in the dry zone

itself (and every year cease to flow for months on end), whereas the majority of large storage reservoirs established in the arid lands with which a parallel is drawn impound waters of rivers rising in rainy or even snow-covered country. The upper Rio Grande furnishes an opportune example. Although its basin is a typical arid zone watershed, the river rises among the snow-clad peaks of Colorado and is fed by mountain streams.

That reservoirs in the Nordeste have produced even punier results than could be expected (with around 2,000 hectares or less than 5,000 acres under irrigation in 1950) is due essentially to (1) lack of research regarding the multiple factors involved in the establishment of reservoirs and (2) failure to utilize even what irrigation potential has been obtained—most agricultural activity having to do with reservoirs is carried out in the storage basin itself, where the drop of the water level exposes moist land. However, these are matters for the hydraulic and irrigation engineers.

The point I want to make here may be a rather surprising one. But a survey of the existing official literature on the Nordeste and discussions with professionals responsible for public policy have led me to conclude that a large part of the opposition to a realistic appraisal of the remedial measures for the Nordeste stems from an erroneous interpretation of the landforms in this area. One of the outstanding features of the region is the large number of gorges carved through ranges scattered throughout the *sertão* (Figure 6). The general belief is that almost all these water gaps are the result of erosion by the outlets of lakes where waterfalls poured over the impounding ranges (14). Some interpretations are hazy as to the origin of these hypothetical lake basins. Others attribute them to crustal movements; at least one lake is ascribed to an upwarping during the Caledonian revolution (which took place some 300 million years ago) (1). All such interpretations lend comfort to the notion that "it is enough to rebuild the ranges, breached by erosion, in order to detain the rivers which escape through these gaps" (2). Once the mountain ranges have been patched up, man will have reestablished the lakes (which became extinct by the progressive cutting down of their outlets), thus providing large volume reservoir storage and even exerting



Figure 6. Watergap carved by the Jaguaribe River through steeply dipping quartzite beds of the Serra dos Orós.

a beneficial effect on the climate of the area (3). Although no proof is presented, the existence of these lakes is unquestioned among those responsible for the plans formulated and put into operation in the Nordeste.

To anyone familiar with the study of landforms, evidence that extensive sedimentary strata blanketed the crystalline undermass in late Tertiary times suggests an entirely different origin for the watergaps. This interpretation may be outlined as follows. The drainage system, freshly initiated upon the unbroken sedimentary covering, conformed to the surface irregularities of the stratified beds, being, of course, entirely independent of the topography and structure of the buried crystalline base. In time, the streams cut into the underlying basement and sawed across the buried ranges, from which the covering was ultimately stripped (Figure 7).

It is true that whatever their origin may be, the gorges generally provide good dam sites. Their abundance, however, hardly justifies the description of this region as "the ideal land for the construction of reservoirs" (5). In fact, areas of adequate topography for large storage systems are not plentiful. In the absence of indispensable technical studies, the notion that they were to take the place of former lakes may have contributed to the premature establishment of some large scale reservoirs. In challenging the lake theory, the physiographer does not pretend that his broad interpretations are a substitute for detailed engineering studies, but they might contribute to avoid construction of dams, before

such studies have been properly effected. There is no substitute, for instance, for a detailed survey of proposed storage basins, but the student of landforms who interprets most of the *sertão* as a resurrected fossil plain, a worn-down, old-age surface, can predict that the terrain, broadly open and unobstructed, is not likely to provide much depth in proportion to the free water surface of the reservoir. In short, the geographical approach will indicate that there is little justification for the belief that construction of such

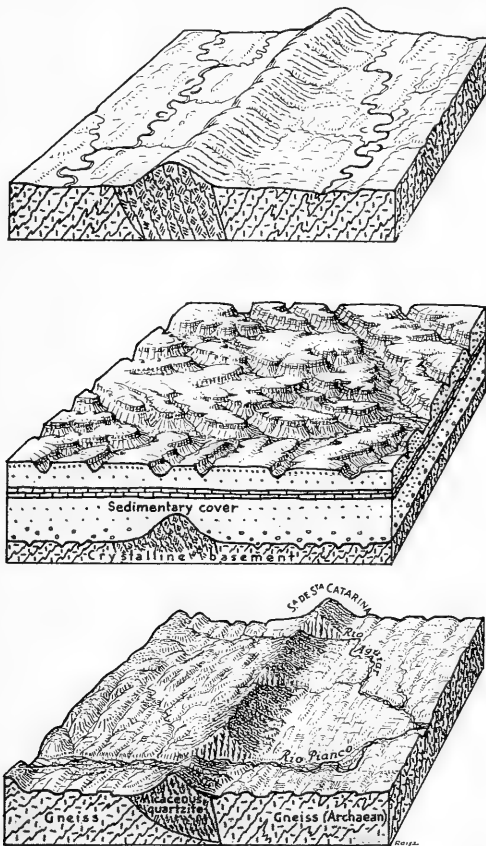


Figure 7. Suggested explanation for the watergaps carved through the Serra de Santa Catarina, Paraíba State, by Piancó River and its tributary, the Aguiar. Sequence of strata in the sedimentary cover is assumed analogous to that exposed in the residual Araripe tableland, some 125 kilometers to west. Following superposition on the undermass, drainage shows tendency to adjust to structure.

reservoirs should be promoted almost in terms of a logical response to conditions of the physical earth.

Promoting Better Use of the Land

The geographer, furthermore, concerns himself with the region as a whole. He is thus susceptible to the fact that the impounding of water for irrigation purposes, when unaccompanied by other measures (as, by and large, has been the case in the Nordeste), at best benefits only the irrigable lands downstream from the reservoir. With the exception of a narrow tract immediately contiguous to the water line, it is indifferent to the fate of the soils in the watershed, yet some of these may be counted among the more promising for agriculture and support a considerable portion of the rural population.

The crystalline *serras*, which rise above the gently undulating *sertão* are a case in point. They receive the benefit of abundant and, what is particularly important, more dependable precipitation. Although the location of meteorological stations, as a rule, is not such as to favor the portrayal of local climatic contrasts resulting from the topography, it is obvious that sharp transitions occur within a very few miles. Observe, for instance, that rainfall at Meruoca, an upland locality (elevation about 670 meters or 2,200 feet), is more than double that of Sobral, a lowland town (elevation about 70 meters or 230 feet), only 23 kilometers (14 miles) away: 1,732.3 millimeters (67.56 inches) and 852.4 millimeters (33.24 inches), respectively. The higher parts of the relief seem to derive additional benefit from the fact that they rise into and are probably dampened by the cloud cover which sweeps tantalizingly across the low country. The mantle of weathered rock and soil is thicker, as much as 25 meters (82 feet) depth having been reported for the Serra da Baixa Verde (13), and the relics of former forests, still to be found in some of the *serras* (Figure 8) may be contrasted with the dry *caatinga* of the surrounding plains (Figure 9).

Although handicapped by less advantageous topography, the *serras*, with their smaller holdings, are devoted largely to farming—corn, beans, sugar cane, fruits and coffee being typical products. Stripped of their former vegetation and improperly cultivated



Figure 8. Agricultural pattern on summit of Serra do Meruóca, western Ceará.



Figure 9. An aspect appearance of the *caatinga* during the dry season.

(Figure 10), they have been ravaged by accelerated soil erosion. Having destroyed the natural conditions which permitted ample water storage, man has not replaced them by appropriate mechanical and vegetative controls. Not only is soil impoverished but



Figure 10. Corn planted on steeply sloping hillsides in the Serra de São Pedro, southern Ceará.

also increased surface runoff results in drought conditions, even with high annual precipitation. A great number of springs, which in the beginning of the last century watered the slopes of mountains such as the Uruburetama and other elevations in the vicinity of Fortaleza, Ceará, are said to have disappeared when the hillsides were cleared and planted to cotton and coffee. Although the area of each of these humid "islands," with deeper, more fertile soil, is small in comparison with the *sertão*, their total area is considerable, particularly in Ceará.

When the 1950 Census was taken, the numerous *serras*, in the state of Ceará alone, supported a population of about 500,000. It is interesting to compare this number of people, already established on the land, with the total of 400,000, which are to be settled, in a remote future, according to plans based on the completion of four major systems of storage and irrigation in various sections of the Nordeste (4). It appears to me that the comparatively small areas of relatively good soil, such as that of the *serras*, must be regarded as very precious indeed and that development schemes should not merely contemplate the establishment of artificial nuclei of settlement, with the construction of large reservoirs, but should make every effort to promote full and

competent use of existing, natural cores of more intensive land occupancy. Since present water deficiencies in the *serras* are largely the result of improper use of the soil, such areas, as Whyte has pointed out, (pp. 182-188), should also be the most susceptible to improvement—those tracts, that is, where the soils have not been washed away entirely.

Most of the general ideas advanced with regard to the potentialities of the *serras* apply to the eastward-facing slopes of the Borborema plateau, formerly hung with the Atlantic rain forest, but degraded by centuries of wasteful exploitation.

In discussing the possibilities of increased production from present water resources, special reference should be made to the agricultural activities carried on at the foot of the imposing Ibiapaba escarpment, on the west, and at the base of a large isolated patch of the once continuous strata—the Chapada do Araripe.

Rising to an altitude of the order of 1,000 meters (3,300 feet), the Ibiapaba is the seat of considerable condensation of moisture. In addition to farms strung along the crest and, to a great extent, dependent on rain agriculture, a strip of irrigated cropland



Figure 11. Belt of cropland at foot of Ibiapaba escarpment, in the vicinity of the town of Ipu, Ceará.

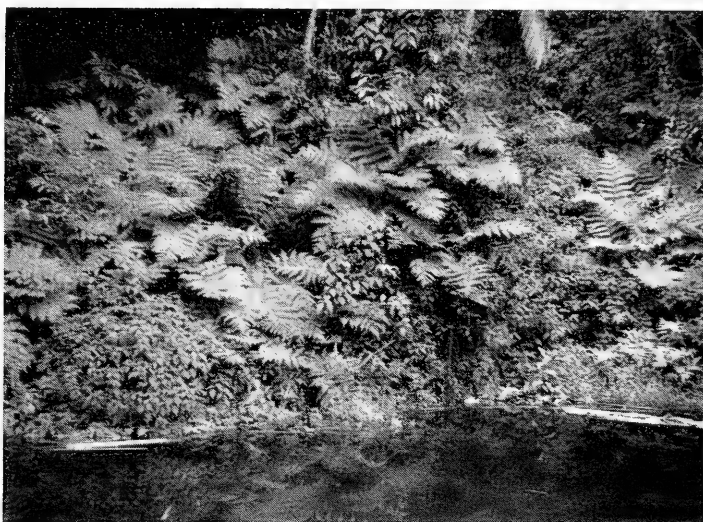


Figure 12. Fern-shaded spring on the flanks of the Araripe tableland near Crato, Ceará.

extends along the foot of the sedimentary scarp and is sustained by a number of small streams which have nicked and notched the steep inface and tap the westward dipping aquifers (Figure 11).

The Chapada do Araripe, the main tabular remnant east of the Ibiapaba, reaches an average altitude of around 960 meters (3,150 feet) and acts as an immense underground storage reservoir. Watered by more than 150 springs (Figure 12), a green belt several miles broad extends along the foot of the tableland in southern Ceará and suggests a veritable oasis to the traveler approaching through the dry *caatinga*. Here, where an intensive use of the soil is possible, a quarter-million people are concentrated. Productivity and value of the land are in direct proportion to the possibility of it being irrigated. Access to water determines, for example, just how many hectares of cane an operator can cultivate.

Because the techniques employed in the utilization of the water issuing from the sandstone beds of the Ibiapaba and Araripe uplands leave much to be desired, there is unfortunately a considerable wastage of water. It has been estimated that losses in the open *levadas* (irrigation ditches) at the foot of the Araripe

plateau represent more than 50% of the discharge of the springs and may even exceed 70% (6). As there is more land suitable for irrigation than water available for that purpose, it follows that the use of available water at maximum efficiency could lead to doubling the producing cropland. It is relevant to add that, in some instances, irrigation water, flowing directly down bare slopes causes soil depletion and erosion.

The Geographical Approach

To the geographer, a complex province such as the Nordeste signifies much more than the mere sum of its component units. Geography does not stop, therefore, with the analysis of each partial landscape, but tries to clarify the relation of the parts among themselves. A geographical study will bring out, for instance, the integration of farming in the *serras* and pastoral activities in the *sertão*. It will show how cattle is moved to the hills after the harvest, to graze what residues are available, and how, in times of drought, both man and beast may find refuge in the mountains. It might go on to mention that some of the leather bags carried by the pack trains one meets on trails leading to the highlands contain manure gathered in the corrals of the *sertão*, which also furnishes a market for the produce grown on the *serras* (Figure 13).



Figure 13. Pack train descending Ibiapaba escarpment near Ubajara, Ceará, with produce grown on humid rim of upland.

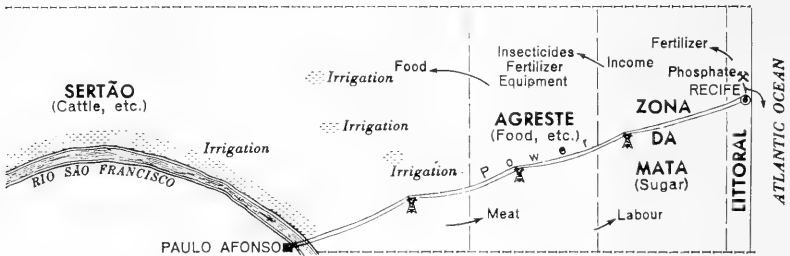


Figure 14. Highly idealized diagram of a development scheme suggested for Pernambuco by Hans W. Singer.

Such an investigation of existing patterns of areal interrelation furnishes a valuable basis for development plans. Economists point out that combined projects, which consider the various diversified parts of a region, are likely to be more productive than those that are confined to one particular type of landscape.

The geographical approach can also provide a fuller comprehension of the spatial relations obtaining between the drought-afflicted backlands and other areas. The study of such interregional patterns are fundamental to a precise formulation of long range development schemes of the type tentatively outlined by Hans Singer for the state of Pernambuco (8). This United Nations economist has put forward a plan, based on what are avowedly initial impressions, which endeavors to take advantage of the different potentialities of the *zona da mata*, where sugar cane production is concentrated; the *agreste*, fairly heavily populated, with much production of food crops; and the *sertão*, with pastoral activities and specialization in cotton and other dry land crops. The scheme takes into account the phosphate deposits (an estimated 40 million tons of high grade calcium phosphate), recently discovered near Recife, an excellent port, and the energy supplied by the Paulo Afonso hydroplant, inaugurated January 1955 on the São Francisco River. The accompanying, highly idealized, diagram is self-explanatory (Figure 14).

Conclusion

I hope to have brought out the fact that geography's contribution to the solution of problems of arid and semi-arid regions can be many sided and wide ranging. Geographers have been fully

aware of their responsibility in providing more factual knowledge "to serve as a proper foundation for schemes of improvement and development, especially in those areas which are commonly regarded as underdeveloped."* Both as a body professional and as individuals, geographers have brought their efforts to bear on the specific problems of water resources and arid lands. But the solution of these problems can be accomplished only by a concerted action of specialists in many fields. Geography, not only can furnish the necessary background against which to plan such integrated action, but has also accumulated valuable experience in the unique function of bringing together, in a coherent and organic body of knowledge, the facts imparted by specialists in the most diverse fields of the social and the natural sciences.

NOTE ON ILLUSTRATIONS: With one exception, all photographs were taken by the author in July, 1951. Figure 4 was taken in January, 1951, by Roberto Maia, and is reproduced by courtesy of O Cruzeiro.

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Agricultural Use of Water Under Saline Conditions

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The question of whether irrigation agriculture can persist permanently has been included among other subjects for consideration at these meetings. The principal difference between irrigated and nonirrigated agriculture, when considered in relation to persistence or permanence, arises from salinity. All waters used for irrigation contain more or less soluble material. It is only a matter of time until these solutes will accumulate in the root zone to the extent that plants will not grow, unless some leaching occurs. This generalization appears final and pessimistic, but, of course, it would be difficult indeed to practice irrigation without some net transfer of water downward through the root zone. Adequate leaching often occurs on irrigated farms without thought or attention by the farmer. If this is not the case, salt will accumulate, and eventually soil and water management operations will have to be altered accordingly.

Water Conductance of Soils

Leaching is accomplished by the downward movement of water through soil. To be adequately drained, any water table that tends to form in irrigated land must be kept well below the root zone. This requires that outlets be available for the ground water and that water transmission in the subsoil be appreciable. Because of its relation to water application methods and to leaching, the rate at which a soil will transmit water is one of its most important

physical properties as far as irrigation agriculture is concerned. The hydraulic conductivity of soil is related to texture. It is generally higher in coarser soils, but it is also influenced by structure and can be profoundly altered by soil management operations and the exchangeable cation status.

Open ditches or covered drains can be used if necessary to control the water table, but the cost of such facilities will be prohibitive if the water conductance of the soil is too low. In subhumid climates, a shallow, stable water table may be a great economic asset for carrying crops through occasional drought periods but, for irrigation agriculture in an arid climate, a shallow water table is a serious salinity hazard. Given an adequate water supply and reasonably favorable soil texture, it might well be argued that in arid climates the hazards from a water table near the root zone considerably outweigh any advantages connected with subirrigation.

The drainage requirements of any given irrigation project will relate to the permissible depth and mode of variation of the water table and the volume of water that the drains must convey in a given time. These, of course, will depend on a whole complex of factors related to soil, crop, climate, quality of irrigation water, and farm management. In any case, the underground drainage must be adequate to carry away the excess water and salt added during irrigation if long-time profitable operation is to be attained.

Water Quality

The quality of irrigation water enters importantly in determining irrigation feasibility and permanence. There have been no recent discoveries of new hazards to irrigation agriculture among the soluble constituents of irrigation water. Some constituents like boron are toxic in minute concentrations. The main problems, however, appear yet to be the accumulation of soluble salts and exchangeable sodium in soil.

The salinity of irrigation water has a direct bearing on such factors as crop selection, method of application of the water, and the leaching required to control salt accumulation in the soil. All these in turn are subject to constraints imposed by drainage conditions.

Progress is being made on methods for measuring and expressing the effect of saline conditions on plants. Reliable information is accumulating on the salt tolerance of various crops. This information is important as a guide for leaching operations and makes it possible to continue agricultural production with salt tolerant crops under conditions where it may not be feasible to maintain low levels of soil salinity.

Application of Irrigation Water

The method of application of irrigation water is important. At low salinity, furrow irrigation can be used. At higher levels of salinity, the requirements for land preparation are more exacting. The shape of the ridge and the position of the seed line with respect to the water line in the furrow may require consideration. At high salinity, flood irrigation must be practiced.

Excess soluble salts can be removed from soil only by the action of water moving downward through the soil profile. Surface flushing operations for salt removal are generally ineffective. Sometimes a trend toward salt accumulation can be reversed by minor changes in the method of irrigation or the amount of irrigation water applied. In extreme cases, ponding of water on the soil surface for long periods is required. In all cases, adequate drainage is a controlling factor.

Principles governing a field leaching operation are simple and straightforward. Soil tests can be used to indicate the need. The process involves covering the soil surface until sufficient water has passed through the soil to remove the soluble salt. The time required will depend on soil properties and drainage conditions. If the exchangeable sodium is high, chemical amendments should be applied. Soil tests are available for indicating the soluble calcium required to reduce the exchangeable sodium to permissible levels.

Leaching Requirement

When the salinity of the irrigation water is high, leaching should be accepted as one of the controlling factors in farm management operations. Although soil salinity tests can be used as a guide, it is helpful to have an estimate of the amount of water to be allocated for leaching purposes. The leaching requirement is the fraction of

the irrigation water that must be leached through the root zone to control salinity at any specified level. It depends on the salinity of the irrigation water and the salt tolerance of the crop. The leaching requirement may be readily estimated from salt balance considerations, and for steady state or long-time average conditions it is equal to the electrical conductivity of the irrigation water divided by the electrical conductivity of the soil solution at the bottom of the root zone. The latter would be 8 millimhos per centimeter for alfalfa, for example. If the conductivity of the water is 1 millimho per centimeter, then the leaching requirement would be one-eighth or 12.5% of the irrigation water. Hundreds of thousands of acres have been irrigated in western United States for more than a half century with water of this salinity and with no apparent decline in productivity. However, in areas of very fine-textured soil where water of this salinity was used, it was not feasible to provide adequate drainage under the existing economic conditions. Consequently, leaching was inadequate, the soil became saline, and the farms were abandoned.

Sodium Hazard

Some irrigation waters cause exchangeable sodium to accumulate in the soil. This is usually due to a high proportion of sodium to the other cations in the water, but other processes are involved. The concentration of solutes that enter the soil in the irrigation water is increased in the soil solution by evapotranspiration. Some of the components such as the alkaline earth carbonates and calcium sulfate may precipitate during this process, thus decreasing the salinity hazard but increasing the sodium hazard. Research is yielding a more complete understanding of the chemical and physical processes taking place in the soil-water system. Recent progress has been made toward finding a general relation between the exchangeable sodium percentage and the relative activity of sodium in the surrounding liquid phase or in a water extract of soil. Classification schemes for water quality take these exchangeable sodium hazards into account, but the prediction of future soil amendment requirements from water analyses is somewhat complicated. Further experience will be required before the rate

of accumulation of exchangeable sodium under field conditions can be reliably estimated from a chemical analysis of the irrigation water. Nevertheless, much of the guesswork has been removed from the agricultural use of water under saline conditions. Tests are available for appraising the salinity and sodium status of soil and for estimating the amount of amendment for reducing exchangeable sodium to an acceptable level. Progress is being made toward putting this information to practical use by farmers.*

* Agricultural research dealing with salinity, exchangeable sodium, drainage, leaching, salt tolerance of crops, and quality of irrigation water has been conducted by numerous agencies in this country and abroad. Information on these subjects has been summarized in the U. S. Department of Agriculture Handbook No. 60 entitled "Diagnosis and improvement of saline and alkali soils." Also see Circular, "Tests for salinity and sodium status of soil and irrigation water." These are obtainable from the Superintendent of Documents, U. S. Government Printing Office.

Consequences of Using Arid Lands Beyond Their Capabilities

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“Using land within its capability” is a phrase that has come to have special significance in the soil and water conservation work of the United States Department of Agriculture. It means recognizing the physical limitations affecting each acre of land and being guided by those factors into the kind or kinds of use for which the land is best suited, and under which it can produce most efficiently on a sustained basis.

The consequences of using any land beyond its capability are generally adverse. This is especially true of the arid lands. In arid climates the balance between land, water, and people is more critical than in any other agricultural province. When the balance is upset the consequences are generally more severe than in humid areas because recovery from the effects of overuse usually takes longer in arid zones.

In the technical assistance program of the Soil Conservation Service in the United States, soils are grouped into eight capability classes for purposes of dealing with land-use problems. This provides an especially effective approach in arid and semi-arid areas where land condition and production are so sensitive to land use.

These eight classes range from Class I, which is the best kind of farm land to Class VIII, which is land with such severe limitations that it cannot be used for forestry, grazing, or cultivated crop production.

The classes fall into two general groups—those suitable for cultivation and those unsuitable for cultivation. Each class is distinguishable from the others by the relation of definite physical features to the intensity of use (cultivation, woodland, pasture, range, and wild life) and the intensity of soil management required for safe and sustained use. Classes I, II, and III are suitable for general agricultural production of the region. Class IV should be restricted to limited cultivation, and Classes V, VI, VII, and VIII are suited for grazing, woodland, wild life, and recreational purposes, in descending order of intensity of use.

Land Abandonment

Presentation of the remainder of this subject can best be done by reference to research and experience in part of the southwestern United States. Here are some classical examples of wide-scale land misuse. In this general area one tragic consequence of land misuse is land abandonment or nonuse. This denotes land use failure. Land abandonment, of course, may be due to physical land failure, or to financial or economic distress. In either case the basic problem is land *use* failure.

Although the two conditions do not divide sharply, it was found in a recent survey and study of land abandonment and rehabilitation in a section of this area that about 60% of land abandonment was due to financial distress and about 40% to severe erosion. The lands that were severely eroded were, in much of the area, lands that were being used beyond their capability. Frequently, the farmer continued to crop shallow, sloping lands in an effort to obtain the occasional rewarding crop; but the usual results were low production for a period and finally abandonment.

The principle of capability use is usually not violated on range lands, and complete abandonment seldom takes place there. However, if grazing is heavy enough to prohibit maintenance of a satisfactory condition of range plants for long periods, the result is low return from livestock and the acceleration of soil erosion. In the end it may mean permanent soil losses that so reduce productivity that the land might as well be abandoned.

Erosion Damage

Studies in the southern Great Plains indicate that lands being used beyond their capability deteriorate more rapidly than any others.

Lands used beyond their capabilities are likely to be sandy or shallow phase soils, have steeper slopes, and, in the western part of the plains, have lower annual precipitation. Under such conditions the production of vegetative cover for the land is frequently not adequate to keep the soil in place and both wind and water erosion take a high toll. Such damage is destructive to any soil, but on shallow phase soil the damage is more likely to be irreparable than on the deeper better grades of land. And yet because in wet cycles these lands often produce high yields, there is a strong tendency to gamble on them each year. This results in their being used beyond their capability.

In the southern Great Plains experience has proved that shallow, moderately sandy, and deep loose sand-hill soils of steep or even gentle slopes cannot be kept permanently productive under cultivation in the 14- to 20-inch rainfall belt. Shallow, fine-textured soils under cultivation on both flat and sloping fields have failed in all areas of less than 18 inches of rainfall.

On the other hand, level to nearly level medium depth, moderately sandy soils have stood up well under cultivation with suitable practices under rainfall as low as 16 inches.

Deep, nearly level, heavy soils have stood up well and can be farmed with suitable precautions wherever found in the southern Great Plains. This kind of soil does not occur, however, in large amounts in areas of less than 16 inches of rainfall.

Research findings, which are verified by the experiences of many farmers in this area, emphasize one of the most serious consequences of using the land beyond its capability—permanent damage to the land. Productive soil is the most important part of the capital structure of farm businesses, and it cannot be replaced. This capital loss showed up in a very pronounced way in lower crop yields after the damaging soil blowing of the 1930's.

Low plant vigor was generally evident in the variation of green coloring of the plants from different fields. This variation emphasized the sharp variation in the amount of nitrogen available.

This unnecessary fertility depletion is more serious in arid land areas where we have not yet learned how to utilize commercial fertilizers effectively, particularly in years of low rainfall. The problem of rebuilding fertility in eroded and depleted soils is further complicated by the limited number of adaptable legumes suitable for inclusion in the cropping systems in arid areas.

Effects on Farm Credit

Soil erosion and other land damage has an adverse effect on farm credit, both to individuals and large areas where land capabilities are being ignored. Land farmed with regard to its limitations is a better credit risk in every instance than land farmed beyond its capabilities. Land used beyond its capabilities creates difficulties in the establishment of necessary reserves farmers must build up during favorable years to tide them over the lean years. Feed reserves are recognized as especially essential to livestock operators who must maintain a flexible position if they are to avoid financial catastrophe.

Sound land use is also required if lending agencies are to provide long range credit instead of the seasonal type which is usually inadequate under such conditions. Increasing numbers of lending institutions are recognizing these principles of conservation farming in providing sound loan services in the arid belts.

Economic and Social Implications

Just a few miles east of Albuquerque, New Mexico, in the 14-inch precipitation belt, there are sizable acreages devoted to the production of beans. Much of the soils there are shallow, steeply sloping, low in organic matter, and are in small farms. Incidence of crop failure is high, and alternative crop choices are very limited. These conditions combine to create a serious long-range economic problem which will grow progressively more acute until a range livestock economy is developed to replace the precarious dryland bean farming. During the past few years many of the occupants of these small farms have supplemented their incomes through employment in near-by national defense projects, industrial developments, and on large ranches and farms.

Population adjustments necessary for a livestock economy in

such an area are never easy for people to make, although some progress has been made in recent years toward the adjustment. Some of the more important roadblocks in the way of making this kind of adjustment at a faster rate include the need for resettlement of people; the necessity for obtaining adequate credit for enlarging and changing the farm business; acquiring needed education in a new type of farming; and inevitable inertia and resistance to change.

In any event, a change from cash crop farming, whenever it exists in such a hazardous zone, to livestock grazing should be speeded up by every practical and feasible means. Two principal objectives will be accomplished: first, it will help stop further irreparable damage to the land; and second, it will establish a sound basis for a permanent agriculture. Only such an approach will enable people to conduct a stable farm business. The alternative is not a pleasant one—further soil resource destruction, blighted hopes and ambitions of people, economic and social stagnation, and finally abandonment of land to the forces of nature, whose rehabilitation job is slower than we can afford.

Role of a Conservation Program

The use of appropriate conservation practices will slow down the process of land damage, even when land is being used for purposes for which it is not suited. However, the cost of applying measures that will safeguard lands under such misuse is too high and soon reaches the point of diminishing returns, especially when an entire farm is being used beyond the capability of its soils. So, in these cases, a conservation program is largely a delaying action that buys time in which to get the land used in harmony with its physical, climatic, and economic limitations. In these cases where suitable conservation measures are not employed, the rapid deterioration of the land makes ultimate solution much more difficult, or even virtually impossible.

Wherever soils are suitable, and adequate water supplies are available, irrigation is an effective means of stabilizing farming in arid areas. Many examples in the Southwest prove the value of this type of land use. Some caution is required, of course, espe-

cially where underground water is being used. In many areas these supplies are already being depleted faster than they are being replenished.

Without irrigation, however, successful farming in the arid and semi-arid lands of the southwestern United States requires mainly that the farmers accept highly variable and fluctuating rainfall as a normal phenomenon. Once they understand this as a cropping limitation, they can develop their farm enterprises in harmony with the pattern. This means gearing the farm program to the dry phase of the weather cycle rather than to the wet periods, as so many have done in the past. The first course is an approach to successful farming, because it recognizes the capability of the land. Any other course courts almost certain failure.

The attainment of these objectives over a significantly wide area of the arid lands requires exercise of local leadership that will move people to act as rapidly as facilities and resources will permit. Farmers throughout the United States now have suitable administrative machinery for this in the form of locally organized soil conservation districts. Soil conservation districts now cover most of the agricultural lands of the nation, and include within their boundaries about 80% of these arid and semi-arid lands in the southwestern United States. Districts are regarded as highly effective mechanisms for solving soil and water problems in an arid region as well as elsewhere in the nation.

Needed Research

Information gained from further research should prove helpful in keeping arid land use within the limits of capability. Such additional investigation might well be conducted along the following lines:

1. Secure information that will make it possible to define more sharply the differences between the characteristics of arid land suitable for cultivated crop production and those unsuited for such use.
2. Develop more adaptable grasses and legumes for these areas.
3. Work further on the possible uses of commercial fertilizers for such lands.

4. Determine the most desirable size of farm and ranch units from an economic standpoint.

Summary

The basic physical soil conservation objective of the U. S. Department of Agriculture, "The use of each acre of agricultural land within its capabilities and the treatment of each acre of agricultural land in accordance with its needs for protection and improvement," is the best approach to solution of the complex land problems we confront in the arid areas of the United States and elsewhere. Sustained production and permanent occupancy of these lands cannot be achieved unless agriculture of the arid areas is based on such a concept.

Possibilities of Increasing and Maintaining Production from Grass and Forest Lands without Accelerating Erosion

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Use of grass and forest in arid lands for sustained production without accelerating erosion requires great managerial skill. A delicate adjustment of vegetation to environment exists. In this adjustment the balance between constructive and destructive forces is sensitive and easily shifted toward destruction.

The climate consists of extremes with great fluctuations from season to season and year to year. The adverse climatic factors are: the wide range of temperature and precipitation in a given place; the great variance in seasonal and annual precipitation; and the occurrence of extremely intense storms after long dry periods. Climatic variation produces much more extreme differences in plant growth and erosion hazards in arid than in humid regions. Because of the delicate adjustment of vegetation to environment, a succession of dry years can weaken vegetation so that heavy, or even moderate, rains can cause severe erosion.

Many mistakes have been made because of wishful, optimistic estimates of climatic changes. The actual shifts of an erratic climate in arid lands must be accepted as they come. We must learn

to take advantage of favorable periods and to guard against the unfavorable weather events which are bound to happen. Perhaps the old frontier rule of preparing for the worst while hoping for the best is still a good guide for arid land residents.

In the southwestern United States there are many examples of the improper use of arid lands. Present day problems in the Rio Grande Valley are to a large extent the result of poor land use in the past. Historical evidence clearly shows that a general decline of watershed lands and resources began during the 1880's. This decline was largely brought on by damage to the natural plant cover through poor grazing management, promiscuous wagon trailing, and injudicious dry farming. The evidences of decline are: the decreased grazing capacity of range lands; deep and continuous gullies slashed through alluvial valleys; shifting sand and sand dunes; and the silting up of river channels and storage reservoirs. Much of the water yield is now from surface runoff and is silt laden. Water once held in the soil to support plant growth is now drained out by deep gully channels. Irrigation diversions on tributaries have been undercut and destroyed. The Rio Puerco is a terrifying example of the destruction caused by accelerated erosion. The lower valley of the Rio Puerco between San Luis and Cabezon and in the vicinity of Salazar once supported a prosper-

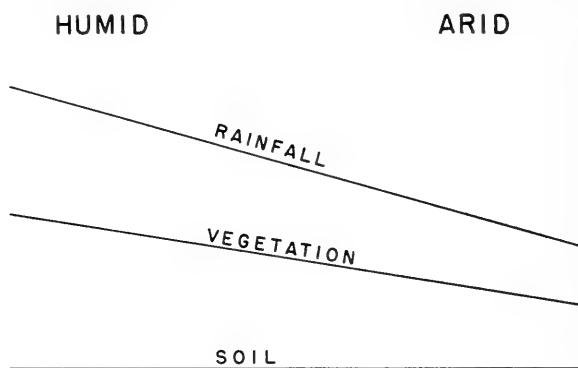


Figure 1. Diagrammatic illustration emphasizing that a more delicate adjustment of vegetation, rainfall, and soil exists in arid lands than is common in humid lands. This vegetation-environment relationship must be recognized in the sustained use of grass and forest lands in arid regions.

ous farming and livestock enterprise as shown by ruins of once substantial ranches and homes. Now the valley is gashed by enormous straight-walled channels 20 to 40 feet deep.

Lower down on the Rio Grande, the river has not been able to carry the enormous load of sediment dumped into it by its muddy tributaries. As a result, adjacent valley lands have become water-logged and are no longer cultivated. The raising river bed also brings an increased flood threat to bordering cities and farms. Sand and mud bars furnish a foothold for salt cedar (*Tamarix* spp.) and other water-wasting vegetation.

Improvement of the land and water situation of the Rio Grande Valley and other similar arid land is not impossible. Restoration of plant cover on the watersheds is a necessary step in this improvement. Unfortunately, many are puzzled when the need for cover improvement and erosion control is emphasized. Often deteriorated conditions are accepted as normal. The great difference between present day vegetation and that of an earlier day is not fully realized. Demonstrations provided by some ranch lands, national forests, and other well-managed areas show what can be and has been accomplished. Research and experience have shown many ways to maintain and improve production on grass and forest lands.

Management of Forage Resources Adjusted to Rainfall Deficiency

A perpetual problem in range land management is how to balance animal numbers with forage supplies. This is troublesome enough anywhere but particularly difficult in dry lands, which are almost universally characterized by large fluctuations in precipitation between seasons and from year to year. Man, misled by optimism or driven by short-range necessity, has all too often overused the ranges. Recovery proceeds more slowly and less certainly than in humid lands. If deterioration is severe, unfavorable conditions may persist in the absence of any use unless the natural forces tending toward recovery are given assistance.

Average annual rainfall in arid lands is of little value in land management. Extremes of rainfall occur more frequently than do mean conditions. In southeastern Arizona and southwestern New Mexico of the United States, rainfall varies exceedingly from one

year to the next, but periods of continuous excess or deficiency may persist for 4 or 5 years. Grazing management systems must be designed to meet the large changes in forage production that result from variations in rainfall (8, 11).

Stocking Based on Below-Average Forage Production

The wide variation in rainfall and the consequent variability in annual forage production makes proper stocking essential. Attempts to adjust stocking each year to the highly variable amount of forage, unless properly done, may have disastrous results. A breeding herd built up to use the forage crop produced in good years cannot be maintained in subsequent dry years. The practical way to utilize the highly variable forage crop is to stock conservatively.

A margin for safety is provided by stocking at a level less than that which the average forage production will support. Ungrazed forage produced in favorable years provides a forage reserve for lean years and also protects the soil. In southern New Mexico, stocking at 65% of average forage production is recommended for black grama (*Bouteloua eriopoda* (Torr.) Torr.) and tobosa grass (*Hilaria mutica* (Buckl.) Benth.) ranges (9). Even at this seemingly conservative rate of stocking, severe reductions of livestock numbers would be needed during prolonged periods of drought such as have occurred three times during the last four decades. Obviously, the desirable levels of stocking will vary widely with climatic regions and forage species, but stocking somewhat below the average forage crop should be practiced on arid ranges. Moreover, the basic breeding herd should be kept low—55 to 60% of the total number grazed. The remainder of the herd should be made up of younger, more salable animals that can be disposed of quickly when dry periods and short forage supplies occur. This practice will safeguard the most valuable breeding herds (3).

Seasonal Grazing for More Forage

Yearlong grazing is the most punishing form of use. If continued, this practice reduces the proportion of desirable forage species and the amount of usable forage; it will also result in thinning of

the plant cover and cause accelerated soil erosion. Fencing or herding so that grazing use is rotated between areas increases production and also provides more vegetation for soil protection. Allowing part of the range to rest during the growing season every second or third year results in a wider variety of the better forage grasses as well as greater forage production.

In many cases, it is possible to take advantage of differences in the growth and palatability of forage species. In southern New Mexico, when black grama is grazed only during the non-growing season, almost twice as much herbage is produced as under yearlong use. Under yearlong use the valuable black grama is replaced by worthless snakeweed (*Gutierrezia* spp.). It is possible to withhold black grama areas during the growing season by grazing cattle on tobosa grass flats, which provide abundant palatable forage during the summer. Tobosa grass is not harmed by judicious summer grazing and is not palatable to cattle during the winter months. This pattern of seasonal use increases range productivity above that possible under yearlong use of either grass type (15).

Proper Distribution of Livestock

Obviously, wells and stock tanks for water should be provided wherever possible so that animals can make effective use of the range. Well-spaced watering places aid in (1) distributing animals over the range, (2) preventing local overgrazing, and (3) keeping livestock in better condition. The number of cattle watered at a place should not exceed the grazing capacity of the area within a 1½- or 2-mile radius of the watering point.

Judicious placing of salt grounds aids in drawing cattle to otherwise little-used parts of the range (12). The use of a mixture of cottonseed meal and salt as a self-feeding supplement promises to be an even more effective method of obtaining better distribution and thereby avoiding overused areas (2).

Control of Noxious Plants

The invasion of grassland by worthless or undesirable plants has resulted in a critical problem throughout much of the southwestern United States (18). Increases in low-value shrubs on

former grassland sites are responsible for lowering grazing capacity, especially where grazing pressure has been heavy. Forage production can be increased by removing these shrubs. For example, in southern Arizona removal of mesquite (*Prosopis juliflora* var. *velutina* (Woot.) Sarg.) on grassland sites when accompanied by conservative grazing has increased perennial grass forage production fourfold. There are other important benefits from mesquite control. Erosion ordinarily active under mesquite is reduced by the reestablishment of grasses. Cattle are also more easily worked and losses from screwworm are reduced (10).

Considerable research is being done to find control methods for many other undesirable plants. Much progress has been made. It must always be kept in mind, however, that there is no permanent advantage in the mere killing of low-value plants unless their elimination is followed by grazing practices which permit increases in desirable forage species.

Reseeding of Adaptable Grasses

Heavy grazing, drought, the spread of noxious plants, and the combination of these factors have depleted the grasses and other forage plants on large areas. Restoration of much of this land within a reasonable length of time depends on the development of practical economic methods for range reseeding. To date, successful methods have been worked out for reseeding many arid sites. However, much remains to be done, and an expanded research program is justified.

Most success with range reseeding on arid sites has been with the use of introduced grasses. Several species of lovegrasses (*Eragrostis* spp.) introduced from South Africa have been used successfully in Arizona and New Mexico. Mild winters, hot summers, and annual precipitation of at least 11 inches, mostly received in the growing season, characterize these areas (1, 13). Grasses from Asia and the Middle East such as crested (*Agropyron desertorum* (Fisch.) Schult.) and intermediate (*A. intermedium* (Host.) Beauv.) wheatgrasses and Russian wildrye (*Elymus junceus* Fisch.) have proved well adapted to areas where winter temperatures are lower and more of the precipitation occurs

in the winter. A few native grammas (*Bouteloua* spp.) and muhlenbergias (*Muhlenbergia* spp.) and other species have given considerable promise but have not been so widely used as the introduced species (6, 14).

Through use of adapted introduced grasses, range reseeding has often increased forage production ten- to twentyfold. With the realization that the great advance in knowledge and widespread use of reseeding on arid lands in the United States is largely the result of research during the last 20 years, considerable optimism is justified.

Better Management of Shrub and Woodland Areas

Shrubs and trees make up the cover on large areas of the southwestern United States. Even the true desert is not really treeless but contains here and there scattered along the drainages and rocky slopes dwarf trees and treelike plants such as yuccas (*Yucca* spp.), paloverdes (*Cercidium* spp.) and cacti. On foothills and mesas are broad zones of orchardlike woodlands of pinyons (*Pinus edulis* Engelm.), junipers (*Juniperus* spp.) and evergreen oaks (*Quercus* spp.) often intermingled with chaparral made up of shrubby species such as manzanitas (*Arctostaphylos* spp.), sumacs (*Rhus* spp.), shrub live oaks (*Quercus* spp.), and ceanothus (*Ceanothus* spp.).

Although the desert trees and shrubs furnished food, medicines, fiber, fuel, and other necessities to the early inhabitants, they are of little economic use now. The development of uses for these unique plants would increase productivity of the desert lands with little risk of increasing erosion. Very likely the increased returns would make it possible to provide greater protection from floods and erosion.

A similar opportunity to find or develop merchantable products is present in the chaparral and woodland types. The present thinking is that portions of these types should be replaced with grasses wherever soil and slope conditions make tree removal and grass establishment practical. Present research is concerned mostly with methods of killing or removing chaparral and woodland species. Markets for the woody material removed are needed to

offset the cost, and some research is being done to develop products such as pulp for paper, chemical extractives, and others. For the comparatively level lands where shrub and tree control is now practiced, the change to grasses is desirable for both forage production and erosion control provided that grazing is carefully managed. In the shrub and woodland zone, erosion is often active because of insufficient effective grass cover to protect the soil. Unless the increased growth of trees and shrubs is reduced, grass cover cannot be increased because the roots of woody plants dominate even the open areas and extract available soil moisture. The necessity for proper control of grazing after brush is removed must be emphasized.

Management of Higher Forested Areas in Arid Regions

At higher elevations, the mountain ranges and plateaus are covered with valuable forests of tall pines (*Pinus* spp.), spruces (*Picea* spp.), and firs (*Abies* spp.).

Thinning and improvement cutting in the ponderosa pine, (*Pinus ponderosa* Laws.) and spruce-fir forests do not present erosion hazards in themselves. The danger of erosion comes from the skid trails and logging roads built and used to remove the products. In thinning, the general recommendation is to remove the slowest growing trees to concentrate the capacity of the site upon the most vigorous trees. When stands are mature or overmature, as in much of the spruce-fir zone, harvest cuttings are made to replace the slow-growing old trees with young fast-growing trees (5).

To prevent excessive erosion, roads must be carefully located to avoid steep pitches and soils that erode easily. Drainage must be provided to prevent water from concentrating on the road surface and in side ditches. Cuts, and particularly fill banks, must be protected. Much of the high country is too steep to be logged by methods now in common use without excessive erosion. For these locations, cable logging, chutes, or other methods are needed for transporting logs with less road building (16).

Improvements in utilization and the development of new markets for wood products will make possible better management to

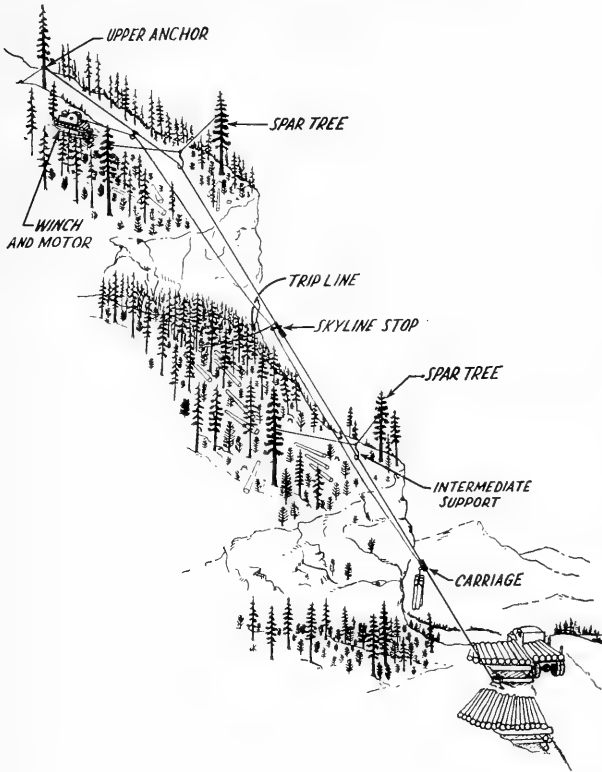


Figure 2. A cable logging system that appears satisfactory to harvest timber on steep watershed lands with a minimum of erosion and other destruction to the watershed.

improve productivity and also to prevent watershed damage. Destructive exploitation is always tempting when risks are high and the profit margin low. Sustained, forward-looking operations are encouraged when products removed are suited to a diversity of uses and when reasonable profit can be obtained without excessive risks.

Effects of Land Management on Water Supplies

Comparatively little streamflow is yielded by the low-lying grasslands and woodlands where most rains are absorbed by the dry soil. Although flash floods follow cloudburst storms, often such

flows are heavily laden with mud. The aim of management in such low-lying areas is to reduce sediment movement. Most of the large water reservoirs lie within this zone and catch the debris dumped into the tributary streams. Although the scanty rainfall supplies plants, they are not competing with man for their supply but rather are racing evaporative forces to take water from the soil before it returns to vapor. These plants provide soil protection, forage, and other products from soil moisture that would otherwise evaporate. Phreatophytes are an exception. These water-loving plants are not dependent on local rainfall but grow along streams and rivers where they steal water that could be put to other uses. Our justified fight against these water thieves must not be carried to the upland vegetation (4).

The permanent rivers, on which the Southwest depends for its water supply, tap the higher elevations where precipitation is more abundant and water to feed streams is in surplus, at least at certain seasons. Just as on lower lands, the protective effect of vegetation is important. Where plant cover is reduced, the capacity of the soil to absorb and store water is diminished. Flash floods and mud flows are all too common after excessive grazing use, careless logging, or wild fire. Where the protective cover remains, streams run clear and contribute little sediment to aggravate downstream troubles. The good quality of mountain waters is appreciated by irrigators as well as by domestic and industrial users.

In some situations, mountain lands can be managed to increase water production. Enough research has been done to show the possibilities of increasing streamflow, but not enough has been done to make general recommendations. Where winter snow is heavy, dense stands of evergreen trees hold snow on their foliage and let it evaporate without reaching the ground. In snow country, thinning in young forest, selection cutting, and patch clear cuttings to open up areas of dense forest have been shown to increase the amount of snow finally contributing to streamflow. These measures are good forest management practices and can be carried out so that both wood and water production are benefited. Another possibility is the replacement of deep-rooted species of trees with shallow-rooted vegetation. This would reduce the

fall soil moisture deficit on areas where soils are deep and less water would be required to prime the soils before runoff occurred (17).

As a general rule, the more arid the climate the less the opportunity to increase water yield by thinning or removing vegetation. With the exception of plants growing along watercourses, the water used by vegetation comes from soil moisture that can be removed from the soil only by plant roots or by evaporation. In dry climates, this moisture is lost from the soil with or without plants. Changes in vegetation are expected to provide more water where precipitation is mainly in the form of snow, or where it falls in large enough quantities to saturate the soil at frequent intervals (7).

Growing Demands; Limited Resources

Demands upon arid lands in the southwestern United States have increased and will continue to increase. Recently, there has been a decline of subsistence farming and ranching and a tremendous growth of urban populations. The concentration of population increases the strain on water resources because no one locality has sufficient water naturally available to it to support its present size and future hopes. Water is no doubt a resource that will continue to be limiting. Managers of forest and range lands have an obligation to protect water supplies. Fortunately, practices that maintain and improve forage and forest production are also beneficial in controlling erosion and reducing sedimentation. A first need on much of our watershed lands in the arid Southwest is repair and rehabilitation. Past damage has been severe, but deterioration need not continue. Improvement has already been made in many areas. Human needs and demands can be expected to fluctuate and vary from one product to another in the course of time. We must safeguard all arid land resources so that future needs can be satisfied.

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Land Reclamation and Soil Conservation in Indian America

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Since I am an archaeologist who specialized in the study of pre-Columbian America, I want to bring to the attention of the specialists in other fields of knowledge a summary of data on the relationships between man and land in arid and semi-arid zones of America in the past. This summary will provide illustrative examples of the kind of information which archaeology can provide on this subject.

The American Indians are classified, from the viewpoint of the relationships between man and natural resources, as follows: (*a*) pre-agriculturists, getting their livelihood by gathering of plants, hunting and fishing; (*b*) proto-agriculturists, farmers using the shifting-field system; and (*c*) intensive agriculturists.

The pastoral way of life which depends on the raising of grazing animals and which might have notoriously harmful effects on soil conservation, was not found in pre-Columbian America.

Although the activities of the human groups belonging to the first two categories may affect natural resources, their low density of population tends to make the damage done, if any, less serious than that resulting from the action of the large, concentrated populations of intensive agriculturists.

Intensive Agriculture in Indian America

At the time of Columbus the intensive agriculturists extended, although not in continuous distribution, from the American South-

west to northwestern Argentina. This zone included the areas of native civilizations of Mexico-Central America (called *Mesoamerica* by the anthropologists) and Peru-Bolivia (called *Andean*) as cultural climaxes. Because of limitations of space, and also because of the reason noted above, I shall concentrate my attention on these two areas.

Mesoamerica

Mesoamerica includes central and southern Mexico, Guatemala, British Honduras, El Salvador, and western Honduras. Owing to a diversity of factors, the most important of which are great differences in altitude and broken relief, it is far from being a geographical unit. In the lowlands, which include the coasts and some of the interior depressions, tropical rain forests and monsoon forests, tropical savannas, and tracts of hot steppe and cactus desert are found. In the mountains and plateaus there are temperate forests, mesothermal savannas and cold steppes.

In the semi-arid zones, constituting most of the area, the degree of aridity depends on the duration of the winter dry season and the intensity, reliability, and efficiency of the summer rains. Also, the regularity of the beginning of the rains—as a determinant of the planting period—is an important factor in the highlands, where early frost might destroy the unripe crops when planted late.

In the rain-deficient sections and in many of those having a markedly seasonal distribution of rains, canal irrigation or other specialized forms of horticulture were important, although not exclusive of rain farming, in pre-Columbian times. The distribution of irrigated lands included the highlands, the intermountain depressions, the Pacific coast and the semi-arid zone of central Veracruz. Hydraulic engineering was most developed in the valley of Mexico. Elsewhere the irrigation works were built on a small scale, possibly with the resources of single local communities, but requiring in many basins centralized control for the allocation of water rights.

The other specialized forms of horticulture to which I referred were:

(a) *Gardens irrigated* with water manually elevated from wells, dug within these plots.

(b) *Chinampas*. These so-called floating gardens are actually artificial islands built near the shores of shallow lakes by piling up layers of aquatic plants and silt from the bottom of the lakes. The porous soil of the *chinampa* is perpetually moist as a result of the infiltration from the surrounding waters. Additional moisture is applied directly to the individual plants by lifting water manually from the canals surrounding the plot, by means of long-handled cloth buckets. As the water is muddy, this amounts to the addition of new soil. Furthermore, aquatic plants and other fertilizers are used.

The Indian methods of land reclamation and soil conservation also included various types of adjustments to farming on slopes, these are:

(a) *Rock walls* built on the contour to form level benches irrigated with elaborate aqueducts, as were the gardens of the Texcocan king Nezahualcoyotl (fifteenth century). Actually, the royal gardens were only a part of an extensive project of land reclamation through terracing and irrigation in the foothills of the mountains to the east of Texcoco. There is an early colonial document concerning the water rights of the Indian farmers cultivating the reclaimed lands. Later, the upper aqueducts and some of the terraces were abandoned and erosion carried away the soil on the top of the hills. However, the middle and lower level terraces are still well kept and cultivated.

(b) *Rain farming terraces*. (1) With retention walls—the distribution of these extended from the valley of Mexico to British Honduras. Most of them are now abandoned; (2) without retention walls but hedged with maguery—these are built to reduce slope gradients, to retain soil and moisture. This system is widely practiced at present in Central Mexico.

Although fairly widespread, the techniques of soil conservation were by no means universal in pre-Columbian Mexico. There is no doubt that in many districts the exploitation of land might have resulted in serious depletion and destruction of soils, but the wholesale damage seems to have been a result of the *technological changes introduced with the Spanish Conquest*. In the first place, large-scale mining operations demanded huge quantities of wood for timber and fuel, thus bringing about the destruction of forests,

to a greater extent than before. Other causes of the destruction of soil were the introduction of herds of grazing animals and the change from intensive cultivation to extensive cultivation with the introduction of the plow. Also, the transfer of manpower from agriculture to other activities and the decrease in population resulting from the epidemics introduced by the Spaniards brought about the abandonment of pre-Spanish irrigation systems.

These technological changes, however, were not always detrimental. The introduction of the plow, which, as previously noted, was conducive to the destruction of soil in some areas, permitted the opening up of new lands to cultivation, in regions of heavy soils not cultivatable with the native digging stick. The introduction of new plants also extended cultivation beyond the limits of the pre-Columbian crops.

Andean America

The Peruvian coast and the Peru-Bolivia highlands comprise the central Andean area. The coast is a desert interrupted by the valleys of the rivers flowing from the Andes to the Pacific. In one of these cases, the Viru Valley, archaeologists have found evidence of occupation by sedentary farmers going back to the third millenium B.C., some 4,500 years ago. At first, farming probably depended on flood waters, but since the first millenium B.C. the agricultural potentialities of the valley soils were fully exploited by means of canal irrigation. More than 2,000 years ago the irrigation system had expanded to its maximum potentiality, permitting the cultivation of 40% more land than at the present time (24,200 acres against 17,300 in 1946). There is some evidence of population decline in the north coast of Peru during the late pre-Spanish periods (after A.D. 1200), but the possible causes are not yet known. They may have been socio-political in nature or may have involved the diminishing efficiency of the irrigation systems, or both.

In the valleys of the south coast, the flow of water available for irrigation is smaller than in those of the north coast, and there are reasons to assume that it was the same in the past. Archaeology shows that the density and concentration of population, the degree of urbanization, and the complexity of the socio-political

structures were directly proportional to the respective water resources of each area.

In the semi-arid and broken highlands, the Indians built huge systems of irrigated farming terraces. The beginning of terracing for agriculture may go back to before the time of Christ, but it seems that its maximum expansion took place in Inca times. After the Spanish conquest the terraces were neglected and most of them fell into ruin.

Applications of Archaeology

Dr. Whyte called attention to the need to "map the cultivated lands in relation to their farming systems and the crops grown thereon" (p. 182). I suggest that this study must be made within the historical context. In many zones the knowledge of the past, the local story of trial and error in land management, might help in planning for the future.

Dr. McClellan asks for sociological and economic research keeping pace with engineering and scientific research (p. 198). Anthropologists have explored the relationships between technical change and society. Man is a social animal and the alteration of the balance between technology and the societal forms, through induced changes of the first, tends to start chain reactions which are as far reaching in their effects as those resulting from the alteration of the ecological balance in nature. This is to be kept in mind by those who have the responsibility of planning the future of arid and semi-arid lands and of the people living on them.

Furthermore, there is the problem of acceptance or rejection. In underdeveloped areas where people live in traditional ways it is absolutely necessary to bear in mind the cultural situations in any project of improvement. Only under that condition will it be possible to guarantee the social acceptance of the technical improvements which have to be introduced. It is a principle well established in cultural anthropology that whatever may be the technical value of programs of aid, these may run the risk of failure if they do not take into account the cultural conditions.

Better Use of Present Resources: Concluding Remarks

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Through countless centuries there has been built up a balanced relationship among water, land, and the vegetative cover. Each dependent on and helpful to the others, they have developed together, through physical, chemical, and biological processes, to create and maintain useful and abundant resources for the habitation and sustenance of man. But man has not used the resources properly; in his ruthless exploitation of land and water resources, man has violated the basic arrangements in a manner that upsets the fruitful balance which created and maintained the land and water resources.

No doubt a great part of the arid and semi-arid regions are man-made in so far as the vegetation has been cut down or burnt for purposes of cultivation, or else has been used for grazing purposes. Though the original cause of the Rajputana desert in India can be traced to geological events, its further deterioration can definitely be attributed largely to human causes. The forests were utilized beyond their natural recuperative powers. The vegetation, wherever it existed, became a grazing ground. All these resulted in accentuating the formation of desert characteristics.

Permanency of Irrigation

Richards comes to the conclusion that, "All waters used for irrigation contain more or less soluble material. It is only a matter

of time until these solutes will accumulate in the root zone to the extent that plants will not grow, unless some leaching occurs.”

I am afraid I find it difficult to accept this pessimistic generalization in its entirety. I can quote cases from India and China, where land has been under irrigated agriculture for more than a thousand years. Richards' remarks would of course apply, when either the water contains salts, or the salts exist in the soil profile, which are brought to the surface during the process of repeated irrigation and evaporation. This situation has been successfully handled in India by crop rotation and leaching the soil, as Richards suggests.

International Cooperation in Reclamation

Whyte has outlined the activities of the FAO who are working on all promising methods for the reclamation of arid regions.

In India an *ad hoc* committee was appointed by the Government to recommend measures for the immobilization of the Rajputana desert. The recommendations included a Desert Afforestation Research Station to study the silviculture of the various species already growing in the desert with particular reference to their succession, to consider the possibility of introducing exotic desert species from other countries and from other parts of India, to maintain a number of seed stores for distribution through departmental agencies, and to propagate vegetation. In addition, they suggested creation of a five-mile wide forest belt several hundred miles long to withstand the onslaught of winds. The committee also recommended the establishment of nurseries for experiments with and distribution of suitable species of plants, shelter belts transverse to the direction of winds, increase in the proportion of area under forest, and adoption of improved agricultural practices by the cultivators. A Desert Research Station has already been set up at Jodhpur and work is in progress on the best method of afforestation and creation of oases for the spread of vegetation.

In 1954 the World Forestry Congress met in India to discuss the place of forests in the land economy of the country. The Congress decided to recommend to the 47 governments the creation of an international commission on desert control and afforest-

ation of arid zones. This new organization, it was proposed, would study problems affecting the dry areas and serve as a center for the collection and dissemination of information to all FAO members and other interested countries. I believe the FAO has already undertaken to collect results of the experiments and observations at present available from several countries and to analyze such results in order to advise other countries in matters of land utilization, conservation of forest, and afforestation policies. I have no doubt that these developments will make a great advance in the direction of a methodical and scientific reclamation of arid and semi-arid lands.

But maximum benefit can be achieved by bringing under cultivation vast areas in arid and semi-arid regions. Moisture is essential for this purpose. In a number of regions of the world both land and water exist. What is needed is to marry these for the good of mankind.

Arid Lands as a Source of Food

The total land area of the world, excluding ice-covered regions, is about 33,500 million acres. Less than 10 per cent of this is cultivated, giving a per capita figure of about 1.25 acres. Our Indian vegetary dietary can be produced from about 0.8 acre per head, although the Chinese have been managing with 0.5 acre per capita. The British require 1.4 acres per head to satisfy their needs, whereas the people with higher standards of nutrition will require two or more than two acres per capita.

One of the chief maladies of present day agriculture has been that in many countries the area under the plow has been decreasing instead of increasing owing to greater demand on land from other quarters like expansion of cities, highways, canal systems, industries, and other matters of defence or strategic importance. The world stands in great need of an increase in crop acreage and better exploitation of water resources. This can be done by reclamation of arid wastes, marginal and saline lands. In India, for example, there is a considerable area of uncultivated land which can be utilized to advantage. Out of 810 million acres, about 330 million acres are sown at present. Only 12 per cent of the surface flow rivers have so far been used.

In any arid land, the problem is definitely the limitations of

water and the available land fit for irrigation. We must first know our assets before making a scientific plan for their utilization. I suggest that this study can be done in four steps as follows:

1. The assessment of overall water available for irrigation and of land resources fit for irrigation.
2. The assessment of the water and land resources at present being utilized.
3. The possibility of using the balance of water and land to the optimum limit for irrigation.
4. The possibility of finding new sources of water.

In the arid land of Rajasthan in India it has been found that out of the total utilizable surface and ground water potential of about 12 million acre-feet only about 4.3 million acre-feet have been utilized. Thus there is great scope for further utilization. Similar will be the case in quite a few of the arid regions of the world. The water potential of any arid or semi-arid region being meager, the problem would generally be to make a judicious, economical, and wise utilization of the supplies available. The more economical schemes could be taken up first, but there should be a long-range plan for fully utilizing the resources.

Better utilization of the water now being used can be achieved in two ways. One is to reduce all possible wastage and the other, to put every cubic foot of water to the maximum utility. Wastage occurs by evaporation, seepage, and transpiration. These can be minimized by taking the water in lined canals and closed conduits and by irrigating the fields by subsurface methods or by sprinkling. For getting the maximum out of water, crop pattern in the region should be studied and modified if necessary. It would be advisable to adopt a crop scheme so that the moisture of one crop helps the succeeding crop. Again, the optimum water requirements of crops should be studied. I am of the opinion that in regions with similar type of soil and climate the total water requirements of a given crop inclusive of utilizable rainfall would generally be the same.

India has done valuable work on water requirements of plants, which can be studied by other countries to advantage. After careful study of climatic conditions, rainfall, water table, type of soil, local agricultural practices, dust and wind storms, high temperatures during the summer and other conditions, we have evolved crop patterns and water requirements for crops in differ-

ent tracts in the Bhakra Project area which is a typical arid region. It is seen that in addition to the above points water requirements for various crops depend upon: (a) nature of crop, (b) intensity of irrigation, (c) Kharif-Rabi ratio, (d) size of holding.

With regard to the above points, it would be useful to establish research stations and agricultural farms in the particular regions concerned to conduct field experiments, collect information, and render the necessary advice.

Other Improvements

The re-use of water arises only in the case of domestic and industrial needs. As McClellan has suggested, surely all possible ways must be considered for the re-use of water. I may add that after domestic and municipal use the same water, after suitable treatment, can be re-used for purposes of irrigation. This has been tried in some parts of India with good results.

I venture to make another suggestion for supplementing the water resources in arid and semi-arid regions. We should study the feasibility and economics of diverting the supplies from some rivers to basins in the neighboring regions. In India the Rajasthan desert is supplied with water for irrigation and other purposes from neighboring states.

Because water is so scarce in arid regions it would be advisable to collect rain water for domestic use even on house tops. Yet another source is dew. Israel has developed some techniques to take advantage of dew for meeting in part the water requirements of plants. Experiments for producing artificial rain should be pursued in an effort to make it a commercial proposition.

Concluding, I would say that the socio-economic conditions of the agricultural population have to be improved if better use of the limited resources available in the arid regions is to be made. Cooperatives for financial assistance and for proper distribution of land should be set up. The colonization of such areas must simultaneously be taken up with financial assistance from the State. Communication and transport facilities must be provided.

I have a firm belief that proper utilization of present resources in arid and semi-arid lands is one of the more effective solutions to provide food for the increasing population of the world.

PROSPECTS FOR ADDITIONAL WATER SOURCES

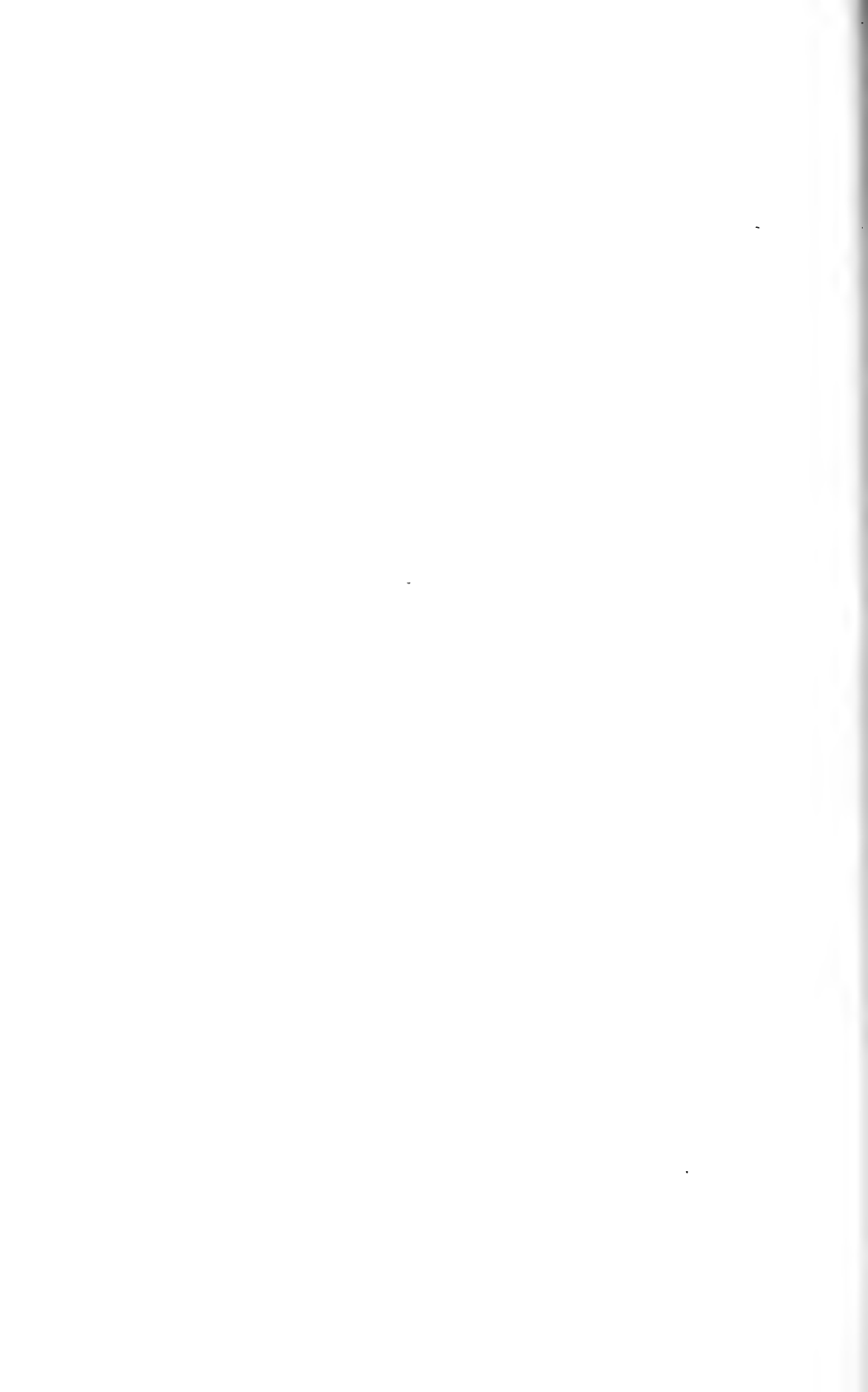
Questions

How practicable is it to demineralize saline water?

How practicable is it to reuse waste waters?

How practicable is it to induce precipitation?

What are the social and economic implications of these programs?



Demineralization of Saline Waters

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It is widely acknowledged that there is a great need for fresh water in many areas of the world. The ability of man to provide food and other bare necessities of life, even on a subsistence level, is dependent in large part on adequate supplies of water. To raise his living standards above the minimum level, man must have water of good quality in relative abundance. From early antiquity, obtaining water has been one of the most pressing problems facing man. Regardless of intellectual, economic, and political progress over the centuries, the problem has not been solved in many areas of the world, and, in fact, has become intensified with population growth.

Even a cursory review of recent attempts to solve water supply problems reveals a widespread consciousness of the needs. In this respect there are no divergent opinions. However, the general agreement on the need for water does not extend to the means of solving the problem.

The conversion of salt or brackish water into usable fresh water has a strong appeal to people in arid regions. In fact, it is being considered as a means to increase supplies in many areas having reasonable amounts of rainfall. The degree of interest and hope of accomplishment are, in general, proportional to local needs and to the shortness of available fresh water supplies.

Unfortunately, there are misconceptions concerning the complexity of the problems involved in saline water conversion. There are unjustified expectations of early success in this field. The non-technical press has been overly optimistic in dramatizing the developments in the conversion of saline water. This optimism

has led many to believe that there will soon be ample quantities of fresh water, produced at a cost comparable to that of natural fresh water supplies. Although this belief is at present unrealistic for the continental United States, the production of usable fresh water from saline sources is neither visionary nor impractical. In some areas of the world, even present day conversion processes can produce fresh water at lower costs than those of natural supplies. There is every indication that demineralization of saline waters, through research and development backed by adequate financial support, and by pooling of knowledge, will help solve the water shortage problem in many arid regions and at a cost commensurate with the resulting benefits.

Current Research Activities

Research in desalting processes by various groups and individuals in this country, scattered and sporadic over the years, is now proceeding at an accelerated rate, largely as a result of coordinating efforts and financial support by the Saline Water Conversion Program of the United States Department of the Interior. In 1952, the Congress of the United States, recognizing the need for new sources of fresh water in arid and semi-arid regions in this country, passed Public Law 448. The purposes of the act are clearly stated:

To provide for the development of practicable low-cost means of producing from sea water, or from other saline waters, water of a quality suitable for agriculture, industrial, municipal, and other beneficial consumptive uses on a scale sufficient to determine the feasibility of the development of such production and distribution on a large-scale basis, for the purpose of conserving and increasing the water resources of the nation.

For those who may not be aware of the specific provisions of Public Law 448, they are summarized here. The Secretary of the Interior is authorized to:

(a) Conduct research and technical development work by means of grants and contracts,

(b) Investigate methods for recovery of and marketing of by-products,

(c) Acquire, by purchase or by other means, technical data, patents and other interests,

(d) Engage, by contract or otherwise, chemists, physicists, engineers and other persons to conduct research and development work,

(e) Cooperate with federal, state and municipal agencies and other organizations in effectuating the purposes of the act,

(f) And, as may be appropriate, to correlate and coordinate the research activities of private organizations engaged in this field.

To carry out these provisions, an expenditure of \$2,000,000 was authorized for a five-year period. An initial appropriation of \$125,000 was made for the year ending June 30, 1953, followed by a supplemental appropriation of \$50,000 for specific use in awarding research contracts. To finance the program for the following year, Congress appropriated \$400,000, one-fifth of the amount authorized in the law for the five years. An equal amount was made available for use during the current year, which ends June 30, 1955.

The Congress designated the Secretary of the Interior to carry out the terms of the act. Because the work and the results relate to several of the bureaus in the Department, it was found that the work could best be administered by a small group known as the Saline Water Conversion Program, within the office of the Secretary, under the Assistant Secretary for Water and Power. To advise the Secretary in broad policy matters, a group was named, consisting of nine qualified persons in various fields related to the program. Provision was made, also, for liaison with other federal agencies having interests in the conversion of saline water. A departmental committee from the Bureau of Mines, Bureau of Reclamation and Geological Survey provides technical and policy assistance.

In carrying out the program, consideration has been given to all known processes for demineralizing saline waters. Support has been given to research groups for investigating various schemes which show promise of economical fresh water production.

This sponsored research has been most fruitful in acquiring fundamental data needed to evaluate the many proposed desalting methods. The five-year plan of research and development being administered in this country by the Saline Water Conversion Program is, as far as possible, being coordinated with similar work elsewhere in the world. In several countries abroad, private and government supported technical groups are engaged in research on saline water conversion methods. Among these are the National Council for Applied Scientific Research (T.N.O.) in The Netherlands, the Admiralty Materials Laboratory in England, and others in France, Sweden, Germany, Switzerland, North Africa, the Middle East, Italy, Australia, Union of South Africa, and elsewhere. Widespread interest in such research has been promoted throughout the world by the United Nations Educational, Scientific, and Cultural Organization and related activities.

In many respects the general program of research in other areas parallels the extensive research now in progress in this country. Much has been accomplished both here and abroad. Regardless of these accomplishments, the financial aid provided has been meager, considering the magnitude of the water needs in arid and semi-arid regions throughout the world.

Status of International Cooperation

The need for cooperative action between nations on matters of saline water conversion is recognized. This is evidenced by the sponsorship by UNESCO and others organizations of meetings, such as the present assembly, for the exchange of ideas and information.

In addition to these sessions, there is currently a fairly active exchange of data by technical press releases, by individual correspondence, and by reporting of research activities in many countries.

An example of realistic cooperative effort was the recent survey trip made by a United States mission, representing the Saline Water Conversion Program, to Europe and Northwest Africa.

The purposes of the visit were: (a) to examine the work underway and that proposed in connection with the Organization for

European Economic Cooperation, cooperative research projects by the three nations, the Netherlands, the United Kingdom, and France for the purpose of ascertaining the extent, if any, to which the United States might participate; and (b) to exchange information on salt water conversion techniques, needs, and economics with those engaged in this field in Europe and northwest Africa.

The report of the mission (3) is highly informative on current research and progress in the areas visited. The observers' findings warrant thoughtful study for guiding saline water conversion activities elsewhere, since they highlight the merits and limitations of many processes. European knowledge and progress in the design and efficiency of certain apparatus may be more advanced than our own along some lines.

Because of divergent viewpoints and approaches to the overall programs, close cooperation and coordination of effort between all research groups in this field should be encouraged and strengthened. This should apply not only to exchange of fundamental data, but should be extended to cross-licensing of patentable devices and through other contractual arrangement in the best interests of all groups. It may be that an international commission or patent committee can be established and directed by UNESCO, or other coordinating agency, to bring about a reasonable and acceptable program for mutual action in this field.

Conversion Processes—Past, Present, and Future

To many people, especially in this country, the idea of conversion of sea water into fresh water is an Aladdin's lamp concept and is of recent origin. This has tremendous popular appeal. This attitude ignores the many complications involved and the high cost of realizing this objective. It is impossible accurately to chronicle the history of man's effort to separate fresh from salt water, but undoubtedly it dates back to antiquity. Credit is given by Hample (2) to Sir Richard Hawkins for the first successfully operated distilling apparatus, as early as 1593. Undoubtedly, unrecorded efforts to secure usable water by miscellaneous means long predated this recorded accomplishment.

Inquisitive search for usable fresh water over the years has resulted in many workable processes for desalting saline waters. Most of the known procedures for desalting have been classified (1) broadly into three major groups according to the type of process used, namely, physical, chemical, and electrical. Within each of these general classifications are many specific methods of water conditioning. These include vaporization, crystallization, sublimation, adsorption, ultrasonics, osmosis, ion exchange, electro-ion migration, and numerous other processes and phenomena.

Of particular interest at the present time is the method of electro-ion migration utilizing membranes which selectively remove cations or anions of the dissolved salts in saline waters. This process has been the subject of much experimentation. New synthetic membranes being developed give hope of increasing the efficiency of this method to a practical range.

Although it was at first thought that distillation had been advanced about as far as possible, that is not true, and much research is now being carried on under the Salt Water Conversion Program on various distillation processes. Those being studied critically are vapor compression stills, vacuum distillation, multiple effect evaporators, critical pressure separation and various combinations of these schemes. As a result of these studies, valuable data have been acquired on potential means for reducing cost. One of the most recent developments in this field is Hickman's modification of conventional vapor compression, which takes advantage of fundamental principles of boiling to increase the rate of evaporation. This modification, although still in the research stage, gives hope of greatly increasing the capacity over conventional evaporators.

Research in these and other methods is revealing the fundamental principles of operation and is pointing out the advantages and disadvantages of many of them from a practical standpoint. The time limitation precludes even superficial discussion here of the merits of these processes. They are mentioned merely to indicate potential avenues for further developments as applicable to specific needs in various areas based on local conditions and available energy sources.

Generalization of any world problem is grossly misleading and unreliable. This is certainly true of the separation of fresh water from saline supplies. The physical, sociological, economic, and political status of peoples and the meteorological and geographical environments in widely separated regions are so varied that there can be no single solution to the problem. These and other factors must be considered before any decision is reached as to the desalting process most suitable in a particular area.

What Cost Saline Water Conversion?

The crux of realistic accomplishment in demineralization of saline water anywhere rests wholly on permissible cost. Everett W. Howe (6) has wisely pointed out, however, that "the cost is never too high when human life itself is at stake." Determination of the cost of desalted water involves a careful survey of the possibilities of selective water use. Comprehensive statistical data are needed for appraisal of the economic practicability of partial or total use of desalted water for miscellaneous regional needs.

The permissible cost of separating fresh water from saline supplies anywhere depends on the urgency of the existing needs, whether they be for irrigation, industrial, municipal, or other uses. Local conditions must govern the acceptable cost of using all types of saline supply. Comparison of treatment cost in different areas is misleading unless allowance is made for local influences. In areas where no fresh water is available, the acceptable cost of demineralization bears little relation to that of areas having relatively abundant natural fresh water supplies.

In semi-arid areas, selection of water supply rests upon the comparative costs of converted water and fresh water imported from remote sources.

In regions where saline water only is available and all fresh water must be obtained by importation or conversion, strict conservation of all fresh water used must be enforced. Scarcity of fresh water promotes greater tolerance of lower quality in water for many uses which in non-arid areas would be considered more demanding. The economics of any particular situation will always

govern the choice between fresh and saline supplies. Untreated or partially desalted saline water must be utilized where and when possible to limit consumption of costly demineralized water, thus minimizing the overall water cost to consumers.

Presently available unit costs of demineralized water from various processes are based upon laboratory research and small-scale pilot plant operations, and should be considered only approximations of ultimate costs. These costs may change considerably in large-scale operations. Research data are invaluable, however, for comparing cost of various desalting processes under specific regional conditions, but may not be broadly applicable except where comparable conditions are known to exist. Acceptable costs for desalted water for military operations in areas wholly devoid of fresh water, or where fresh water is in short supply, would be prohibitive in areas where water from this source is in competition with imported water or where reuse of existing local water is practicable.

Little effort has been made, individually or collectively, to grade quantity and quality of water for man's specific requirements. Intelligent planning and wise use of salt and fresh water would, we believe, produce results fully commensurate with the effort and cost involved.

At the beginning of the Saline Water Conversion Program, the cost of converting sea water to fresh water by the best known process was estimated at \$400 to \$500 per acre-foot. For economic evaluation of demineralization processes, two arbitrary cost goals were set, one for municipal water and one for irrigation water. These goals were \$125 and \$40 per acre-foot, respectively (38 and 12 cents per 1,000 gallons). For these criteria, no distinction is made between sea water and brackish water as the supplies to be converted (5, p. 2).

No process has been developed up to the present time which has met the desired initial cost goals. In fact, all schemes proposed or in actual pilot-plant or full-scale production now show costs in excess of these criteria. However, the results of current research indicate that the goal of producing fresh water at a cost which municipal and industrial consumers can pay seems to be in sight.

For example, it is estimated that simple solar distillation apparatus, located in the southwestern area of the United States, will produce water at a cost of from \$1,600 or \$1,700 per million gallons, or slightly less. It is believed that the design of solar stills can be improved to produce water from saline sources for one dollar per 1,000 gallons, or \$1,000 per million gallons. Costs estimated recently for other desalting methods are \$1.15 per 1,000 gallons for vapor compression and \$1.75 for a six effect flash evaporator.

For many uses, the ultimate cost to the consumer can be reduced by blending the distillate produced with the raw saline supply. For instance, if the raw water contained total dissolved solids of 4,000 parts per million, and if water of 2,000 parts per million were usable for certain requirements, then the cost of delivered water would be cut in half.

The primary demand for fresh water in arid and semi-arid regions is to supply water for domestic use and for irrigation. It is the latter use of water which is of the greatest importance in the adaptation of treatment of saline supplies to make such water suitable for the growth of crops in regions where there is absence, or at least a shortage, of fresh water supply for irrigation.

In many cases there is a lack of realistic evaluation of this phase of the problem. The quality of the water necessary for irrigation varies widely with a number of factors. These include total dissolved solids in the irrigation water and the ratio of various salts contained in the supply. Of great importance, also, is the soil condition in the selection of crops to be grown. In studying this problem, H. E. Hayward, in his many publications, has amassed and published voluminous data on the subject.

In determining the cost of conversion of saline waters to produce water of satisfactory quality for irrigation purposes, one must evaluate all these factors, and the choice of crops grown will be influenced by the degree of treatment required in specific cases. It is important that permissible water quality be evaluated in the light of these limiting conditions.

The research program financed by grants and aids made possible through the provisions of U. S. Public Law 448 is already highly

productive. In the short period of less than three years, assembled data have revealed the merits and estimated cost of demineralized saline supplies and have made it possible to predict ultimate costs of water production by various methods which are being studied.

Constructive research now in progress gives more hope of the possibility of reducing costs to acceptable values than in any previous period.

Application in Arid and Semi-Arid Regions

The role which power or energy plays in demineralization cannot be overemphasized. Davis S. Jenkins, Director, Saline Water Conversion Program, Department of the Interior, has so appropriately remarked, "for processes using an external energy source, the cost of energy alone for converting sea water will be, at the minimum, in the order of \$20 an acre-foot (at 5 mill power). Thus it becomes important that nonconventional energy sources such as solar energy, wind power, and geothermal energy be explored vigorously in connection with process development and use."

There are many arid and semi-arid regions near the sea or other saline water sources where demineralization systems could be developed. Augmentation of fresh water supplies in many of these locations is necessary because of industrial growth. The establishment of industries in areas where existing water supplies are inadequate to meet the civil, agricultural, and industrial needs also depends on an additional source of fresh water. Conditions of this type are found in many places in this country and throughout the world. At such locations, economic salt water conversion offers a form of relief from water shortage difficulties.

The conditions cited are illustrated in a number of rapidly growing industrial communities in this country, such as the Texas City area in Texas, in southern California, and even along the eastern seaboard. In these areas, ample supplies of saline water are available and at some locations within these areas, sources of waste heat could be utilized for desalting purposes.

Such conditions justify careful investigation to determine the cost of producing fresh water for industrial uses for comparison with the cost of importing water from remote sources.

It is obvious that in areas where no industries exist and where there are no local sources of energy, production of fresh water from saline supplies utilizing waste heat is not possible. However, it may be entirely possible to develop industries in some such regions by the installation of small multipurpose plants designed to produce power, steam for industrial purposes, and fresh water as needed for industrial and other uses. For areas lacking conventional fuels, nuclear energy might be utilized as a source of heat for such a combination plant. Although not now attractive cost-wise for demineralization alone in the United States, the development of practical reactors designed for power generation with provision for heat recovery would open many arid regions for selective industries, especially those having low unit water consumption. The recoverable heat from such units could be utilized for saline water conversion in a number of separation processes. Such a multipurpose project offers an intriguing approach to the problem of water supply in many arid and semi-arid areas.

The need for saline water conversion is not limited to coastal areas. Many inland areas which do not have adequate fresh water have saline sources available. Many inland water sources usually considered to be fresh water are in reality fresh only seasonally, and for parts of each year should be classified as saline.

Most tidal rivers are subject to variations in quality on account of penetrations of salt water upstream during periods of low river flow. Many inland streams are intermittently too saline to permit using the water for irrigation, industrial uses, or for human consumption. Ground waters often contain high concentrations of dissolved salts, impairing their use for various purposes. Many of these waters are far less saline than sea water, and therefore can be demineralized more cheaply.

In addition, exchanges of water near coastal points of use with water being diverted there from inland fresh water sources may be feasible in some areas. As set forth in a recent report by the Secretary of the Interior (5), this would result in indirect benefits from saline water conversion to certain regions too far from the sea for economical direct service with converted sea water.

Recommendations

Our measure of the needs for saline water conversion and its permissible cost cannot be reduced to any common denominator. There is much confusion in this respect, since the degree of treatment and imperative needs for specific purposes are seldom fully defined. Before such matters may be intelligently evaluated, there must be critical specifications with respect both to the proven needs of an area and permissible economic balance between capital investment, operational cost, and benefits accruing therefrom.

In a recent address, Thorndike Saville (4) made a statement on the need for a national water policy in this country which in many respects is applicable to other nations. Although proposed for conservation of fresh water, the fundamental principles stated are equally pertinent to the use of saline water. Following are excerpts from his address:

The needs for water, some of them competitive, for all purposes, must be forecast in the light of all available facts. The means to supply these needs must be canvassed; existing and new sources, re-use, treatment of wastes, ground water storage, importation from other drainage areas, etc., . . . planning is essentially a local and regional function and should involve to the highest degree possible the participation of those who are to be benefited (or injured) by the program.

The most reasonable approach and optimistic hope for the future will depend upon some of these basic principles.

The increased efficiency of known desalting processes accomplished through research and development is encouraging, but continued improvement in this respect must follow the laws of diminishing returns, and beyond certain limits no future cost reduction can be expected. As earlier indicated, there are, however, other avenues of exploration which give promise of reducing the cost of desalting processes by taking advantage of potential credits accruing from operating ingenuity. Some of these are:

(a) Use of low grade fuel available in the area or reasonably near the site of the conversion plant.

(b) Combination of processes involving maximum utilization of potential energy sources, including nuclear power.

(c) Utilization of off-peak (dump) power, at reduced rates, especially in areas supplied with hydrogeneration and atomic power.

(d) Drastic conservation of high grade demineralized water by reserving it for preferred selective uses.

(e) Re-use of all available sewage and industrial wastes, with or without treatment.

(f) Grading of water quality for selective uses and maximum use of saline water for all permissible industrial, agricultural, and municipal requirements.

(g) Programming of all desalting projects as multipurpose developments, depending upon the economic justification for such work.

(h) Miscellaneous potential credits, including those resulting from recovery of by-products from concentrated brine, particularly trace elements.

We would not presume to present here any detailed plan, realizing the ramifications of such programming of cooperative activity, but suggest the following action:

(a) Pooling of knowledge through world efforts as has now been intelligently organized and planned by the United Nations Economic and Social Council, UNESCO, the United States Government, and other allied groups. This initial program of proven worth should be extended and amplified.

(b) Continuation and acceleration of the existing United States Saline Water Conversion Program's method of cooperative action between governmental agencies and private industries, and extension of this program or adoption of similar programs in other countries.

Industrial, agricultural, and municipal needs for practical saline water conversion point to an opportunity for private capital in a potentially lucrative enterprise. There is undoubtedly an extensive world market for exploitation, especially in present underdeveloped lands. Up to the present, industries developing and manufacturing equipment have manifested only passive interest in such world markets.

A recently published release by the United Nations Economic

and Social Council, entitled "The Development and Utilization of Water Resources," concisely detailed the world's needs for solution of water problems. The document was prepared by the Secretary General of the United Nations in compliance with the resolution submitted by the Council. Although this report was not specific as to the world saline water conversion needs, many of the recommendations contained therein are applicable to desired cooperative action for solution of the water supply need in arid and semi-arid regions everywhere. The descriptions of world conditions presented in the document and the suggested programming of future action deserve thoughtful study as they relate to the pressing demand for fresh water in areas where only saline supplies are available.

These general recommendations can be carried out only if backed by trained administrative and technical organizations furnished with adequate funds for financing continued research, statistical studies, design development, and allied endeavors.

Voluminous data on saline water separation processes have been acquired from the research sponsored by the Saline Water Conversion Program. Valuable as this program is proving to be, it is merely one step leading to realistic development of practical processes applicable to specific conditions. The knowledge being acquired is pointing out the potential merits of several processes being investigated. Invaluable fundamental and practical information has been, and is being, obtained which should be translated into the design of commercial or semi-commercial installations as rapidly as possible. There still is need for further research in this field, but sufficient knowledge has now been acquired in one or two processes to minimize the financial risk of proceeding to the next step of installing pilot or demonstration plants for further development of these schemes. The need of further action is realized and one process is now under test on a small pilot model in Arizona and South Dakota.

The Saline Water Program should be extended by Congressional action beyond the termination date of July, 1957.

The overall program should also include cooperative action by state grants and other assistance from industry and public

utilities in areas requiring the solution of water shortage problems, either actual or potential.

Summary

To people in areas not penalized by inadequate fresh water, the water shortage difficulties of arid regions may be of casual interest only. The need for solving these problems, however, presents an international task of the greatest importance. The availability of water to support human life in any region has great significance in world affairs. A practical method of making fresh water available to the arid regions of the world would have a beneficial and stabilizing effect on the social, economic, and political life of all nations.

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Demineralization as an Additional Water Source for Arid Lands

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In this paper a general outline will be given of the actual desalting processes and their possible development in the near future. At the end are some references to recent literature, in which technical details may be found.

In arid zones saline water often occurs in the form of: (*a*) sea water at the shore, (*b*) brackish water in salt inland lakes, (*c*) more or less mineralized ground water.

Economically acceptable processes of demineralization may add to the possibilities of solving arid lands problems.

Up to the present demineralization has been practiced in special cases at relatively high costs, particularly by: (*a*) distillation with vapor compression—small units in sea vessels, e.g., submarines, and big installations in some places like Kuwait (2,650 tons per day) Curaçao and Aruba (3,200 and 1,600 tons per day); (*b*) ion exchange—on a rather large scale for water softening in industry (boiler feed water), and only on a small scale for demineralization; (*c*) distillation by solar energy—small units for domestic use.

Coordination of Research

All over the world research is being carried out to improve the economy of different demineralization processes. Coordination and cooperation have developed fast in recent years. In the United States it has been carried out under the Saline Water Conversion Program, Department of the Interior, Washington;

in Europe under the O.E.E.C. (Organization for European Economic Cooperation), Paris, which is part of the Economic and Social Council of the United Nations. OEEC has established a Working Party No. 8 (W.P.8) on "demineralization of salt and brackish waters," in which several European countries (Belgium, Denmark, France, Germany, The Netherlands, Norway, Sweden, United Kingdom) are represented. This cooperates with Australia, the Union of South Africa, and with the United States through the director of the Saline Water Conversion Program (David S. Jenkins) and the Rockefeller Foundation.

Since I am chairman of Working Party No. 8, I shall give an outline of the actual status of that committee's activities.

In 1953 an *ad hoc* group of experts prepared a report for Working Party No. 8 on existing methods and possibilities for further development from a technical and economic standpoint. On the basis of this report W.P.8 recommended further investigations in four directions, namely, distillation with vapor compression, electro dialysis, ion exchange, and solar energy distillation.

Four countries, the United Kingdom, The Netherlands, French Algeria and French Morocco proved to be willing to form a research center for one of these directions, in cooperation with other countries that would be willing to share the costs and profits. Meanwhile some of these proposals have been worked out. The actual situation is as follows.

Status of Current Research

Distillation with Vapor Compression

This needs complicated machinery and skilled labor. Total costs depend largely upon fuel prices and are almost independent of the salinity of the raw water. Hence this process is especially to be recommended for the treatment of sea water and for large units, leading to lower investment per ton of product.

The crucial point is the forming of deposits of calcium and magnesium salts in the apparatus, since periodical descaling causes very expensive maintenance. Incrustation can be prevented by adding special chemicals, affecting the pH, but at the same time corrosion under high temperature must be prevented.

It is also possible to add dispersing agents, modifying the

physical nature of the scale-forming agents, thus rendering them non-adherent to the metal heating surfaces, or to add sequestering agents, maintaining scale-forming solids in solution.

Much research already has been done in this field, especially in England. The United Kingdom has now set up a two-year program for additional investigations under the guidance of the Department for Scientific and Industrial Research, to be carried out at the Admiralty Materials Laboratory.

Other European countries have been invited to share in the costs, the know-how, and other profits. The work will be supervised by a steering group, in which the collaborating countries are represented.

W.P. 8 has quoted the target value for the total cost, including capital investment, for reducing sea water (20,000 ppm Cl') to a salt content of 300 ppm Cl' (by mixing sea water with the distilled water) for a capacity of 10 tons per day at \$1.30 per ton. For a big installation of 1,000 tons per day the cost would be 30 cents per ton. It should be borne in mind that these figures have no absolute value; they give only an idea of the economic level of the process, in comparison with other solutions.

Electrodialysis

This process has been studied especially in the United States (Ionics, Inc., Boston, Mass.) and in the Netherlands (National Council for Applied Scientific Research, T.N.O.).

The process of desalting by direct current, passing through a three-compartment apparatus with 2 membranes, e.g., of cellophane, has been known for a long time. It is, however, hardly applicable to sea water, since a rinsing liquid is needed of similar or lower concentration than that of the fresh water to be obtained.

However, quite recently a new possibility has been opened as a result of the introduction of highly selective membranes, which permits the use as rinsing liquids of salt solutions of a considerably higher concentration than the dialysate. Moreover, great progress has been made by constructional improvement, especially by placing a great number of selective membranes in shunt with extremely narrow compartments (0.5 millimeter).

Some three years ago a T.N.O. apparatus on a semi-technical scale for desalting a water with 1,000 ppm Cl' to a content of 300 ppm Cl demanded 18 killowatt-hours per ton. At the actual moment the energy consumption can be as low as 0.5 kilowatt-hours per ton and even less. The cost of investment in such apparatus is low in comparison with distillation or ion exchange.

Under the auspices of W.P. 8 a certain number of countries have already decided to take part in this project.

In the United States a small electro dialysis apparatus of this kind has been delivered by Ionics to various consumers in order to get practical experience under different circumstances.

In the Netherlands, the National Council for Applied Scientific Research has planned a two-year research program, in which desalting of waters of different composition will be practiced in large-sized units. The principal aims of the investigations will be to find out the optimal dimensions of desalting units for various applications and constructional improvement of the installations.

In 1953 W.P.8 estimated the target value for a daily production of 10 tons of a water of 300 ppm Cl' from brackish water with 1,000 ppm Cl' at a total cost of 30 cents per ton. Up till now no indications have been found that under proper conditions the results will not come up to the expectations.

For a capacity of 1,000 tons per day the expected cost would decrease to 8 cents per ton. The cost level largely depends upon the price and the durability of the membranes and the price of electric current. This may explain the great differences in the figures, given above, from those published in the 1953 Report on Saline Water Conversion as a result of the work of Ionics, Inc. According to Ionics the total cost of desalting from 1,000-300 ppm Cl' for a capacity of 1,000 tons per day would only be 1 cent per ton.

It should, however, be acknowledged that desalting problems mostly occur in regions with relatively expensive electric power.

The Ion-Exchange Process

This demands high expenditure for chemicals for regeneration. The amount of chemicals needed is almost proportional to the

amount of salt to be removed, so that the application is practically restricted to brackish water.

It may be possible to decrease the production cost by improving the regeneration process. To this end ion exchange can be practiced in stages, several resin beds being used in succession, accompanied by counterflow regeneration. Electric current can also be applied in regeneration to save chemicals.

Much research has already been done in Algeria, since this method of demineralization is especially adapted to a country where skilled labor is scarce and power comparatively costly. France has set up a project for further research in Algeria and is willing to cooperate with other interested countries under the auspices of W.P.8.

The experts group of W.P. 8 have estimated the total cost of desalting in the range from 1,000-300 ppm Cl' at \$1.60 per ton for a capacity of 10 tons per day.

Solar Energy

In the same way the French protectorate of Morocco intends to do more research in the field of distillation with solar energy, a process that must be restricted to small quantities in view of the large installations required. It is cheap in operation, as it does not require any fuel or electric energy, nor any chemicals.

Factors Affecting Application

In view of possible applications in the further development of arid regions, we must distinguish between: (a) water for human consumption, (b) water for animal husbandry, (c) water for agricultural purposes. Other factors are the availability of electric current and skilled labor.

Human consumption asks for water of high quality (300-500 ppm Cl') in relatively small quantities, whereas production cost can be rather high.

For *cattle breeding* the salt content may be 500-1000 ppm Cl'.

For *agricultural purposes* large quantities of medium quality (750-1,000 ppm Cl') must be available at a low price.

It would seem that in the near future demineralization of brackish ground water in arid zones will become a practicable

solution for human consumption. For very small quantities, distillation with solar energy may be recommended. For larger quantities electro dialysis may prove to be the best process, and for desalting of sea water both distillation with vapor compression and electro dialysis may be successful. Ion exchange will also be practicable for brackish ground water in smaller quantities.

For desalting highly mineralized ground waters (5,000 ppm Cl⁻ or its equivalent), as occur in many parts of the world, e.g., Algeria, Morocco, Australia, and South Africa, electro dialysis may prove to be the unchallenged best solution, at least for application to animal husbandry.

The present status of technical development does not yet permit applying demineralization to the large quantities of water needed for irrigation. However, in a more remote future the results of the research which is now going on in so many places and, perhaps, the availability of cheaper energy resources may lead to more favorable conditions.

Consideration should therefore be given to means and ways to foster further investigations in this field, if possible on an international basis. I therefore propose as a basis for discussion that a lasting contact should be established between the UNESCO Advisory Committee on Arid Zone Research, the United States Saline Water Conversion Program, and Working Party 8 of O.E.E.C. in order to promote worldwide coordination.

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The Salinity Factor in the Reuse of Waste Waters

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In the arid zones of the seventeen western states and other arid regions throughout the world, it is generally recognized that the total area of irrigable land far exceeds the acreage that may be served with available supplies of irrigation water. For example, the 1950 Census of Agriculture reports over 24,000,000 acres of irrigated land in the seventeen western states, and the future program for irrigation agriculture calls for the use of as much as 30,000,000 acres of land. An even higher estimate of 51,500,000 acres of irrigable land in the seventeen western states was made by the National Resources Board in 1936.

Paulsen has stated (2) that the "total average annual water supply in the 17 Western States is about 390 million acre-feet as compared to the present withdrawal use of about 100 million acre-feet. Except for irrigation, only a small part of the water withdrawn for use is consumed, estimated by some to be as little as 10 per cent." This statement suggests a very favorable situation, but the distribution of water supplies is such that some areas have surplus water at all times whereas other areas seldom have sufficient water. In the Southwest, the average annual runoff is less than one-fourth inch, and no streams flow out of the Great Basin. This indicates the importance of planning for irrigation agriculture so that there may be a more effective use of all available water resources. Such a program involves, among other

measures, the reuse of drainage and return flow water from irrigated land and the use of sewage effluent and industrial wastes whenever possible.

Bowen and Powell have discussed two major possibilities of additional water supplies: the induction of precipitation, and the demineralization of saline waters. I wish to direct my attention to one aspect of the third question proposed as a subject for discussion at this technical session: "How practicable it is to reuse waste waters?" This is the salinity factor in the reuse of waste waters. Three points will be considered: (1) the characteristics which determine the quality of water for irrigation use; (2) the characteristics of return flow water and drainage as they relate to the quality of water for agricultural use; and (3) the conditions under which saline waters may be used to augment the water supplies essential to the maintenance and extension of irrigation agriculture in arid lands.

Quality of Irrigation Water

Although the quantity of available water is the primary consideration in the development of irrigation agriculture, quality of water becomes a more and more critical factor as the supplies of surface and ground waters are depleted. Four characteristics determine quality of water for irrigation use: (1) the total concentration of soluble salts, (2) the concentration of sodium and the proportion of sodium to calcium plus magnesium, (3) the concentration of bicarbonate, and (4) the occurrence of microelements such as boron in toxic amounts.

In many cases, the total concentration of soluble salts is the best single index for evaluating the quality of irrigation water. The salt content of most irrigation waters ranges from 0.1 to 5 tons of salt per acre-foot of water (approximately 70 to 3500 ppm). The amount of salts in river waters in western United States varies from as low as 70 ppm in the Columbia River at Wenatchee, Washington, to 740 ppm in the Colorado River at Yuma, Arizona, 1,574 ppm in the Sevier River at Delta, Utah, and 2,380 ppm in the Pecos River at Carlsbad, New Mexico. The salt concentration in river waters may vary materially, depending upon the sampling site, and this factor is important in relation

to return flow downstream. Thus, the Rio Grande has a range in salt concentration from approximately 180 ppm to 1,775 ppm at different points on the river.

Ground waters from pumped wells constitute the principal source of irrigation supplies in many areas, and the range in salt concentration may be much greater than for surface waters. For example, analyses of a large number of wells in the Coachella Valley, California, indicated a range in soluble salts varying from 130 ppm to 8,500 ppm. In addition, wells in close proximity to each other may have very different salt concentrations. Two wells in this valley within a half mile of each other have salt concentrations of approximately 400 and 8,500 ppm, the former well being 65 feet deep, the latter 180 feet.

The principal ions found in natural waters are the cations calcium, magnesium, and sodium, and the anions bicarbonate, sulfate, and chloride. Potassium, nitrate, fluoride, boron, and other constituents may be present in low concentrations. Sulfate and chloride salts usually predominate, but occasionally waters may be high in bicarbonates and less frequently in nitrates.

The sodium factor in irrigation water is related to the alkali hazard and is determined by the absolute and relative concentration of the cations. If the proportion of sodium is high, the alkali hazard is high and, if calcium and magnesium predominate, the hazard is low. The soluble cations in the irrigation water have a pronounced influence on the distribution of the exchangeable cations in the soil, and it is for that reason, in part, that the sodium content in irrigation water is important. If sodium constitutes less than one-half of the cations in the irrigation water, there is ordinarily very little danger of unfavorable sodium soil conditions developing from the use of the water but, as the proportion of sodium increases, the hazard increases.

In some instances, waters may be low in total salts but high in bicarbonate. This condition tends to aggravate the sodium problem in soil where the amount of bicarbonate is considerably in excess of the calcium plus magnesium. In such a case, residual sodium carbonate is present and, as the irrigation water evaporates from the soil, calcium and magnesium carbonates precipitate, and the sodium percentage of the soil solution increases. This is

followed by the replacement of calcium by sodium on the soil particles, the exchangeable sodium percentage of the soil increases, and the physical condition and permeability of the soil are likely to be impaired. In addition, the hydrogen ion concentration of the soil may decrease and organic matter may be dissolved, resulting in the dark color which is characteristic of a so-called black alkali soil.

The Salinity Laboratory has proposed a scheme of classification in which waters are divided into four classes based on salt concentration and into four other classes with reference to the probable extent to which soil will adsorb sodium from the water and the length of time required to affect the soil adversely. These are designated as the salinity hazard and the sodium hazard. The salinity hazard is measured in terms of electrical conductivity expressed in micromhos per centimeter at 25°C. Class 1 water ranges up to 250 micromhos per centimeter; Class 2, from 250 to 750; Class 3, from 750 to 2,250; and Class 4, in excess of 2,250.

The relative proportion of sodium to other cations in an irrigation water has usually been expressed in terms of soluble sodium percentage, but it appears that the sodium adsorption ratio which is simply related to the adsorption of sodium by soil, has some advantage for use as an index of the sodium or alkali hazard of water. This ratio is defined by the equation

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{(\text{Ca}^{++} + \text{Mg}^{++})/2}}$$

where sodium, calcium, and magnesium represent the concentrations of these ions in milliequivalents per liter. The sodium hazard is largely determined by the proportion of sodium to calcium plus magnesium present, together with the total salt content as indicated by electrical conductivity. Thus, the curves are given a negative slope to take into account the relation of the sodium hazard to total concentration. For example, a water with an SAR value of 9 and a conductivity of less than 168 would be an S1 water, from 168 to 2,250, an S2 water, and greater than 2,250, an S3 water. This system is somewhat arbitrary and tentative, but field and laboratory observations appear to support it.

TABLE 1
Permissible Limits of Boron for Several Classes of Irrigation Waters (5)

Boron Class	Sensitive Crops (ppm)	Semitolerant Crops (ppm)	Tolerant Crops (ppm)
Excellent	<0.33	<0.67	<1.00
Good	0.33 to 0.67	0.67 to 1.33	1.00 to 2.00
Permissible	0.67 to 1.00	1.33 to 2.00	2.00 to 3.00
Doubtful	1.00 to 1.25	2.00 to 2.50	3.00 to 3.75
Unsuitable	>1.25	>2.50	>3.75

Boron is a minor constituent of practically all natural waters, and irrigation waters should be analyzed for this element if there is any reason to suspect its presence at toxic levels. Although boron is an essential microelement for plant growth, it may be toxic at concentrations only slightly in excess of those needed for optimum growth. Toxicity may develop with boron-sensitive crops when the concentration is as low as 1 ppm but, for most crops, water containing 1 to 2 ppm is satisfactory, and waters up to 3 ppm may be used with the more boron-tolerant crops. Water containing in excess of that amount of boron is, in most cases, unsuitable for irrigation purposes. The permissible limits of boron for several classes of irrigation waters considered on the basis of the relative sensitivity of the crop to boron are given in Table 1.

Characteristics of Return-Flow Water

The pollution of streams by irrigation residues and the characteristics of return-flow water have been discussed by Scofield (3), Howard (1) Wilcox (6), and others.

In some cases, the water available for irrigation is unfit for irrigation use in its natural state, owing to unsatisfactory quality, but there are other instances where the quality of the irrigation supplies has been impaired by drainage and return flow downstream. The major effects of use and reuse of irrigation waters as related to quality are (1) an increase in the total amount of dissolved solids, (2) the loss of calcium, magnesium, bicarbonate, and sulfate by precipitation, and (3) an increase in the quantity and proportion of sodium and chloride in the water.

TABLE 2
 Discharge and Salt Burden for Seven Stations on the Rio Grande above Fort
 Quitman, Texas
 (Annual means and total for the year 1949^a)

1 Station	2 Miles	3 Total Concentration		5 Discharge (acre-feet)	6 Dissolved Solids (tons)
		Dis- solved Solids ppm	Conduc- tivity, (micro- mhos per cm)		
Otowi Bridge, N. M.	0	206	320	1,323,000	370,440
San Marcial, N. M.	184	353	520	1,054,000	505,920
Elephant Butte, N. M.	240	404	610	813,500	447,425
Caballo Dam, N. M.	268	441	670	712,165	427,299
Leasburg Dam, N. M.	318	489	730	689,143	458,280
El Paso, Tex.	375	750	1160	463,540	472,811
Fort Quitman, Tex.	456	2631	4030	134,030	479,827

^a These data are assembled from records of the U. S. Geological Survey, the U. S. and Mexico International Boundary Commission, the U. S. Bureau of Reclamation, and the U. S. Salinity Laboratory.

Data for the Rio Grande illustrate these effects. Table 2 gives the discharge, salt burden, and total concentration of salts for seven stations on the Rio Grande above Fort Quitman, Texas. These data are for a representative year and illustrate the effect of return flow on the quality of irrigation water.

The distance from the Otowi Bridge, New Mexico, to Fort Quitman, Texas, is approximately 450 miles, and in this stretch of the river there are many diversions to irrigated lands. The four major irrigated areas are the Middle Rio Grande Project between Otowi and San Marcial, the Rincon and Mesilla Valleys between Caballo Dam and Courchesne, and the irrigated areas in Texas west of Fort Quitman which include the irrigation in El Paso County and that in the Hudspeth District.

Middle Rio Grande Valley Project	67,000 acres
Rincon and Mesilla Valleys	85,000 acres
El Paso County	57,000 acres
Hudspeth District	12,000 acres
Total	221,000 acres

These values are estimates and, in past years, there have been wide fluctuations in the amount of irrigated acreage owing primarily to variations in available water supplies. For example, in El Paso County, the irrigation acreage reached a peak of over 67,000 acres in 1950 and dropped back to slightly less than 57,000 acres in 1954.

The first point to consider is the salt burden of the river, which is expressed as dissolved solids in tons (column 6). These data indicate that the salt burden from Otowi Bridge to San Marcial increases significantly, but, from the reservoir area at Elephant Butte to Fort Quitman, Texas, it is very uniform, the differences probably being within the limits of measurable error. On the other hand, the discharge figures (column 5) indicate that there is a marked decrease in stream flow until essentially all the water has been used below El Paso. This decrease in flow is the result of diversions to the irrigated lands along the river above Fort Quitman. The effect on quality of water of a nearly constant salt burden and a decrease in stream flow is reflected in columns 3 and 4 which show the total concentration of dissolved solids in parts per million and as conductivity expressed in micromhos per centimeter. There has been an approximate sixfold decrease in discharge from Elephant Butte to Fort Quitman and slightly in excess of a sixfold increase in total concentration of salts over the same stretch of the river. Thus, flow decreases and the concentration of salt increases, while the salt burden is virtually constant. This indicates that the tonnage of salt which is carried back to the stream in the return-flow drainage is approximately equal to the amount of salt diverted from the river in the irrigation water. If this were not the case, the tonnage of dissolved solids would probably decrease in a downstream order.

Although the total dissolved solids do not change materially from Elephant Butte to Fort Quitman, there is a marked increase in the content of sodium and chloride present (Table 3). These data illustrate the effect of use and reuse of water on composition. The tonnage of sodium has increased threefold and the sodium concentration, over 30 times; chloride tonnage has increased twelvefold and concentration, 117 times. On the other hand, there

TABLE 3

Sodium and Chloride for Seven Stations on the Rio Grande above Fort Quitman, Texas
(Annual means and totals for the year 1949^a)

Station	Sodium			Chloride		
	ppm	meq/l	tons	ppm	meq/l	tons
Otowo Bridge, New Mex.	19	0.84	34,761	7	0.21	13,396
San Marcial, New Mex.	45	1.95	65,288	24	.69	35,066
Elephant Butte, New Mex.	55	2.40	61,070	31	.87	34,125
Caballo Dam, New Mex.	62	2.71	60,368	44	1.24	42,579
Leasburg Dam, New Mex.	73	3.16	68,117	52	1.47	48,845
El Paso, Texas	147	6.41	92,940	125	3.52	78,672
Fort Quitman, Texas	601	26.15	109,546	874	24.65	159,298

^a From same sources as Table 2.

has been a large reduction in the amounts of sulfates and bicarbonates.

On the basis of the data for discharge, salt burden, salt concentration, and composition of Rio Grande waters, it is clear that the quality of irrigation water downstream may be affected adversely where there are diversions for irrigation that deplete the flow. The data also indicate the importance of an accurate knowledge of the quality of water if it is to be used for irrigation.

Use of Saline Waters for Irrigation

With accurate data on quality at hand, the next consideration is: can waters of low quality be used without inducing undesirable effects on the properties of the soil to which they are applied and the crops which are to be grown?

If waters of high salinity are used for irrigation without proper management or adequate drainage, the salts accumulate in the root zone and the concentration of the soil solution increases. As the salt concentration or osmotic pressure is built up, there is a decrease in the ability of the plant roots to absorb water in adequate quantities. Experimental work has shown that retardation of plant growth is virtually linear with an increase in osmotic pressure of the soil solution and, in most cases, it is largely independent of the kinds of salt present. When the osmotic pressure of the substrate has increased sufficiently, the entry of water into roots will cease, and most crop plants will die.

When the irrigation water applied is high in sodium and the soil becomes partially saturated with sodium, the clay particles are highly dispersed and may move downward through the soil to lower levels. This results in an unfavorable soil structure in which the first few inches of the soil profile may be relatively coarse textured, but lower in the profile where the clay has accumulated, there is a dense layer that is frequently very low in permeability. When such soils are wet, they tend to "run" together; when dry, they form hard clods, with large cracks on the surface.

In addition to the adverse effects of saline and high-sodium waters on soil characteristics, and the reduction in the intake of water by plant roots where the substrate becomes excessively saline, some salts are toxic to crop plants when they occur in soils in excess amounts. The ions which are most likely to cause toxic reactions are chloride, sodium, bicarbonate, and sulfate. Among the microelements, excess boron most frequently produces symptoms of injury.

Since undesirable soil conditions develop and unfavorable crop responses are likely to occur when the quality of irrigation water is unsatisfactory, the question arises: under what conditions and to what extent can saline waters be used to supplement available supplies in areas where water shortage is a major problem? Time does not permit me to discuss in detail the major aspects of this question, but the following lines of approach to the solution of the problem are suggested for consideration. First, selection of suitable land for irrigation; second, use of proper water-management practices; and third, selection of salt-tolerant crops which are adapted to local climatic conditions.

Information regarding the salinity and sodium status of the soil, its hydraulic conductivity or water-transmission properties, the texture of soil and character of substrata, water-table conditions, drainability, and the topography of the area is necessary in considering the possibilities of using water of poor quality. Preleaching is required if the soil is saline, and leaching plus amendments may be indicated if the soil is saline-alkali and non-gypsiferous. Drainage is essential to remove excess salts, to

prevent the accumulation of salts by irrigation, and to prevent the occurrence of high water-table conditions.

With respect to water management, irrigation should be controlled in such a way that a favorable salt balance will be maintained. This occurs when the output of salts for a given area exceeds the input (4). Enough water, in excess of the consumptive use or evapo-transpiration requirements, should be applied to remove from the irrigated area approximately as much salt as is transported onto the land by the irrigation water. Since plants absorb water from the soil solution but take in only a small proportion of the dissolved constituents, there will be a gradual increase in the salinity of the soil unless the amount of water applied to the land is sufficiently in excess of the plant requirements and the losses of water by surface evaporation so that salts in solution are carried out of the root zone and into the under-drainage.

Successful water management involves two operations which are opposed to one another. In the first instance, sufficient water must be applied to insure the movement of salts through the profile so as to prevent an accumulation of salts and maintain a favorable salt balance. On the other hand, excessive use of water must be avoided in order to prevent the development of high water-table conditions and the consequent drainage problems.

A second consideration in water management is the possibility of using "blending" methods in cases where some of the water supplies are too saline, but other supplies of good quality are available. If soil properties and drainage conditions are satisfactory, waters of high salinity may be used by "blending," or mixing, waters of poor and good quality in such proportions that the salinity of the water applied to the land has been reduced to reasonably satisfactory limits.

The selection of appropriate crops may serve to ameliorate a situation where the use of saline water has resulted in saline conditions. Field and plot tests at the Salinity Laboratory and elsewhere have demonstrated that there is a wide difference in the relative salt tolerance of the crops grown in the western states. For example, the chances for satisfactory yields of field crops

grown under saline conditions will be greater if crops such as sugar beets or cotton having high salt tolerance are planted rather than field beans, which have a very low salt tolerance. Likewise with forage crops, better results may be expected if some of the salt-tolerant grasses are grown instead of salt-sensitive clovers such as Alsike, red, and Ladino varieties. With vegetable crops, garden beets, asparagus, and spinach will be more successful than green beans or celery. In selecting salt-tolerant crops for a given area, it is important to understand that climatic factors may profoundly influence the response of plants to salinity. For this reason, the choice of suitable salt-tolerant varieties will depend upon local climatic conditions.

Summary

The quality of water supplies becomes a more and more critical factor with the increasing need for additional water for irrigation in semi-arid and arid areas. The major characteristics which determine water quality are: total concentration of soluble salts, concentration of sodium, concentration of bicarbonate, and the occurrence of minor elements such as boron in toxic amounts. The reuse of waters returning to the stream after diversion for irrigation commonly results in a significant increase in total salinity. In some cases, increased concentrations of sodium, chloride, and other elements may affect soil characteristics adversely or may be directly injurious to plant growth. For these reasons, it is important to determine the characteristics of all questionable waters. With this information at hand, the possible solution of the use of such waters depends upon the use of appropriate soil- and water-management practices and the selection of salt-tolerant crops.

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Induced Precipitation

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It is assumed that the reader is familiar with the processes of inducing rain to fall from clouds by introducing materials like dry ice, water, or silver iodide into the clouds at an appropriate stage in their development. No attempt will be made to review the previous history in this field, but an account will be given of two new developments which may have an important bearing on the future of weather control. The first of these deals with some new discoveries in relation to silver iodide seeding, the second with an unexpected contribution from a field of science normally thought to be outside the bounds of cloud physics.

Silver Iodide Seeding

A vast number of seeding operations have been carried out in the past few years in which silver iodide has been dispensed into the atmosphere from smoke generators on the ground. It is safe to say that the net result of these operations has been to produce more controversy than they have rainfall, despite the fact that in the laboratory, silver iodide is unquestionably a highly efficient freezing nucleus.

Looked at from a physical point of view, and quite apart from the question of whether there has been any effect on rainfall, two obvious points require checking: (*a*) whether the silver iodide remains effective as a freezing nucleus when exposed to the atmosphere; and (*b*) whether it can attain the requisite height, which in summer might be of the order of 15,000 or 20,000 feet.

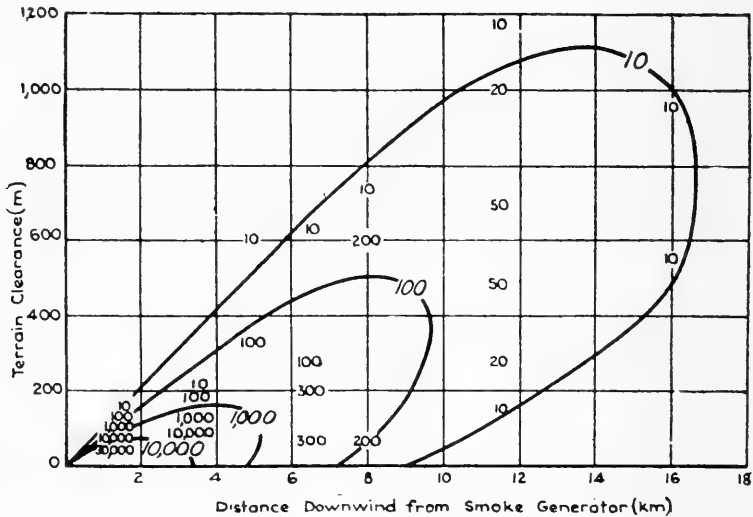


Figure 1. The concentration of active freezing nuclei downwind from a silver iodide ground generator.

Until recently these points had never been investigated and it was therefore decided to study them experimentally. Tests have now been carried out in Australia by Smith and Heffernan (2) and by Smith, Heffernan and Seely (3) with the following results. When a silver iodide generator emitting 10^{16} nuclei per hour is run in flat terrain under typical convective conditions, the distribution of effective nuclei downwind from the generator is as shown in Figure 1. It is seen that the freezing nucleus concentration drops to a low level at a distance of 10 to 12 miles downwind and that appreciable concentrations do not extend above heights of 2,000 or 3,000 feet. The rapid decrease in concentration cannot be accounted for simply by diffusion of the freezing nuclei and calculation shows that they must be subject to a rapid decay in activity. Figure 2 gives the decay rate for two typical burners, showing in one case a decay of 10^4 times in 30 minutes.

Bolton and Qureshi (1) conducted a separate investigation to arrive at the physical reasons for this decay and found that the most important single factor controlling the decay rate is the ambient temperature of the atmosphere. The rate of decay is in

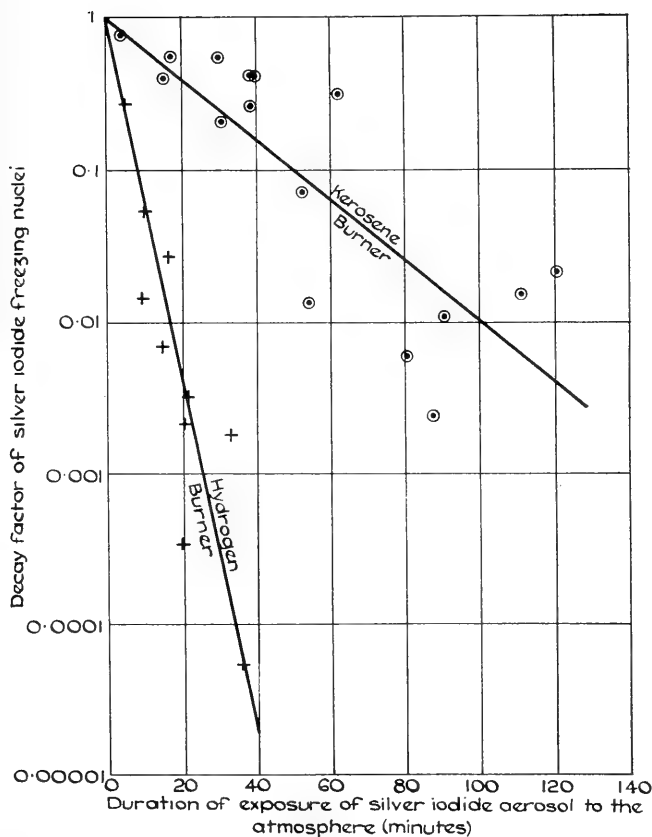


Figure 2. The decay in activity of silver iodide particles from a hydrogen burner and a kerosene burner respectively.

fact a very steep function of air temperature as shown in Figure 3. While the silver iodide might decay by a factor of 10 in a few minutes at ambient temperatures between 20° and 30° C, the decay is only a factor of 10 in several days at a temperature of -15° C.

This result explains the failure of many ground seeding operations which have been carried out at relatively high temperatures on flat terrain. What is more important, it suggests the methods by which silver iodide might be successfully used for producing effects over wide areas.

Conclusions

The results above suggest immediately several experiments in silver iodide seeding which might be of outstanding importance in the whole problem of weather modification.

1. Silver iodide seeding from aircraft operating at moderate or at high altitudes. Under these conditions the decay rate of the silver iodide might be low and the material is already at approximately the height where it can become effective in clouds.

2. A seeding experiment in which silver iodide is dispensed from a high mountain peak where the ambient temperature is near or below 0°C .

The results also bring out the importance, in any experiments of this kind, of independent measurements being made to verify:

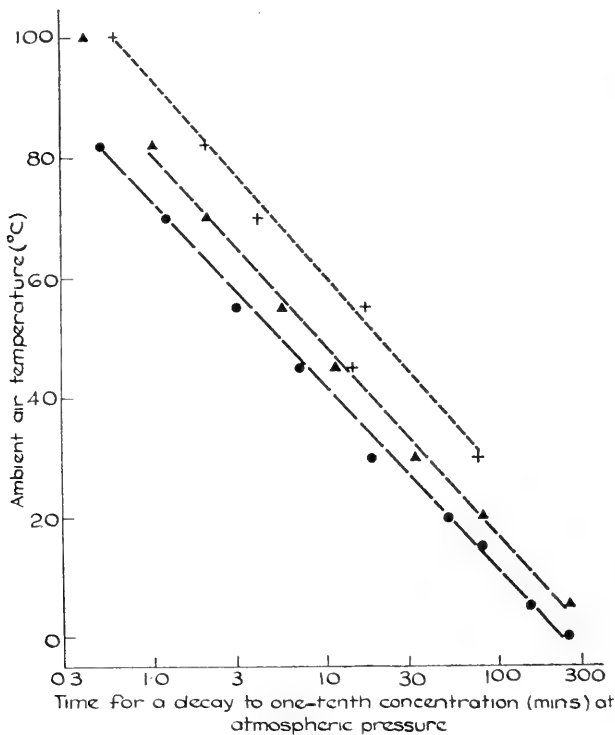


Figure 3. The decay in activity of silver iodide particles as a function of air temperature.

(a) that the silver iodide is being emitted in an active form; (b) that it diffuses in such a way as to enter appropriate cloud systems; (c) that it does not suffer a high decay rate on exposure to the atmosphere.

Influence of Meteoric Dust on Rainfall

During the latter part of 1954 and early 1955 some new results were obtained from an unexpected direction which may have a crucial bearing on the whole problem of artificial stimulation of rainfall.

It has become almost an axiom of meteorology that if in any given month the values of a meteorological quantity are totaled for an adequate number of years and over an adequate area, they

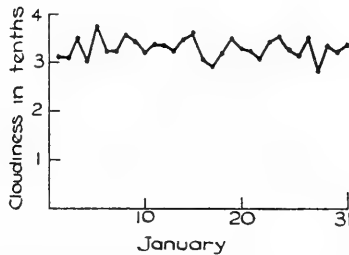


Figure 4. The cloudiness measured at 9 A.M. in Sydney for each day in January over the period 1900-53.

will average out and give a mean which (apart from seasonal trends) does not vary substantially from one day to the next. A good example of this is the cloudiness of Sydney for the period 1900-53 for each day in January which is shown in Figure 4. This has a mean value of 0.33 with variations about this value of not more than a few per cent.

If the daily rainfall of Sydney for the month of January and the first few days of February is plotted in the same way, the day-to-day variations are very much greater and in some cases show departures of 2 to 1 on one day as compared with another. In Figure 5 is given the daily rainfall totals for Sydney for the period 1859-1952, showing distinct maxima on January 13, 22, and February 1.

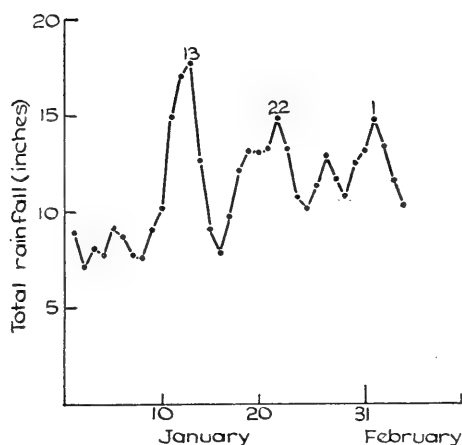


Figure 5. The total rainfall of Sydney for each day in January over the period 1859-1952.

One's first reaction is that these variations are due to statistical fluctuations. If they arise from purely random causes they would normally smooth out as records of more and more rain gages are totaled. As a next step Figure 6 shows the January rainfall for 20 stations in the state of New South Wales, all more than 100 miles from Sydney. The peaks are still present and, furthermore, they occur on precisely the same dates as those in the Sydney record. It begins to appear, therefore, that this is a real phenomenon and the rainfall in this area and for this particular period

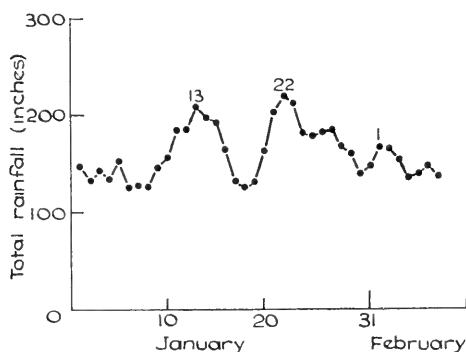


Figure 6. The January rainfall of twenty stations in New South Wales for the period 1890-1946.

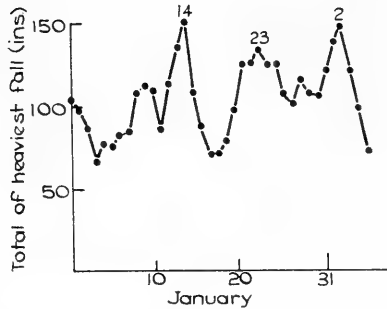


Figure 7. The January rainfall of fifty stations in New Zealand for the period 1900-52.

was considerably greater on January 13 and 22 and February 1 than on other days in January.

Turning now to an adjacent geographical region, namely New Zealand, which is some 1200 miles away, the results of 50 stations for the period 1900-52 are given in Figure 7. Again there are peaks in the rainfall which happen in each case to be one day later than those in New South Wales.

Turning to the northern hemisphere, Figure 8 shows bulk rainfall records, again for the month of January, for four widely separated regions in the northern hemisphere, namely Great Britain, The United States, Japan, and the Netherlands. These, too, show characteristics almost identical with those in the southern hemisphere.

It appears therefore that there must be some worldwide influence on rainfall which leads to more rain than usual occurring all over the world on particular calendar dates.

If, in fact, these variations in rainfall are a worldwide phenomenon, they cannot have their origin in moving weather systems as normally conceived of. They must be due to an effect which can act simultaneously over the whole globe, namely an extraterrestrial influence. In addition, it must be an influence which is tied to particular calendar dates. The only extraterrestrial phenomena known to the author which satisfy these requirements are meteor showers, the majority of which recur each year on the same dates. The meteor particles exist in vast elliptical orbits around the sun,

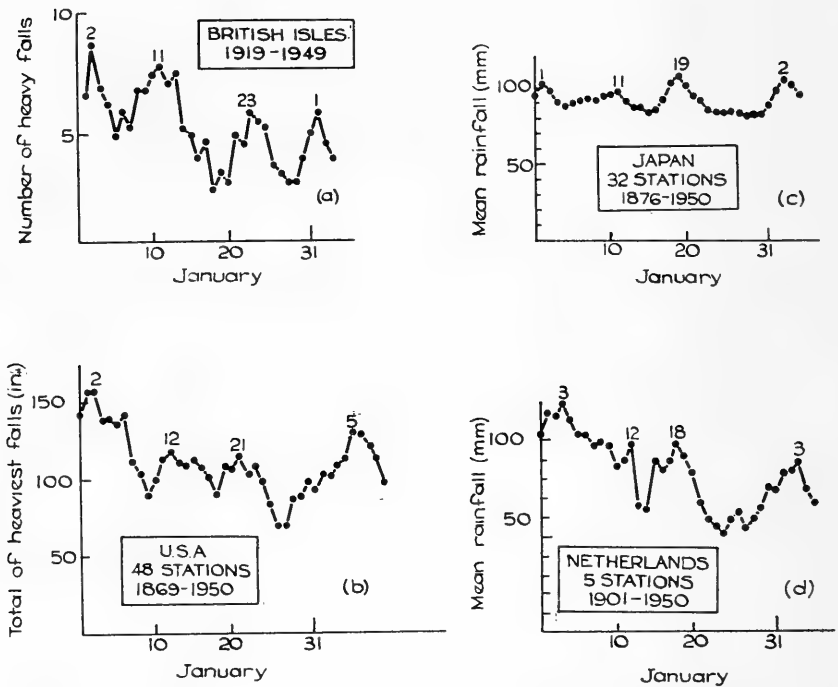


Figure 8. The total rainfall for four regions in the northern hemisphere.

and the earth passes through these streams year after year as it revolves in its own orbit.

There is only one prominent meteor shower during the month of January, namely the Quadrantids on January 3. Going back into December, however, there are the Ursids on December 22 and the Geminids on December 13. It will be seen at once that these occur almost exactly 30 days before the world peaks in rainfall which have already been discussed. The hypothesis has been advanced, therefore, that the phenomenon is due to the effects of meteoric dust falling into cloud systems in the lower atmosphere, the time difference of 30 days being accounted for by the rate of fall of the dust through the atmosphere.

If this hypothesis is substantiated it might have the most profound effect on our concepts of artificial control of the weather.

It implies that the fundamental rainmaking process in the atmosphere is a seeding process and that the atmosphere is much more free from rain-forming nuclei than has previously been supposed.

Conclusion

These results suggest that the arrival of dust in the upper atmosphere and its descent to the ground might turn out to be one of the most important factors controlling rain formation. It focuses attention on several broad fields of study which would be important in this regard:

1. The study of meteors in all their aspects, particularly the neglected field of meteoric dust.
2. The physics of dust falling through the atmosphere.
3. The properties and distribution of freezing nuclei in the lower atmosphere.

From the point of view of artificial weather modification, it suggests: (*a*) that the effects might be very much greater than was otherwise supposed; (*b*) that the most effective seeding operations might be those which are designed to influence the weather on a continent or hemisphere wide basis, rather than operations intended to cover a few square miles of territory only.

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Some Relationships of Experimental Meteorology to Arid Land Water Sources

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Since the fall and early winter of 1946, when our first cloud seeding experiments were brought to a successful conclusion, many things have happened to clarify as well as confuse the picture of the present state of experimental meteorology. With about eight and a half years of experience behind us, what conclusion can be drawn in relation to successes or failures?

As in any other new science, advance has been rapid as well as slow. Startling new discoveries have occasionally emerged from the less spectacular plodding advance as new facts in atmospheric physics have become established.

Variation in Concentration of Ice Nuclei

With the 1946 demonstrations that extensive cloud systems not only exist for considerable periods as supercooled clouds (1) but may also be profoundly and rapidly modified by relatively small amounts of dry ice fragments (23), the question arose as to how variable the concentration of ice nuclei was in the natural atmosphere. To gather statistical data in this regard three hourly observations of the concentration of ice nuclei were inaugurated at the Mt. Washington Observatory. These studies have been continued from January 1, 1948 to date. The more than 18,000 observations show that natural ice nuclei concentration may vary

by a factor of a million (25); there are periods of a half day to several days when values are relatively high, but there are other days when the concentrations are very low. During the six and a half years of record, a trend is noticeable toward higher concentrations of moderate counts (5×10^2 to 1×10^4 per cubic meter) with lower levels of both high and low counts. It is not easy to determine whether this trend is caused by increased cloud seeding activities or, what is more likely, an increase in area of the drought stricken regions of the Southwest United States. Air trajectory studies have shown a high correlation between the high counts at Mt. Washington and dust storms and related air movements from the Southwest.

Importance of Ice Nuclei in Controlling Precipitation

In some of the early flight studies of Project Cirrus, particularly during February 1948 when a series of exploratory flights were conducted over and near Puerto Rico, we were able to determine conclusively that ice crystals were not unique in causing heavy precipitation (24). Subsequent studies by Langmuir (13), Woodcock (32), Bowen (5), Mordy (20), d'Albe (1), and others have demonstrated that quite often in the subtropical regions of the world the precipitation cycle may be controlled, if not completely dominated by the presence or absence of large salt nuclei. The presence of the "trade wind inversion," which normally limits the vertical development of clouds to levels which never cool below 0°C ., together with the relatively long life cycles of individual cloud elements, is conducive to the development of this "warm cloud" rain. In almost all cases, however, there are exceptions to the rule. Large cumulus clouds break through the inversion or develop when the inversion is absent, reach high altitudes, and produce excessive rain.

Thus, although it is likely that a certain concentration of large salt nuclei may initiate the precipitation cycle even in such large supercooled clouds, there is no reason to believe that the precipitation pattern will be dominated by the salt particle effect if optimum concentrations of ice nuclei are present. Much further research remains to be done in separating these two distinctly different effects.

Since it is such cloud systems which produce the Kona Storms of Hawaii, the "blow down" storms of Central America, the hurricanes of the Caribbean and Atlantic seaboard regions, and the major rain-producing storms of regions like the southwestern United States, it is of great importance to learn the techniques for "taking away" the effects of natural atmospheric nuclei and replacing them with controlled amounts of more dominant artificially introduced nuclei. Until we learn how to do this effectively, any talk of weather control is unrealistic.

Importance of Ice Nuclei in Regions Like New Mexico

Starting in 1948 and continuing for three years, cloud-seeding studies were conducted in New Mexico by Project Cirrus. The flight studies were primarily of an exploratory nature and were not planned to attempt to produce economical amounts of rain. That some of the seeding flights were followed by substantial amounts of precipitation in the seeded regions was incidental to the primary objective, which was to establish the nature of the clouds and the effects that might be induced by using various amounts and varieties of seeding materials (16).

For the New Mexico studies dry ice, silver iodide and water ice, water and gaseous ammonia were used. A total of twenty seeding experiments were conducted in 1948, 1949, and 1950 (27). Since these were experimental studies, the experiences resulting from each flight were used to modify each subsequent flight study. Based on the results obtained, the following general conclusions were established.

1. Cumulus clouds in New Mexico commonly contain large amounts of supercooled cloud masses.
2. The bases of such clouds under summer conditions vary between 12,000 and 14,000 feet msl.
3. The freezing level commonly occurs at 16,000 feet.
4. The most spectacular effects of seeding with dry ice or silver iodide occurred on days when the first clouds appeared over the cloud breeding spots not later than 1000-1100 o'clock.
5. The most striking seeding effects by aircraft occurred in clouds which were growing vigorously and were seeded when their

TABLE I

Flight No.	Date	Seeding Agent	Results
45	October 1948	CO ₂ /AgI	Development of large storm.
106	July 1949	CO ₂	Removal of large cloud from line of cumulus
108	July 1949	CO ₂	Towering, followed by consolidated rain-storm.
110	July 1949	AgICO ₂	Development of large storm.
168	July 1950	CO ₂	Development of cirrus overcast.
172	July 1950	CO ₂	Towering, followed by consolidated rain-storm.

total vertical thickness was between 8,000 and 9,000 feet, and thickness of supercooled cloud was 4,000 to 5,000 feet. Seeding was effected at the top of the clouds with temperatures of about -12°C . Crushed dry ice fragments with no particles larger than 1 cubic centimeter were scattered through the top portion of the cloud at a rate of about 2 pounds per mile.

6. Under these conditions initial radar echoes followed the seeding operation by 14 to 21 minutes. The echoes invariably brightened rapidly and showed close relationship to the upper air motions related to the areas seeded.

7. Heavy rains occurring with a sparsity or complete absence of lightning were the most striking effects observed after dry ice seeding. Observations of the appearance of the cloud tops associated with the experiments showed regions where spectacular towering occurred, followed by a rounding off and consolidation of the ice crystal tops, especially where rains persisted for 2 to 4 hours.

8. The largest effects followed combined seeding of dry ice and silver iodide with the latter introduced either by airborne or ground-based generators.

9. When cumulus cloud developments started in the afternoon, cloud dissipation was the common result of seeding activities.

10. Large cumulus clouds which do not develop to the precipitation stage are of relatively common occurrence in regions like New Mexico and Arizona. When precipitation fails to occur,

much of the cloud shifts to false cirrus streamers of ice crystals, which often dominate the afternoon and evening sky.

II. During periods of dust storm activity, clouds are commonly seen to shift completely to ice crystals when still quite small. At other times clouds in one region of the visible sky will show profound modification, while clouds in another region will develop in a normal manner. In some instances these effects are probably due to tongues of air containing natural ice nuclei. In some cases such effects may be attributed to the effect of silver iodide ground generators.

Precipitation Pattern Due to Orographic Clouds in New Mexico

Since the bases of most large cumulus clouds that form in New Mexico are at altitudes several thousand feet above the highest mountain summits, naturally occurring precipitation generally falls on the *down wind side* of the mountains. The cultivated areas and range lands which depend on this natural rainfall delineate this precipitation pattern in considerable detail. An excellent example of this effect is to be seen in the bean-growing area of New Mexico, situated east of the Sandia and Manzano Mountains, to the southeast of Albuquerque. In direct contrast, the orographic effects of mountains in subtropical regions and in places where the mountain summits rise higher than the cloud bases normally produce precipitation patterns on the upwind side of the mountain slopes. In such regions the area on the lee side of the mountains often shows regions of rainfall deficiency and actual "rain shadows." Good examples of this pattern are to be seen in the rain forest west of Hilo in the Hawaiian Islands and the rain forest on the western slopes of the Olympic Mountains in northwestern Washington.

If methods are developed which effectively modify the "natural" rainfall from orographic cumulus in places like New Mexico, attention should be directed to this phenomenon since the end result might cause trouble. If the precipitation pattern from seeded clouds tends to appear further upwind than the "natural" rain, the end result might be of little benefit to anyone. This danger may occur in any region of marginal rainfall.

Based on the few seeding experiments made with Project Cirrus the rain areas developed over the regions which ordinarily receive rain. Thus, if any conclusions might be drawn from these few experiments, the type of seeding we conducted might be expected to produce an augmented total yearly rainfall rather than a redistribution of precipitation.

Studies of this sort should become an essential part of any long range plan of arid lands research concerning atmospheric water sources.

By proper control it might be feasible, for example, to augment ground water supplies by causing more precipitation on mountain slopes with drainages running into thick gravel deposits.

Movement of Air in Valleys Bordered by Mountains

One of the problems involved in seeding clouds from ground-based silver iodide ground generators is that of getting the silver iodide particles into the cloud to be modified. Several significant studies of this phenomenon were made southeast of Albuquerque during July 1949.

On July 14, 1949, an attempt was made by S. E. Reynolds and the writer to introduce dry ice into an orographic cumulus, using a large pilot balloon. The target cloud was a relatively small but vigorously growing orographic cumulus above the western edge of the Manzano Mountains about five miles east of the launching site. Upon release, the balloon carrying about a half pound chunk of dry ice started moving in a southerly direction and was soon lost to view. Reynolds and Schaefer then decided to get closer to the cloud base, so took another balloon with dry ice over to the edge of the mountain nearly under the cloud base. Upon release, the balloon, observed with binoculars, immediately started rising toward the cloud without deviation. Just before this second balloon entered the cloud base, the first balloon was seen to join it, drifting up rapidly from the south!

Within less than thirty minutes after the balloons entered the cloud a radar echo due to precipitation formed, which was then followed by rain.

A day and night study of air movements in the Rio Grande Valley of New Mexico during the month of July showed that mountain, valley, and drainage winds fit into a recurring diurnal pattern. These air motions may be studied by watching smoke plumes, smog patterns, zero lift balloons, and ordinary pilot balloons.

The early morning situation is dominated by a drainage wind flowing down the river valley from the north. This continues until the mountain slopes become sufficiently heated to start convective movements, at which time the wind swings to a westerly and then a southwesterly direction. This wind then stops blowing in the evening. It is then followed by an easterly mountain wind which carries the cold air produced by radiative cooling down into the valley. These air movements are of sufficient magnitude to impress their pattern on a microbarograph. These traces are the most convincing evidence of the recurrent diurnal fluctuations in air flow of the area.

On July 21, 1949, B. Vonnegut of the Project Cirrus group started a silver iodide smoke generator at 0530 and at the same time began releasing a series of zero lift balloons at the research station south east of Albuquerque. The air flow followed the described pattern. At about 0830, an isolated orographic cumulus cloud started forming about 25 miles south of the station. Visual and photographic observations of this cloud showed that its top grew at the average rate of 160 feet per minute between 0830 and 0957. At 0957, the summit of the cloud was at 26,000 feet and its temperature about -23°C . At that time the top of the cloud started growing at the rate of 1,200 feet per minute. This rapid rate of growth continued for fifteen minutes. At 1012 it had reached an altitude of 44,000 feet, with a calculated temperature of -65°C . At this altitude, the rate of growth slowed down considerably.

The first radar echo was observed at 1006 at 20,500 feet, where the temperature was -9°C . This echo occurred at 25 miles and an azimuth of 165°C . With the generator located at 5,600 feet msl, the smoke plume from the silver iodide generator moved toward the Manzano Mountains in such a manner that it was

probably close to the cloud base at 0800. Observations of visible smoke plumes in the Rio Grande Valley show that, while there is a tendency for an early morning inversion to stabilize the air, this condition rapidly changes as the sun begins heating the valley floor. Together with the orographic effect of the mountains, it is very likely that the stability of the air in the early morning would have prevented a rapid dilution of the stream of silver iodide, so that an effective seeding reaction probably occurred just above 18,500 feet, where the temperature was colder than -4°C . Assuming a rise within the cloud of 120 feet per minute, this would have the silver iodide producing an effect at about 0940.

Our other experiences in New Mexico have shown that seeding effects may be expected to produce an initial radar echo within 15 to 25 minutes. Thus, the initial radar echo at 1006 would be in very good agreement with the mechanisms that might be expected to control the precipitation cycle. The initial precipitation area covered about one square mile and was deep within the cloud. It is very unusual for precipitation to develop at such low altitudes in New Mexico. Within four minutes the precipitation echo had increased to seven square miles, and two minutes later it had extended upward to 34,000 feet, where the temperature was -43°C . The rapid vertical growth with an average of 1,160 feet per minute, which was first observed at 0957, continued until 1012. The outward manifestation of this upheaval shows a remarkable linearity. Extrapolation of this line shows an excellent relation of the probable triggering effect of the silver iodide.

This single local storm developed continuously into a large zone of precipitation.

In the early afternoon, Flight 110 was activated with two Project Cirrus B-17's. Twelve separate seeding operations were carried out between 1445 and 1530, utilizing from one-third to four and a half pounds of crushed dry ice, depending on the size of the cloud masses seeded. During the afternoon, 1.2 inches of rain fell at the radar site. A remarkable fan-shaped pattern of precipitation developed in the region downwind from the seeded region. This has been analyzed in considerable detail by Langmuir (15), who concluded that much of the rain that fell in New Mexico on July

21 could be related to the silver iodide and dry ice seeding operations. The writer flew into this storm in the early afternoon and observed that it consisted of a great mass of cumulus with heavy precipitation moving in a northeasterly direction.

These observations present strong evidence that the convective clouds, which daily form over the mountains in the Rio Grande Valley in the summer, tend to serve as chimneys which lift the valley air to higher levels of the atmosphere. Silver iodide or any other material introduced into the valley region is carried by the converging air and effectively introduced into cloudy regions where they may affect the cloud structure, if still active as either condensation or ice nuclei, or both.

Effectiveness of Silver Iodide as a Nucleus for Ice Crystal Formation

A great deal has been written about the role of silver iodide as an ice crystal nucleus. Although much research has been conducted since Vonnegut's original paper (30), silver iodide still remains the most effective foreign particle for ice crystal nucleation. Many different factors have been shown (4, 11, 21, 31) to affect its potential activity. It has such complex crystal habits, however, that much caution is required in concluding that all or any of these factors cause irreversible effects. Recent studies by the writer show that silver iodide is most effective if it first serves as a condensation nucleus in the liquid water zone of a cloud (26, 29). If this occurs, the particles serve as freezing nuclei at a threshold temperature between -4° and -5°C . If the silver iodide particle enters a liquid water droplet, there is the possibility that the effects of sunlight, low humidity, temperature, certain impurities, and other factors which have been cited for their deactivation effects may be nullified. The active program of laboratory study and field evaluation currently underway in many parts of the world may be expected to shed much light on the properties of this important cloud seeding material within the next few years.

Use of Silver Iodide for Increase of Snow Pack

One of the most important aspects of water supply in regions of submarginal rainfall is the snow pack of the high mountains. With improved methods of moving water by pipe line and canal,

it is often possible to have this source of water hundreds of miles from the arid regions where it is to be used.

Seeding operations in high mountainous areas have excellent potentialities. Since most mountains rising above 8,000 to 10,000 feet msl are higher than the dew point level of winter air masses, the upper levels are commonly covered with clouds. These are often supercooled and, except where seeded by blowing snow near the surface, are deficient in ice nuclei. Silver iodide generators placed at convenient locations are often operated with ambient temperatures close to or even colder than 0°C . Under such conditions deactivation by the temperature effect is of little or no concern.

Wintertime orographic clouds rarely have the vertical thickness or lifetime of summer clouds. They occur for longer periods, however, and if effectively seeded may be forced to yield much of the condensed cloud water in the form of snow crystals.

Although considerable progress has been made in the study of snow pack increasing (10, 12), much remains to be done. By controlling the particle size of silver iodide, it should be feasible to control the temperature of nucleation. The smaller the particle, the colder the threshold temperature of nucleation. Thus, it may be possible to move the lower level of the snow pack area by controlling either or both the concentration of ice crystals and the temperature at which they form. By producing silver iodide particles of highly uniform size, the effectiveness and efficiency of smoke generators might be greatly improved in the same manner as with our artificial fog generators developed during World War II. This may be achieved by effective control of the quenching speed of the jet of vaporized silver iodide. By delaying the introduction of cold air into the vaporized stream, the smoke particles will grow much larger, but they will be less numerous than when the vapor is rapidly diluted. It should be feasible to form mono-dispersed particles over the size range of 0.004 to 1.0 micron diameter. Thus, under nearly the same operating conditions the number of particles may be varied by a factor of 100 million.

This is a field of research in experimental meteorology which has hardly been touched but it may yield rich dividends in commercial operations as well as basic research.

Need of Basic Research in Atmospheric Physics

Much basic work remains to be done in the exploratory phases of experimental meteorology. Despite the extensive and widespread commercial cloud seeding which has been underway for the past 4 to 5 years, certain aspects of the problem have been seriously neglected.

Perhaps the simplest and yet one of the most neglected fields has been the cloud survey. Despite some localized studies (3, 7, 17, 22) great gaps remain in our knowledge of these fundamental features of the lower atmosphere. There has been a tendency in the past to assume that cloud behavior was similar in most places. However, a little study in the field of what may be called "comparative cloud structure" quickly demonstrates the danger of such extrapolation.

While it is possible to discover similarities in the clouds which form near and over the Hawaiian Islands and those of Puerto Rico, a cumulus forming in such trade wind regions is far different in properties, appearance, and precipitation mechanism from one over a mountain bordering the Rio Grande of New Mexico. In turn these two will have characteristics entirely different from a cumulus forming near the Priest River Valley of northern Idaho.

Fortunately, cloud surveys are becoming more common. Recent studies in the midwest (9), Puerto Rico (8), Sweden (19), and the northwestern United States (2) have established techniques which may be adapted to local conditions and available personnel and equipment. These procedures vary from exact measurements of many individual clouds to the patterns of cloud systems forming localized thunderstorms.

Supplementing these local observations is the current preparation of what might be termed a dynamic cloud atlas. Time lapse cloud movies are being obtained in many parts of the world under sponsorship of our Foundation (28).

A widespread photographic coverage of cloud systems in the United States and its surroundings is underway through the cooperation of such groups as the U. S. Forest Service, the National Park Service, various universities, the Boeing Airplane Co., private industrial meteorological organizations, the U. S. Weather Bureau, and cooperative individuals. In addition, similar cloud

movies are being obtained through the cooperation of the Air Weather Service of the USAF in such scattered places as Sweden, England, Germany, Italy, Japan, Hong Kong, and Bermuda.

From the more than 30,000 feet of film now on hand, a series of movies will be prepared to illustrate the variations and similarities which occur in clouds that form under a wide variety of geographic, topographic, and climatologic situations. Such films will be made available for educational purposes by the Foundation.

Future Prospects of Increased Water Supplies from the Atmosphere

Although it must be admitted that there is no currently available *easy* solution to the tapping of unlimited water from the sky rivers which flow over arid lands, there are still many research angles to probe. Under certain physical conditions such as have been described in this paper, it is fairly certain that some additional water may be secured above that subject to the variations of natural conditions.

The future possibilities of securing additional water supplies in arid regions from atmospheric sources depend on several factors.

The most immediate may be expected from improvements in current techniques of cloud-seeding activities. The most remote is the natural variation in the general world circulation, which in the past produced so much rain and snow as to cause the great alluvial deposits that cover the Rio Grande Valley hundreds of feet deep.

The most important in the foreseeable future is the promise indicated by the studies and hypotheses of Langmuir (18) and Bowen (6), which suggest that optimum concentrations of effective ice nuclei may play a dominant role in controlling hemispheric weather. Although their findings are still the subject of considerable controversy, it seems reasonable to expect that a proper understanding of trigger effects in the atmosphere, which may cause singularities, abnormal weather patterns, extensive storms, and the persistencies, which lead to drought or flood, will eventually lead to a certain degree of weather control.

The time which will be required to reach this goal will depend to a major degree on basic research and the vision, enthusiasm,

curiosity, and imagination of a few good research scientists, aided by the cooperation and good will of a much larger segment of interested people. Groups such as those comprising the Arid Lands Conference are in a vital position to be of much help in this regard.

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Some Problems in Utilizing Water Resources of the Air

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Two pioneers (pp. 291 and 300) in the field of weather modification have discussed some of the problems that lie ahead in man's attempt to extend his control over nature. In view of the wide differences of opinion that still exist on the question of "rain-making," it may appear to some that little or no progress has been made. However, progress has been made—at least in the sense of finding out what some of the most important problems are and what areas need further exploration. There seems to be general agreement that more facts and more data are needed. And the necessity and importance of getting them was brought out at the Mid-Century Conference on Resources for the Future. Meteorologist Athelstan Spilhaus stated, "To summarize in one sentence: If the control of the sea and the air and the useful things in them is kept clearly as the objective in this search, it will then be an objective large enough and with such a tremendous pay-off that it should attract the best scientific minds" (8).

It will be the purpose of this paper to discuss some problems connected with the collection and interpretation of the facts which are needed before an intelligent answer can be given regarding the potentialities of weather control as a solution to the arid lands water problem.

Survey of Moisture Resources Available in the Atmosphere

Precipitation is the end product of a large number of events on both the macro and micro scale. The amount of precipitation de-

depends upon the water content of the air. It would therefore seem reasonable to determine for various regions the available supply of moisture, primarily in the form of clouds, since they represent the most likely source material for rain. The frequency of occurrence of clouds of various types and thickness, water content, etc., could be determined and estimates made of possible precipitation increase providing the moisture could be made to precipitate out. "Census" counts of clouds precipitating naturally could be made. In some areas, studies like these have been started and the World Meteorological Organization Technical Report No. 1 "Artificial Inducement of Precipitation with special reference to the arid and semi-arid regions of the world" (12) describes a preliminary survey reviewing the general atmospheric conditions necessary for cloud seeding operations and the likelihood of finding such conditions in the arid and semi-arid areas. However, in many areas the basic meteorological data are inadequate. To fill these gaps it will be necessary to find economical ways of extending the observational network to obtain the information that will have direct bearing on the particular questions to be answered.

Distribution of Condensation and Freezing Nuclei in Time and Space

In addition to the usual meteorological observations, there is a need for more data regarding the nature and distribution of the particles in the atmosphere on which water droplets and ice crystals form. Studies by the previous speakers and others indicate there are large fluctuations in the number of these particles from time to time and from one location to another. Aside from the problems of instrumental errors, important sampling questions arise here regarding the representativeness of the measurements. How large a sample is necessary to represent adequately the average concentration over an area? These and other questions might be answered by sampling experiments and statistical theory.

Regarding the nature and source of these particles, a Japanese investigator (3) identified the central nucleus of natural ice crystals as belonging to the clay mineral group in about ten out of fifteen individual cases studied. Is this typical, or would another sample taken at a different time or place show something else?

Schaefer (5, 6) reported that some soil and dust particles have nucleating properties. Bowen (1) suggested a relationship between rainfall and variations in meteoritic dust although the evidence on this point is circumstantial in nature as pointed out by Neumann (4) and Swinbank (9). Without question, more direct measurements of the quantities concerned are needed before most of the theories proposed can be confirmed or rejected.

Collecting such data is expensive and no program for indiscriminate collection of such data is recommended. Initial efforts are likely to be confined to those areas where the role of nuclei in the rain-making process seems to be of greatest importance or interest for one reason or another. As more data become available and are examined, unexpected relationships will be uncovered, some of which will be fortuitous and therefore misleading. Therefore a program for collecting the data should also include plans for objective and unbiased evaluation of the data, but these plans must be flexible enough to permit promising clues to be recognized and followed-up effectively. The methods of sequential analysis used successfully in other scientific fields might be used here. Maximum effectiveness in this program requires the coordinated efforts of the climatologist, meteorologist, cloud physicist, chemist, hydrologist, statistician, and astronomer.

Analysis and Interpretation of Field Data

If the collection of the field data is supplemented by laboratory experiments and studies of physical theories, it should be possible to estimate the relative importance of vertical motion and the supply of condensation and freezing nuclei in the production of natural rain. Data on the natural variation of these particles could be correlated with rainfall occurrence, cloud structure, and electrical effects. These data might shed new light on Bowen's meteoritic dust hypothesis or reveal other important effects that influence precipitation. For example, the role played by atmospheric electricity is not understood, but other pioneers in cloud modification including Gunn (2) of the Weather Bureau and Vonnegut (11) are giving careful attention to this subject.

Because of the absence of a complete physical theory on the

formation of rain and necessary supporting data, most evaluations on rain-making to date have been statistical in nature and insensitive in detecting changes of less than about 20%. When used properly these methods can be powerful tools in extracting information from the data, but they cannot make good data out of poor data. It is unfortunate that nearly all the rain-making evaluations have been made on commercial cloud-seeding operations, which are not primarily designed as experiments for the purpose of obtaining scientific information.

Data on the natural distribution of condensation and freezing nuclei should also be useful to those engaged in commercial cloud seeding. As mentioned earlier, there is evidence that the natural supply of nuclei is variable (7). At the present time most commercial cloud seeders operate on the assumption that the natural supply is inadequate, and attempt to overcome this deficit by adding more. Suggestions have been made that adding too many artificial nuclei to the atmosphere may result in "overseeding" and inhibit rainfall. In view of the possibly large fluctuations in the concentration of natural nuclei due to variations of wind blown dust, volcanic ash, meteoritic dust, sea salt, etc., it may be reasonable to ask how Nature knows the optimum concentration for rain and how she prevents "overseeding." Obviously this leads one to speculate on the interesting possibility that there may be some situations in which rainfall would be increased by *removing* nuclei from the air.

The data discussed above should also be useful in determining the economic value of weather modification in the arid lands. The monetary value of a rain-increasing project will depend upon the additional water resources available in the air and the cost of putting some of this water on the ground. If this cost is relatively low and if there is a reasonable chance of success, an intensive effort is justified. In this country, President Eisenhower has appointed an Advisory Committee on Weather Control which plans to give particular attention to the economic implications and scientific basis of weather modification in their report, which is expected to be available in 1956. On the international level, the World Meteorological Organization's Committee on Aerology (10)

has prepared a report on the possibilities of artificial control of weather.

Conclusion

Time does not permit a discussion of numerous other problems. The large number of questions that remain unanswered may suggest that little progress has been made. In relation to the total task to be accomplished, progress has been small, but in relation to the effort that has been expended, progress has been satisfactory or rapid. Progress has been overshadowed by wild speculations, unsupported claims, and extreme statements which have raised false hopes. It is clear that the immediate solution to weather modification is not in sight, but from a long range point of view there is no reason to be pessimistic. Man is gradually learning to control such things as the atom and cancer, and there is no good reason to think that weather is beyond his reach. The failure to achieve satisfactory control by presently known methods does not prevent other and better methods from being found. At one time it was thought that there was one precipitation mechanism. Now several other methods are being considered. In other words, there is an indication that, if Nature does not make it rain one way, she provides another. Perhaps it will be the same for man. If we do not control the weather in one way, we will ultimately control it in some other way. This will require greater discoveries which will depend upon our vision and willingness to approach the problem with an open mind.

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The Economics of Water Sources

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I have been asked to make a statement, in the nature of an afterthought at a natural science conference, on the economics of water sources, and, in a general way, on the economics of arid lands. One of the characteristic distinctions between the natural and the social sciences is that the former have a superabundance of facts and data, whereas the latter have a notable deficiency of these. Since facts and data are frequently, if begrudgingly, capable of cutting short and bringing to an untimely end an otherwise healthy discussion, it is not surprising that natural scientists are noted for their taciturnity, while social scientists are blessed with a superabundance of talk. This no doubt accounts for the time limit which has been placed on my remarks, as well as the fact that a natural scientist has been chosen to talk on economics, possibly with the hope that he would stumble into some facts that would bring his discussion to a timely end.

Water Economics

Attention has been given to the prospects of additional water resources: artificial precipitation, demineralization, and water re-use.

Artificial Precipitation

A diligent search for economic data on artificial precipitation leads only to the conclusion that economic statements on artificial precipitation cannot be made at this time. One can cite several individual cases, for example that of Shreveport, Louisiana, which

recently obtained a year's water supply after 5 years of drought for a \$20,000 contract with a commercial cloud seeder. The great majority of the people of that city no doubt feel that \$20,000 next year, and the next, will keep them in water. The economist's conclusions, however, will wait the adding up of all the \$20,000's that have been or can be spent without success, which in effect is what the President's Advisory Committee on Weather Control and the World Meteorological Organization's Committee on Aerology are now engaged in.

Demineralization

For demineralization the picture is much better.

1. *Competitive Prices.* To answer the economist's first question—competitive prices. (I must apologize to our international friends, that I speak only of United States conditions, and to our Republican friends, that I use the 1952 dollar.) Bulk municipal water is priced at \$50–80 per acre-foot, irrigation water from the government at \$2–6, and from private companies up to \$40. In marginal areas or critical situations prices are higher, for example, one Texas town was hauling water at \$1000 per acre-foot. The cost to the user of pumping underground water from wells is \$4–5 per acre-foot per 100 feet of lift. In the area studied users are pumping 150–400 feet, thus paying \$6–16 per acre-foot, and this sets the competitive price.

2. *Production Costs,* the economist's second question. The demineralization processes on which engineering estimates have been made (some of them of the most rudimentary sort) may produce from sea water at costs of from \$114 to \$1000 per acre-foot and from brackish waters as low as \$20. In detail (all estimates except as noted):

	Dollars/acre-foot
Using solar energy for multiple effect distillation (It will never get below)	1069 700
Simple solar evaporation (It may get to)	775 400
Triple effect distillation	700
Vacuum distillation using waste diesel heat	528
Ten effect distillation (actual cost)	415

Vapor compression distillation	429
Supercritical distillation	148
Vapor compression distillation (Hickman)	114.
Electrolytic membrane	
885 ppm feed	4
4,635 ppm feed	20
10,000 ppm feed	40

Conclusions. Brackish water conversion can be competitive now when water costs or supply are marginal. Sea water conservation is not there yet, but the outlook is hopeful.

3. *Transportation Costs*, the economist's third question.

Water should be a cheap commodity, and it is, as chemical commodities go. A cheap bulk chemical will sell for about \$15 per ton, that is, \$20,000 per acre-foot. Quarried bulk limestone, one of the cheapest chemical raw materials, will cost \$1.20 per ton, that is, \$1650 per acre-foot; salt in brine about 30¢ per ton, that is, \$400 per acre-foot. The \$40 per acre-foot we are shooting for is equivalent to 3¢ per ton. Think of that. If we had to put a postage stamp on it to transport a ton it would double the price! And that brings us to the problem of transportation costs. This subject needs serious study by engineers. We have two operations that are comparable: (a) aqueducting of water under essentially gravity flow, and (b) pipelining of water and liquid petroleum products.

In the former category are the piped aqueducts such as the Owens, the Colorado, the Delaware. The Colorado aqueduct delivers water to Los Angeles, a distance of 273 miles, for \$30 per acre-foot, about 11¢ per acre-foot mile. Also included are the canals, which are cheaper, for example, the Gulf Coast Canal is estimated to deliver water for \$8 per acre-foot, about 2¢ per acre-foot mile. So if we were to transport water by gravity flow, say 50 miles from the converting plant at the seashore, or 50 miles from a brackish source, the transportation cost would be \$1 to 5 per acre-foot. It would double the price of present irrigation water, increase the cost of converted brackish water by 10%, and be insignificant if one were already using converted sea water at current estimated costs.

Unfortunately most transportation of converted water will not be by gravity flow but will be uphill all the way—there's no

way of damming up the ocean. This means resorting to a pipeline, pumping against a head of water every foot of the way. This is much more costly, running \$3 to 7 per acre-foot mile. Thus the 50-mile haul would cost \$150 to 350 per acre-foot.

The magnitude of these figures may surprise some who have been talking only of water production costs. I hope that it will stimulate some serious engineering study of water transportation costs over various typical distances and types of terrain.

4. *Markets*, the economist's fourth question. Is there a market of sufficient magnitude for converted water? As we have just seen, since the ratio of value to transportation cost is low, the marketing area for water is limited to the vicinity of the production area. Pilot studies have been made in certain water-deficient areas, such as California and Texas 50 miles from the sea and under 500 feet elevation, showing that an additional 11,000,000 acre-feet could be consumed and 10,000,000 of present consumption displaced. At \$40 per acre-foot, that is an \$800,000,000 business. Only two chemical companies and only thirty manufacturing companies have larger sales. There is most certainly a market, but the exact extent and location of it will depend on precise market research to determine how much water will be used where at successively lower selling prices.

5. *Social and Economic Magnitude*, the economist's fifth question. How seriously would it affect the present economy? Answer: Staggeringly. Consider now the world's largest chemical plant—it produces 3000 tons per day of product. In the year 2000, one area, southern Texas, will be able to utilize 12.3 million acre-feet of water. How many water conversion plants will it take to convert this water? 10? 100? 1000? No. It will take 15,000 plants the size of the world's largest. One plant every 150 feet from the Sabine to the Rio Grande; wall to wall for 450 miles. Twelve million acre-feet is in tonnage about 40 times the entire nation's petroleum production and about 400 times the chemical production.

6. *Value*, the economist's sixth and last question and the philosopher's first. Assessing the value of water is a treacherous undertaking. The smaller the group assessed the more likely the error and the more certain the chance for differing opinions. Very few

disputes over conclusions developed when the Bureau of Reclamation appraised the water situation in southern Texas and concluded that a \$1.1-billion investment in a canal plus a \$100-million annual operating expense would ultimately increase the gross annual income of the area by \$6 billion over the present income. Not many have denied the value of that water. At the next level, when a water-short community is deciding whether to encourage agriculture or manufacturing there will be a considerable argument and permanent uncertainty over the decision. At the lowest level, when an individual farmer, for example, is deciding which crop to grow or whether to put an additional acre-foot on his present crops, there is very little scientific certainty and a great possibility for error. In fact, farmers, being in general poor at cost accounting and not having the facts to begin with, very frequently make other than optimum choices. Depending on the purpose of the compiler, water values may be based on gross income, on net profit, on payout period, on total employment, even on esthetic values, among other things. In the United States, where under scientific management net profit usually controls the decision, there are not enough available experimental data on the physical results of water use to set a proper value on it. What is needed is a careful study by economists and engineers of the value of water used for various purposes and under various conditions; and especially if irrigation is to continue a major user of water, studies are needed by agronomists and agricultural economists to place a definite value on water used for specific agricultural purposes.

Water Re-use

In general, topics of competitive prices, transportation costs, markets, and values have been discussed in the preceding section on demineralization in order to provide an orientation for the demineralization costs there cited. Those factors apply equally well to other methods of securing additional water sources such as water re-use.

The re-use of water in the United States is much more common than most people realize. In the United States 70 million people drink from sources which are used also for sewage disposal. Probably 69,990,000 of them are not aware of it. A properly designed

sewage treatment plant can, and many do, produce an effluent of better quality chemically and biologically than many public raw water supplies. In the United States about 125 municipal sewage plants utilize the effluent in agriculture. In addition, in at least a half-dozen cases, sewage effluent is used for industrial operations. Sewage effluent in general will cost about \$10 per acre-foot, and one industrial plant is purchasing it for \$6. However, municipal effluents would in general supply only a fraction of the industrial requirement. Most industries make only one use of water, but in almost every case it would be possible to reduce water use greatly if a water shortage should develop. One plant in the Texas-Gulf Coast area reduced its requirement from 672,000 acre-feet per year to 44,000 by re-use; another from 224 acre-feet per year to 4. But there is no possibility that even combined municipal and industrial reclaimed effluents can make more than a fractional contribution to irrigation supplies.

Full and economic utilization of industrial waste waters will require further intensive research and development to provide suitable processes and a major educational campaign to persuade managements of the necessity.

Generalized Economics of Arid Lands

In making a few general remarks on the economics of arid lands, I take the liberty of the social scientist who, out of the necessities of the present stage of development of his science, must make broad generalizations from what the natural scientist would judge inadequate or faulty data. If I am in error, blame it on the natural scientist who dares to navigate these tricky waters, rather than on the economists who by much practice have learned to shoot the rapids without spilling a drop.

Land Value Fluctuations

Our economic systems and theories have been developed quite largely in lands enjoying adequate and regular rainfall. Under these conditions the value of the land, first for agricultural, then for industrial purposes, depends upon the inherent quality and productivity of the soil, on topography, and on the location relative to the markets and raw materials. Land, therefore, even after

the industrial revolution, became a property with a quite permanent value. Fluctuations in value occurred only through discovery of mineral rights, general fluctuations in the economy, and through an encroachment of urban areas. In arid lands, however, all these factors are overshadowed by the overwhelming importance of water to any utilization of the land. Accordingly the value of lands in arid regions is subject to another major fluctuation, namely, that in the availability of water. The predictability of land, values, therefore, unlike those in humid regions, becomes as uncertain as long range predictions of weather and climate, and, as we have seen in more than one short range cycle in our own time, economic displacements of great magnitude can occur through this unpredictability. When an economy contains a significant segment as an arid land component, the fluctuations of the latter may initiate sympathetic fluctuations of more serious consequence in the general economy.

“*Oasis Economy*”

Except for some variation in place utility and in inherent productivity, in the humid regions the value of land changes gradually from point to point and provides a broad gridwork on which human activities may be placed with considerable freedom of choice. In the arid regions, however, as we have just discussed, except for mineral values, the value of the land is insignificant in the absence of water, and thus the condition arises that *the value of a given piece of land is not inherent in the land but is the value of the available water at that point*. Despite this major economic fact there has been no readjustment of the economic principles developed in humid regions, in that our laws and economic system still consider land the primary value in all areas.

More particularly, unlike humid areas where the value of land varies gradually from point to point, in arid areas the value of land changes abruptly at the boundaries of water availability. Although not caused completely by availability of water, this characteristic of arid land population distribution is one of the first things noted by the humid-land traveler in arid regions. Arid land population and activity distribution is characterized by a few spots of population separated from each other by great distances

having practically no population. I use the term "oasis economy" to describe the situation.

There are social and economic consequences of this oasis economy which, time permitting, could be further explored. As an example of a minor sociological consequence I shall cite the restriction in dwelling environment offered in the oasis economy. In the humid regions the degree of urbanization, being high in the center of the metropolitan areas, gradually decreases toward the periphery, typically reaching the rural level before beginning to rise again as the outskirts of the next city are approached. This gradual change allows the dweller in those regions a wide variety of choices in balancing the rural and the urban in his dwelling environment. Not so in the arid lands, for example the Southwest. Here, although it is true that the degree of urbanization decreases outward from the center of the city, at the city boundary, namely at the termination of water, gas, and other utility services, there is a very abrupt transition to a completely rural environment. Thus the dweller in the arid regions has essentially only two choices; either urban residential living or semi-isolated, ranch type, in many cases supplying his own water, gas, and even power.

Oasis Economy and Advancing Technology

It should be pointed out that solutions such as are discussed in this volume on prospects for additional water resources are solutions which may intensify the oasis economy rather than alleviate it. Any solution which increases the availability of water at one spot, possibly at the expense of another spot, will aggravate the situation. Technical advances will be made in water supply and transportation of water, and most of these, if only for efficient utilization, will intensify the oasis economy. For that reason it should be stressed, especially for the engineers, that the better use of present resources and the better adaptation of plants and animals present possibilities for eliminating the oasis economy and making arid lands generally available for habitation as we of the western world understand the normal pattern of land use. I make this point particularly because it happens that the solution to additional water resources lies so largely in applied research and engineering, whereas the solution to better use of present resources

and better adaptation of plants and animals lies more in the comparatively neglected area of fundamental and long term research.

Appropriate Use

Still another anomalous situation arises through the historical entry into arid lands by humid land people. For the past several centuries the pattern for development of new lands has been that when first opened up they constituted the hinterland of civilization and were considered useful only for agriculture and other extractive industries. Then as civilization and industrialization advanced, these rural areas were gradually taken over and converted to urban and industrial uses. This situation was satisfactory as long as adequate rainfall permitted appropriate use of the lands for either agriculture or industry. This is definitely not true in the twentieth century arid lands. And yet, up to this time we have been largely continuing the historical sequence of wasteland, farm land, city land. I submit the proposition that the use of irrigation in the arid lands of the twentieth century is not an appropriate use of that valuable resource, water, but it is an attempt to follow a historical precedent and increase the value of the land. Actually from the standpoint of water use, agriculture is a marginal use of water. In the United States the water that will support one worker in arid land agriculture will support about 60 workers in manufacturing.

Those who are used to our present economy will ask: "Who is going to supply the food." The answer is: The railroad trains run in both directions, let the humid regions ship food into the arid, since with the arid lands reaching the limit of their water supply, the humid regions can produce more efficiently anyway and have by no means reached the limits of their capabilities. The arid lands should then look toward industrial rather than agricultural expansion. If we can ship cotton, we can ship cameras; if we can ship radishes, we can ship radios; if we can ship watermelons, we can ship watches. Only then can the arid lands provide employment and a continued high standard of living both for the present inhabitants and for the many who are swelling their numbers seeking the favorable climate and living which the lands afford.

Better Adaptation of Plants and Animals to Arid Conditions

Questions

What screening procedures would lead to the selection of more productive plant and animal species for arid regions?

What are the genetic and physiological bases for drought resistance in plants and animals?

What are the prospects of increasing drought resistance through genetic research?

How can we develop a program of revegetation?

What are the economic possibilities in the development and utilization of arid land plants and animals?

What are the possibilities of maintaining larger human populations in arid areas?

Adaptation of Plants and Animals

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The growing world population, together with the need to raise the standard of living for millions of people who suffer hunger or malnutrition, makes the increase in world food production an urgent and vital requirement.

The Food and Agricultural Organization annual reports show that shortages in animal products have always been more evident than those of other food materials (6). It is quite obvious that control of livestock diseases and parasites, systematic animal breeding programs, and improved agricultural methods, together with building of more irrigation projects, would augment animal production. Producing abundant cheap animal feed, however, will always remain the main factor in materially increasing animal production. This was proved on a country wide basis in New Zealand. After 24 years of work it was found that raising the plane of nutrition among the animal population caused more production in annual butter fat per cow than selection, grading up of herds, or elimination of poor producers (10). Better use of our arid and semi-arid lands that cover millions of acres could help in providing this essential cheap animal feed.

Continuous overstocking of arid or semi-arid zones has greatly reduced their productivity. Through ages of misuse, man has in the most unwise way exploited millions of acres by extensive and uncontrolled grazing. This has caused denudation of plant cover, which, hand in hand with erosion, produced aridity and in many cases man-made deserts.

Consideration of better use of such land is gaining more interest by certain international and governmental organizations as well as by many scientific bodies and institutions.

Most of the efforts for improvement of arid zones have been directed at studying the plant side. Search has been made for adapted species, methods of planting have been developed, and considerable areas have been reseeded. Although animals were responsible for aridity, less effort was devoted to studying grazing management. Moreover, less attention has been given to the human factor which often is the real cause of the lack of balance between the fodder reserves and the misuse of the grazing lands. Studies of all phases of the problem must go hand in hand if we are to find a solution.

Plants and animals adapted to any given arid environment will differ from place to place. To obtain maximum productivity in arid zones we have to use the best adapted animals that can graze drought-resistant plants. The range should be kept in a state of productivity to be used by the present and future generations.

For the selection of plants and animals better suited to arid zones, a thorough understanding of the ecological, genetic, and physiological basis for drought resistancy has to be borne in mind.

Ecologists are mainly interested in adaptation to external environments. Physiologists are primarily concerned with equilibrium of functions within the organism. Geneticists are concerned with the hereditary makeup of the organism. Range technicians must make use of the relation of all these factors to one another.

Drought-resistant perennial plants are equipped with morphological and physiological characters that enable them to withstand drought. The most important of these are: (1) deep penetration and extensive development of the root system, (2) relatively high osmotic pressure of the cell sap, and (3) higher capacity for regulating transpiration (9).

Certain annual plants can complete their life cycle in a comparatively short time, thus avoiding, rather than withstanding drought. This subject is dealt with by Shantz.

Animals adapted to arid zones are the result of interaction of two main factors, namely heredity and environment. Under arid

conditions animal life is characterized by extreme ecologic and physiologic adaptation to feed scarcity and to absence of free water. Since climatologically most of the arid zones are extremely hot at least for a certain season of the year, animals to be adapted to such conditions should have a high degree of heat tolerance. Although better range management practices might partially improve the environment by providing better feed, shade, wind-breaks, etc., this usually takes a long time.

Selection of Animals

As possibilities of modifying environment conditions are limited, the best adapted animals for the use of the limited available feed and water reserves must be selected.

Fluctuation in weather conditions does not materially change body temperature of warm-blooded animals. It activates thermoregulatory apparatus to counteract the external change. According to hereditary capacity, animals differ in ability to dissipate body heat. Heat dissipation can be increased through the effect of several factors such as increase of surface area, change in color of body coverings, vasodilatation of subcutaneous vessels and/or increased vaporization through sweating, and acceleration of respiration rate.

Species capacity to counteract any external change rests upon a genetic basis, but the environment may stimulate or limit its expression (1).

Wright (13), in discussing general principles governing form and function in different classes of domesticated animals, has shown that the environmental temperature and the rainfall are the most important factors which influence the distribution of domesticated animals. He also brought together certain broad principles formulated by the earlier zoologists, which were found to affect form and function.

As to direct climatic effects he referred to Bergmann's rule, which implies that animals tend to be larger in size in cold climates than do comparable species in warmer regions. This rule was amplified by Allen's rule which states that in general the peripheral parts of the same species tend to be enlarged under

conditions of high temperature with a substantial increase in surface area and heat dissipation. Wright introduced what he called Wilson's rule. In describing the coats of mammals, Wilson distinguished between the bristly external hair covering and the soft woolly fibers which are commonly hidden beneath these coarser hairs. He stressed the fact that in cold countries animals tend toward the woolly coat, whereas in warm regions the tendency is toward more development of hair and disappearance of wool.

Animals inhabiting warm and humid regions show greater melanin pigmentation than the same species in cooler and drier regions. In arid desert regions the skin is characterized by the accumulation of yellow and reddish brown phaeomelanin pigment (Gloger's rule). Wright considers that rainfall, through its effect on quality and seasonal growth of vegetation, acts indirectly upon size, conformation, and density of the animal population as well as on their grazing habits and structural formation.

Knowledge of the fundamental physiology of farm animals regarding heat tolerance and capability for withstanding unfavorable conditions is not yet adequate to set up scales for comparing different breed adaptability (5).

Rhoad (12) developed the Iberia heat tolerance test for calculating a heat tolerance coefficient for cattle. This simplified device, being a field test, has its advantages. Its results however, are liable to be affected by many external factors. Comparisons of tropical and half-tropical crossbreeds with the pure temperate breeds on the basis of this test show a high heat tolerance with concentration of the tropical blood. The fact that such coefficients do not evaluate other physiological factors in relation to productivity has always to be borne in mind.

The Arabian camel (*Camelus dromedarius*) is a distinguished illustration of the effect of environmental conditions on a species (9). Its size and length of limbs and neck coincide with Bergmann's and Allen's rules. Its hairy coat and yellowish brown coloration is a good proof for Wilson's and Gloger's rules. The flexible sole of the foot, the callous horny pads that bear most of the animal's weight during the sitting position, the water sacs in the rumen, the cloven upper lip, the mouth which is almost un-

affected by injury of thorny bushes or trees, as well as many structural modifications, all operate to make the camel best suited to arid conditions and food scarcity. The camel's hump was developed to store a food reserve in the form of fat. Babcock (2) has pointed out that fat metabolism produces not only energy but also free water, which exceeds in volume the volume of the original fat. This has a profound significance in metabolism, more especially in the camel, which has to exist for long periods in waterless regions.

Similar combinations of exo- and endo-adaptations could be traced in other domesticated animals that were developed under arid conditions such as the Arabian horse, certain strains of fat-tailed sheep and zebu cattle.

Conditions in the deserts and semi-deserts usually result in a certain amount of topographic isolation of animals. This provides enormous potential variability through occasional crosses between isolated populations. Natural selection under such conditions as Allee (1) has stated "will act as a sieve that eliminates the unfit and allows the fit to pass through. In another sense, natural selection is a causative force that determines the pattern of hereditary units through selective sorting after recombination."

It is most probable that the Arabian horse, the horse of the desert with its noble qualities of endurance and speed, as well as its specific anatomical constitution, has been developed through such a pattern of inheritance.

Breeding of Animals

Phillips (11), in discussing methods of breeding that can be applied in underdeveloped areas, recommended the use of the following methods: (1) selection within the native types, (2) grading up with already improved types or breeds from other countries, (3) development of new types out of animals that are graded up only a part of the way to the improved type.

A detailed discussion of these methods has appeared in a recent Food and Agricultural Organization publication, showing the use and limitations of each method (11).

Compared with artificial selection, natural selection is very

slow in establishing new combinations of characteristics through mutation and recombination of genes. Haldane has estimated that it takes 10,000 years for a favorable combination of fifteen genes to become established, whereas under artificial selection this could be accomplished in relatively few years. This emphasizes the importance of artificial selection for improvement of animals and plants in arid zones.

There is, however, a fourth method of improvement that can be used in arid zones, that is the *introduction of preadapted species*. Certain strains of goats, fat-tailed sheep, and zebu cattle that have originated in arid environments are likely to be successfully adjusted for introduction to similar arid regions.

In planning for such trials, Wright (13) recommends two methods for comparing homoclimatic areas, i.e., climatographs and hitherographs. The former is based on the relation of air temperature to relative humidity, and the latter, on the relation of temperature to rainfall.

Examples of preadaptation are more prominent in the plant kingdom. Crested wheatgrass (*Agropyron cristatum*) is a native of the wide plains of Siberia and Central Asia, yet its merits in reseeding depleted areas was first proved in the northern Great Plains of the United States and not in the eastern hemisphere where it originated.

Harding grass (*Phalaris tuberosa*) and subterranean clover (*Trifolium subterraneum*), both Mediterranean species, are now considered the best adapted to many areas in southern Australia.

Recently, *Kochia indica* (Wight), a native of India and Pakistan, has been successfully established in the coastal belt of the Egyptian western desert, under less than 6 inches annual rainfall. The species, although originally a salt soil plant, proved to have enough drought resistancy to withstand the semi-arid conditions of the new habitat. Although useless in its original country, its high palatability and easy establishment made the species of some use under Egyptian conditions.

In comparing improved breeds and local breeds, Hagedoorn (7) expressed the fallacy of looking down upon local "unimproved" breeds of domestic animals and plants just because each individual

compares unfavorably with a corresponding individual of an "improved" breed. He repeated that there is only one real measure of superiority in domestic animals, that is adaptation to the conditions of agriculture into which the breed must fit. In discussing the suitability of animals to arid zones, he stated: "One sheep weighing a hundred pounds has only one head and one set of legs; two sheep, weighing a hundred pounds together, have two heads and two sets of legs so that they can be in two different places to hunt the scanty herbs, and for this reason, in conditions where the sheep of fifty pounds can just live, a hundred-pound sheep must necessarily starve." He was referring to differences in comparative adaptability of breeds. However, in any one breed or line, it is obvious that fewer, larger, thriftier animals kept in good flesh are certainly better than a greater number of small undernourished ones.

Cooperative Planning in One Country

In planning for improvement of production under arid conditions it is essential to treat all phases of the problem. A. T. Semple believes that cooperative work could be accomplished if plant scientists handle the problems of plant production and study the effect of animals on plants. Meanwhile, animal scientists would handle the livestock problems and determine the effects of plants upon animals. This division of responsibility, if carefully planned within a research organization, would maintain cooperative work and lessen both duplication and the chance of overlooking any part of the problem. Tackling a group of problems from all angles at one time might be the best screening procedure for selection of better adapted plants or animals for arid regions.

The establishment and adequate financing of one or more arid zone experiment stations may thus be a good approach to the problem. The plan for the Ras el Hekma Desert Range Research Station, which covers 25,000 acres in a 6-inch rainfall area, includes the following points:

1. Analysis of background information to indicate potentialities, covering climatological studies, topographic mapping, soil moisture, land survey, and classification. Aerial surveying through

interpretation of air photos was found to be of great value to the program.

2. Study of the human factor in relation to land use and land tenure as well as to livestock numbers in all phases of the program. Unless the recommended practices are acceptable to the people and in harmony with their customs and way of life, the whole program of improvement is bound to fail. The extensive damage that has been done in most of the desert and semi-desert areas resulted from factors beyond the control of the people who are always held to blame. The instability of life and lack of property rights are the real causes of over-grazing and nomadism. Nomadic life is a forced way of living and will be dropped when a good alternative is available.

3. Species adaptability tests, including methods of establishing plant species by reseeding and their response to grazing, is the means of pointing the way for large-scale reseeding. We have tested almost 300 species of native and introduced plants. Only a few proved to be of some use such as *Phalaris tuberosa*, *Ehrharta calycina*, *Agropyron desertorum*, *Medicago sativa*, *Melilotus* species, *Sanguisorba minor*, *Atriplex* species, *Kochia indica* and *Prosopis juliflora*. Many natives hold much promise once seed supply is developed; the following are examples: *Dactylis glomerata* var. *hispanica*, *Stipa lagascae*, *Oryzopsis miliaceae*, *Cynodon dactylon*, *Poterium varicosum*, *Plantago albicans*, *Moricandia nitens*, *Polygonum* spp., and *Lotus creticus*.

It is worth while to mention that it was comparatively easier at the beginning to obtain foreign seed and information from already established stations abroad than to collect our own.

From observations of how many species failed to establish themselves against how much less succeeded, one may very soon observe and recognize the better adaptation of the native species.

Selection of sites needs careful study. In our case, one screening nursery and twelve outplanting plots have been established along a 300-mile strip of land.

4. Study of soil and water conservation methods and application of certain practices, including water spreading systems.

5. Natural recovery through protection and management.

This includes taxonomic as well as ecological work. Fencing of several areas representing different conditions of soil proved its efficiency in quick restoration of plant cover. In a two-year period of protection, the number and size of native plants already mentioned under (3), growing in fenced areas, have considerably increased in comparison with those in unprotected areas.

6. Study of livestock health, breeding, feeding, and management to insure that animals will be best adapted and fully productive. In many instances improvement of the ranges was followed by the spread of certain animal diseases, mostly parasitic infestations. The study of existing parasites is carried out to help in finding the correct rotation of grazing. Range and livestock management should be handled in a way that will control such infestations and insure maximum productivity.

7. Study and use of available concentrates from the Nile Delta to allow possibilities for using all the roughage produced in the desert.

8. Water development for domestic and livestock use and for limited irrigation including supplemental forage production.

9. Establishment of a training center for range management, serving also as an extension center.

Fruitful Lines of Action

In summary, it may be concluded:

1. With available information, more work must be conducted in animal physiology, to be able to set scales for drought resistance in animals. Yet the use of existing breeds of animals originated under arid conditions and having certain characteristics exo- and endo-adaptive to these conditions has its practical and scientific significance.

2. As most of the characteristics that will counteract environmental changes rest upon a genetic basis, and as the patterns of inheritance in breeds of animals under desert and semi-desert conditions usually help in developing such characteristics, the use of these breeds in improvement programs is highly recommended. The extent of such use has to be governed only by the results of experimental studies on comparative productivity.

3. Inasmuch as plants, the grazing animal, and the human race should be considered as a community living in a symbiotic group, screening procedures for selection of more productive species and development of programs for revegetation of arid regions should be tackled from different angles at one time, through the establishment of well-equipped experiment stations adequately staffed and financed.

4. Fodder production generally is increased under proper management. Water development paves the way for better use of the range. The present destructive uncontrolled rights of use now prevailing in arid and semi-arid lands should be subjected to the fulfilment of certain land improvement requirements. Fencing of a certain percentage of land within a reasonable time, followed by proper use of the range, should allow for complete property rights on the land. Loans to encourage and support land ownership in desirable types of use might materially increase production in arid lands.

5. Nomadism is a symptom more than a disease. Once a chance of stable life is given through proper land use and ownership and through controlled grazing, there will be little reason for its existence. With improvement of forage and water resources and the development of a settled way of life, a number of technicians, laborers, and livestock producers could be absorbed to help development and formation of proper desert communities.

This, in general, is the approach and pattern which one single country like Egypt might be able to develop to solve partly the problems of its 22 million, rapidly growing population, who live crowded in 6 million acres surrounded by deserts. However, there are certain other fields where work on arid land problems might be advanced most fruitfully through international collaboration.

International Cooperation

Most of the stations where arid land improvement is carried out at present are field stations conducting empirical trials. Future programs on arid land development will need and have to depend more on basic research in such fields as physiology of drought resistance, genetics, soil science, ecology, solar energy, and

other fields which need intensive laboratory studies conducted over a long period of time. These obviously are too big a task for individual countries.

Information about arid land problems is not always available to most of the interested people. The dissemination of this type of information is another field that needs more international co-operation.

Successful introduction of grasses and legumes into different countries, although quite recent, has been in many cases outstanding. The establishment of an international unit to help procurement and proper distribution of plant material might facilitate exchange of seeds and information from different arid lands in the world.

Meetings, such as the international arid lands meetings, provide a very worth-while means for exchange of ideas among world experts. More of this type should be planned in different parts of the world and at regular intervals.

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Better Adaptation of Plants to Arid Conditions

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Stated briefly, the task is to explore the fundamental and applied aspects of research in order to suggest ways and means of transforming low-production-per-acre areas into more profitable agricultural use.

At the outset, it must be realized that we are confronted with a soil-climate-plant-harvest complex. It is an agricultural problem. It has been with us ever since Man began his attempts to supplement that which Nature provided by domesticating animals and plants. If it differs at all from problems facing other phases of agriculture, it differs in degree only.

Since, in general, production is low in arid areas, it is likely that animals will be used for a long time to harvest the forage crop grown on non-irrigable land. Thus, we substitute "animal" for "harvest," and so we have a soil-climate-plant-animal complex.

Drought Resistance

The capacity of plants to survive periods of drought with little or no injury is usually termed "drought resistance." The term "drought" is not in itself subject to any rigid definition. Certainly it includes soil drought and atmospheric drought, the latter involving high temperature, low humidity, and high wind velocity, singly or in combination.

It has not been sufficiently emphasized that the term drought resistance is a very inclusive term comparable in its scope to the

term disease resistance. Plants may be susceptible or resistant to smuts, rusts, mildews, and so on. As research on plant diseases developed, it was found that there were races of many of the disease organisms and resistance to one race of rust, say, was no indication of the reaction to be encountered with another race. Disease resistance has many facets.

Use of the term drought resistance is even more nebulous because the term has not yet been satisfactorily defined. Water is an essential factor in photosynthesis since in the manufacture of food the carbon of carbon dioxide is united to the water brought up from the soil. This water remains in the plant until the food is oxidized or broken down, when it may be released. In addition, (1) water is an essential component of protoplasm, (2) it serves as a solvent for oxygen and carbon dioxide, (3) it has a high specific heat and absorbs much excess heat energy, (4) it aids in the transportation of raw materials and foods, and (5) it maintains turgor in living cells. In addition to satisfying all these needs the plant requires large amounts of water to replace that lost by bleeding, through the action of glands, by guttation, and by transpiration (55).

Arid land species may be ephemerals, which are "drought-escaping" (60); succulents, which are a distinctive group of plants not only in structure but in metabolism and water economy (61); or "drought-enduring" species, whose cells can endure a severe reduction in water content for extended periods of time without serious injury, for example, creosote bush *Larrea tridentata* (59). Only plants of the latter group are truly drought resistant.

Physiological Bases for Drought Resistance

Attempts to explain drought resistance on a purely morphological basis have proved inadequate, although certain structural features of plants undoubtedly aid in their survival in dry habitats (50). It seems clear that one of the basic factors in drought resistance of plants is a capacity of the cells to endure desiccation without irreparable injury. Desiccation of the protoplasm in itself does not result in death of the plant, according to Iljin (27, 28), but rather the mechanical disturbances such as pressure, stretching, and tearing, which result from dehydration of the cell.

Similarly, attempts to explain drought resistance under controlled environments on a purely physiological basis have not to date been entirely satisfactory, although certain facets have been explored. Aamodt (1) and others are of the opinion that drought resistance must be determined by direct testing of the plants under controlled conditions. The difficulty has been that any one investigator has limited his study to one or two factors, whereas in the field many factors may be operative at the same time. For instance, high temperature is one facet of drought, but the ability of a plant to withstand the effects of high temperature is not necessarily correlated with the ability of a plant to survive in arid conditions. Still, high temperature is one factor and studies by Julander (29) and others have indicated that in some species resistance to high temperatures may be taken as an index of drought resistance.

In regions where plants are subjected to lengthy periods of summer drought and heat, perennial plants must in some manner withstand the severity of the summer period. During such a period plant growth becomes very limited or ceases entirely. Laude (32), using 20 perennial grasses, conducted a critical study of the nature of this condition which he termed "summer dormancy." With its Mediterranean type climate a dry summer period of 5 to 6 months prevails at Davis, California. Normally, all 20 species are summer dormant under natural rainfall conditions. Thirteen of the 20 species continued vegetative growth throughout the summer when watered at weekly intervals; four species ceased vegetative growth even though supplied with water, although they did retain green tissue; and three species did not even retain green tissue (Table 1).

Another test was devised to allow a period of summer dormancy and then supply water to the seven species that failed to continue growing in the first test. Four of the seven commenced growth after a short dormancy period, but two species of *Stipa* did not respond to water until September, and *Poa scabrella* did not break dormancy until cool weather prevailed with the first fall rain.

In still another test, Laude severed the lateral roots 18 inches from the center of the rows, and the vertical roots at 2- or 4-foot depths by cuts under the blocks. This was done in late July. Soil moisture samples taken August 3 indicated that the soil was dry

TABLE 1
Effect on Vegetative Growth of Supplying Soil Moisture

Supplied at weekly intervals throughout the dry summer period to twenty perennial species in the field at Davis, California, 1947-1950 (32).

Species Continuing Vegetative Growth	Species Ceasing Vegetative Growth	
	Retaining green tissue	Retaining no green tissue
<i>Agropyron desertorum</i>	<i>Melica californica</i>	<i>Poa bulbosa</i>
<i>Bromus carinatus</i>	<i>Poa nevadensis</i>	<i>Poa scabrella</i>
<i>Bromus catharticus</i>	<i>Stipa cernua</i>	<i>Poa secunda</i>
<i>Bromus stamineus</i>	<i>Stipa pulchra</i>	
<i>Dactylis glomerata</i>		
<i>Ehrharta calycina</i>		
<i>Elymus glaucus</i>		
<i>Festuca arundinacea</i>		
<i>Lolium perenne</i>		
<i>Oryzopsis miliacea</i>		
<i>Phalaris tuberosa</i> var. <i>stenoptera</i>		
<i>Poa ampla</i>		
<i>Poa compressa</i>		

to the permanent wilting percentage to a depth of 6 feet. Undisturbed plants showed considerable foliage development by September 12, whereas those with roots severed at the 2- and 4-foot depths did not resume growth until after rain had fallen late in October.

In *Poa scabrella*, however, the initiation of summer dormancy is associated with long photoperiods and high temperatures. Coolness and availability of water break this dormancy.

It is seen from these studies that different environmental factors, singly or in combination, are associated with the initiation and the breaking of summer dormancy: moisture availability, temperature, and day length.

The drought resistance of a plant, then, is a reflection of the interaction of a number of physiological and morphological responses to the many environmental factors operating during the life history of the plant.

One aspect, to my knowledge, has not yet been sufficiently investigated. I refer to the effect of soil type on the survival capabilities of different species in arid areas. For example, our field

plots and seedings in California have demonstrated that *Ehrharta calycina* produces well in light soils in the 18-inch winter rainfall belt in the Great Central Valley of California, but on "tight" soils plants will survive only a year or two at the most. *Phalaris tuberosa* var. *stenoptera* does very well on these "tight" soils. In very sandy soils of coastal California the performance of *E. calycina* is remarkable, whereas *P. tuberosa* var. *stenoptera* survives only in the lower, more favorable, swale sites. This will be referred to again later.

Many studies have been conducted, of course, on mowing or grazing effects on the capacity of plants to withstand drought conditions (64). In general, plants higher in food reserves are more tolerant of heat injury. According to Julander (29) large accumulation of colloidal carbohydrates, especially levulosans, is associated with drought resistance. Heavily clipped plants do not accumulate food reserves during drought and are less resistant.

It would seem, in summary, that physiological investigations on the nature of drought resistance should be intensified and correlative studies should be conducted on the sites and in the environments where the range plants are used.

Genetic Bases for Drought Resistance

Olmsted (53) reviewed his work on photoperiodism of native range grasses of the midwestern United States. He found considerable variation, both interspecific and intraspecific, in their photoperiodic behavior. Intrastrain behavior also differed. A southern Texas strain of *Bouteloua curtipendula* showed less intrastrain diversity than the others. A strain from central Oklahoma exhibited the most intrastrain diversity in all respects, including photoperiodic behavior.

Knowles (30) determined the extent of variation within *Bromus mollis* and the relation of this variation to the environment. An adventive species not present in California before 1870, it was abundant in most regions of the state by 1900 (56). In the short span of 70 years two distinct ecotypes are recognizable in California: a late coastal ecotype and an earlier maturing interior ecotype. In addition, there is some genetic diversity within the ecotypes.

Turesson (67) and Clausen, Keck, and Hiesey (5, 6) have done

outstanding experimental work on plant ecotypes. Turesson showed that if collections of a species from different habitats were grown together under the same environmental conditions their distinctive characteristics are frequently heritable. Clausen *et al.* by means of reciprocal transplants exhibited intrinsic differences between strains of wild species.

Gregor and Sansome (18) and Stapledon (62) reported prostrate habit of growth to be more common in coastal forms of bunchgrasses, but this appeared to be related to years of close grazing. Turesson (67) found the same situation in perennial dicotyledons from the maritime areas of western Europe. And Love (unpublished) found it to exist in *Stipa pulchra*, a native California bunchgrass.

Love (35) reported that interspecific *Stipa* hybrids remained green longer than the parental species. These hybrids are sterile, and no doubt failure of seed production contributed to a longer period of green feed. He stated that it may become possible to interplant strains of two species which would cross and produce a population of vigorous hybrids interspersed among the parents. Technological difficulties involved in harvesting and processing *Stipa* seed have stopped this particular project. However, the fundamental idea may well be applicable to other closely related cross-pollinated species.

Genetic studies with maize (*Zea mays*) were conducted by Heyne and Brunson (23) on the reaction of seedlings to high temperatures. In selfed lines and crosses between them, they studied linkage relations in eight of the ten linkage groups. Close association was found between heat tolerance and the *Su su* (sugary vs. starchy) and *Pr pr* (aleurone color) loci, and possibly including the *Cc* locus (color factor affecting *Pr*). Hybrid vigor had no effect on heat tolerance of the seedlings.

Stebbins (63) reviewed his research work on interspecific hybridization of grasses. Since the production of new types by this process is a long and difficult process, he concluded: "If a particular grassland region already possesses many productive forage species which are ideally adapted to it, the improvement achieved by this method is probably not worth the time and effort

that must be put into it. But if desirable and well-adapted species are not available for the regions concerned, a *condition which is more or less true for most of the regions of the earth having a Mediterranean-type climate*, with long, rainless summers, then this radical method of breeding may in time be rewarding." (Italics mine.) As will be pointed out later, I cannot agree with the italicized portion of the above statement.

There is general agreement with Stebbins' statement that at least 70% of grass species are allopolyploids, the result of wide crosses. But there is also general agreement that newly developed (the so-called raw) amphidiploids are quite dissimilar to old established allopolyploids, especially in their cytogenetic behavior (7). This does not mean that, ultimately, benefits will not be reaped from interspecific hybridization. It does mean that results from such a program are likely to be very much in the future.

Love (36, 38a) called attention to the difficulties inherent in such radical hybridization programs. In 1952 he outlined the fundamental research needed to put such a project on a sound, scientific basis after reviewing this field of endeavor. The review showed beyond a doubt that the best chances of success would be obtained from beginning hybridization work at the diploid level. He also called the attention of the world's grass breeders to an entirely new development (17, 58).

They found that "colchicine treatment of full sibs of a true-breeding variety of sorghum gave variants possessing a number of ancestral characteristics of which some bred true immediately." This treatment of emerging shoots does not necessarily cause polyploidy, but may also cause somatic reduction. Huskins (26), who pioneered this work, wrote: "If the production of homozygous diploid tissues could be induced frequently enough, it would have some advantages and few disadvantages for the plant breeder over the production of haploids."

Clausen (4) and his colleagues have pioneered a new field by hybridizing apomictic species of *Poa* that belong to distinct sections of the genus. They have crossed forms so widely separated geographically that they previously had no opportunity for hybridization. They have obtained transgressive segregation and

greater tolerance to differences in environment. The program is based on the fact that in a predominantly apomictic plant, occasional hybrid seeds may be obtained, which in turn develop into plants that are essentially apomictic. This obviates the necessity of spending years to stabilize a desirable type. Just how much this type of program will contribute to production of arid lands remains to be seen.

In the self-pollinating cereals, *Hordeum vulgare* and *Triticum aestivum*, somatic variability is carried between lines only, and the population consists of a small number of homozygous biotypes. Mixtures of such biotypes planted, harvested, and reseeded for several years at a number of locations result in a preponderance of plants of one biotype, not necessarily the same one, at each station, although no biotype is completely eliminated (19, 31, 65) In other words, a local inbreeding population has diverse biotypes available for response to changed environments that may occur in the future.

Cooper (12) reported the results of a comprehensive ecological and genetical study on heading responses in local populations of cross-pollinating species of *Lolium*. He had shown earlier (11) that the flowering responses in these species are closely adapted to local conditions of temperature and day length. Cooper's material satisfied Mather's (47) two criteria: gene effects must be additive on the average and the non-heritable variance must be independent of the genotype. In each local population heading behavior is uniform under the conditions for which the population has been selected, but genetic diversity may be revealed under changed environmental conditions.

These results support Mather's statement that the population can possess high immediate fitness for its present environment and yet maintain a reserve of variability for evolutionary change. And as Cooper (12) wrote: "Such a population structure provides the genetic basis for local ecological adaptation."

Frandsen (16) pointed out that natural selection may perhaps act on the improved strains when grown in practical agriculture. Often soil conditions are better at the breeding stations. This and other favorable factors "may cause a shift in the genetical composition of the improved strains due to natural selection, a fluc-

tuation which could go in the direction of less productive types." He emphasized that effective breeding work must be combined with a continuous improvement of the environmental conditions which man can influence.

Although few genetic studies have been conducted on drought resistance, especially in forage plants, one can expect that genetic diversity exists just as it does for heading response to photoperiod and temperature in cross-pollinating species of *Lolium*. Similarly, there can be little doubt that self-pollinating species have a reservoir of diversity in the homozygous biotypes that is available for selection by the plant breeder.

Screening Procedures Leading to Selection of More Productive Plants for Arid Regions

Before discussing screening procedures, I should like to describe briefly what has occurred naturally in California in the short span of 185 years. As a matter of record, great changes occurred in the floral composition of some parts of California in as few as 30 years. I believe this brief review will provide some interesting ideas on what might be done to improve the more rapid utilization of introductions and new types of plants.

The majority of alien plants of California have been introduced unwittingly, and according to Robbins (56) "many have become highly undesirable, constituting our worst weeds." According to Parish (54) "It will be safe, then, to assume a very definite date for the beginning of that foreign invasion which since has so greatly modified the plant population of the state. For it must have been a virgin flora that greeted the eyes of Fr. Serra and his companions, when, on the 14th day of May, 1769, they reached the bay at San Diego. . . . The few previous explorers . . . had made but transient landings, but the followers of Saint Francis brought with them flocks and herds, and in the careful preparations for their expedition they had been particularly charged to provide themselves with a store of seeds of useful plants. . . ."

The first mission was established, then, in San Diego in 1769. The last of the chain of missions was built 800 miles to the north, near Sonoma, Sonoma County, in 1823.

Hendry (20) and Hendry and Bellue (21, 22) made admirable

studies of the seeds found in adobe bricks from the walls of old buildings, including missions, whose construction dates are known. If time allowed, it would be interesting and enlightening to discuss in detail the introduction and spread of weeds, species by species. Only a few can be mentioned, but these will serve to point up the problem. *Hordeum murinum* L. (common foxtail) is one of the most widely distributed grasses on range and pasture lands. Seeds were found in adobe bricks from missions constructed in 1775 and in 1780. Brewer and Watson (3) reported it abundant in the south coastal area by 1860, in 1890 Hilgard (24) described it as a "fearful nuisance" in Central California, and in 1902 Davy (13) reported it rapidly coming in on the ranges of northwestern California.

According to Robbins, twenty important alien grasses were fairly well established in the state by 1860. These include annual *Bromus* spp. and *Hordeum murinum* with obnoxious seed characteristics, and desirable annual species of *Bromus*, *Avena*, *Lolium*, *Medicago*, and *Erodium*. From 1860 to 1900, *Bromus mollis* and several obnoxious annual *Hordeum* species became well established.

The rapidity with which these alien annuals invaded an area is attested by Davy (13). From Sherwood Valley, Mendocino County, he gained an idea of the primitive flora. When the valley was first settled in 1853, *Danthonia californica*, a perennial bunchgrass, was the dominant and most valuable grass of the hillside and valley floor. In 1902 the prevalent grasses were *Bromus racemosus*, *Hordeum murinum*, *Festuca myuros*, and *Aira caryophyllea*, all introduced species except the latter. Reports indicate that one good forage grass, *Bromus mollis*, was not present in the state before 1870, but in the short span of thirty years it was very abundant in most regions of the state (56). Talbot *et al.* (66) again called attention to the "great extent to which the native vegetation over vast areas in California has been replaced by plants introduced from the Old World."

What is the explanation for the rapid spread of these annual plants in California? They have proved to be extremely well adapted to the environmental conditions in the state, having superseded, under past and present management, the original

bunchgrasses that were abundant before settlement by Europeans (8).

Oryzopsis miliacea was introduced into California in 1879. Attempts to use it in range seeding programs were unsuccessful. Not until it was tried in the ash of brush burns was its place in revegetation recognized (37, 41). Similarly, in the midwestern United States, *Agropyron desertorum* (formerly called *A. cristatum*) was introduced in 1898 and again in 1906. Not until the 1930's were commercial seedings really successful (14).

In California *Medicago hispida* has spread over much of the range land. On two terrace soils, however, it has never become well established. *Trifolium hirtum* from Turkey, introduced by the U. S. Department of Agriculture, and *T. incarnatum* were first tried on these soils in 1944. *Trifolium hirtum* was so successful that in five years it was in seed production, and many thousands of acres were seeded to it and *Trifolium incarnatum* and *T. subterraneum* (38, 44). For the last two species, seed supplies were already available. The recent introduction and spectacular adaptation and usefulness of *Trifolium hirtum* in California is in rather direct contradiction to Whaley's (68) statement. He wrote that although imported plants ought to be subjected to continuing investigation, "We must, however, face the fact that the world's flora is now well known and that the likelihood of discovering a plant that will grow satisfactorily in such regions as those with which we are concerned, and produce in quantity substances of considerable usefulness, is at best slight."

This brings to mind the work of Duisberg (15). By means of alcohol extraction he produced an edible livestock feed from the desert shrub, *Larrea divaricata*. If industrial use could be made of associated resins and acids, as well as the feed constituents, perhaps the latter could be supplied to the livestock industry at economically practical costs. This type of research on plants other than grasses and forbs might well pay dividends.

Experience with *Oryzopsis miliacea* and *Trifolium hirtum* indicate that these species are adapted to certain ecological niches. The screening procedure necessary is to find these ecological niches. The *T. hirtum* story is worth pursuing further. It was known that these terrace soils were extremely deficient in phos-

phorus. The obvious approach was to apply sufficient phosphorus so that the desired plants could be grown. However, all attempts to establish *Medicago hispida* failed, although many elements were tried. Such fertilizer plots overseeded in later years with trifoliate clovers gave remarkable forage yields, averaging three to four times that of the unimproved range. In fact, *T. hirtum* succeeded even without additions of phosphorus.

The lesson to be gained is that one plant will succeed on a soil where another has failed. This idea is not new, for it is the very basis of successful agriculture, but perhaps the idea has not been carried far enough in our thinking about range lands.

In addition, then, to climatic adaptation we have established the fact that two other factors must be considered: soil and the plant species.

If we think of the plants on the range as a crop, the next consideration is how to harvest it. In other phases of agriculture, special harvesting methods are generally required, depending on the crop. For example, it is readily appreciated that lettuce, barley, and cotton have different harvesting requirements.

In most agricultural crops a weed is recognized as a weed, e.g., *Amaranthus* spp. in cotton. This also applies to some of our range weeds. It is recognized, too, that the weeds reduce crop yields by competing with the crop for water and nutrients. A poisonous plant such as *Halogeton*, and extremely undesirable ones such as *Hypericum perforatum*, and some of our brush species stand out as special problems and their control may be attacked in orthodox ways.

In general, however, the problem of weeds and weediness on our ranges is not so simple. It is often one of degree.

On much of California's foothill ranges the cover includes the following winter annuals. They may be grouped into two classes:

Undesirable	Desirable
"the weeds"	"the crop"
<i>Gastridium ventricosum</i>	<i>Erodium botrys</i>
<i>Festuca</i> spp.	<i>Bromus mollis</i>
<i>Hordeum</i> spp.	<i>Avena</i> spp.
<i>Bromus rubens</i>	<i>Trifolium</i> spp.
<i>B. rigidus</i>	<i>Erodium cicutarium</i>
	<i>Medicago hispida</i>

Everyone may not agree with this order, but I have placed what I consider the most undesirable first on the list. *Bromus rigidus* is a borderline grass. It is palatable and nutritious when young, but the ripe panicles are obnoxious because of the barbed awns on the seeds which do not readily shatter. For this reason it is placed in the "undesirable" column.

In some fields, undesirable species may comprise 90% of the ground cover. What method of weed control can be used to change this balance? No chemical has yet been developed that will perform this miracle.

It was customary in the early days in California, as elsewhere, to turn animals into a field or area and leave them there as long as possible. In the fall there was a scarcity of feed, but in the early spring, an excess. Since the introduced annuals spread so rapidly, this grazing system must have favored them. Given free choice, animals will select and choose their forage plant by plant. As the more palatable plants are consumed, livestock turn to the less palatable ones.

Continuous use, then, favors the less desirable species. It should be obvious, then, that if we want to discourage such weedy annuals, we must change our harvesting program.

Experiments to test this idea were reported by Love (34) and Jones and Love (33). Both mowing and grazing were used. In a clipping experiment half of each of twenty-four plots of *Stipa*, seeded in the fall of 1942, were mowed April 1, 1943, and the other half, May 13, 1943—about six weeks later. Counts made in January, 1944, showed a reduction of 30% in stand in the first set compared with a 71% reduction in the late-clipped plots.

In the second experiment fall seedings were subjected to intensive grazing by sheep at two different dates, beginning April 2, 1943, and April 20, 1943. Plant counts were made September 23, 1943. Eight perennial grass species in plots totaled 255 plants in the first field and only 75 in the second. Apart from actual numbers, those plants in the first field were healthy and vigorous at the end of the dry season in 1943, whereas those in the other field were poorly established with weak root systems, barely holding the crowns in contact with the soil. Love wrote (34): "The fact that during this critical period (i.e., the first spring following

seeding) the grazing animals did not damage the seedlings, but, on the contrary, reduced the competition provided by the annuals, is a fundamental one and points the way to the improvement of the California range."

Eight years of tests on a livestock ranch confirmed the preliminary tests (38, 39, 40, 45). Thus it was that Murphy, Love, and Berry (52) were able to recommend grazing methods following the biological control of *Hypericum perforatum*.

These experiments have brought into focus the fourth element of our complex climate-soil-plants-livestock.

Some of the ecological interrelationships of range plants were learned from these experiments. For instance, good stands and growth of desirable winter annuals, particularly legumes, reduced the succeeding population of summer weeds such as *Hemizonia* spp. and *Trichostema lanceolatum* (38, 44). The latter can grow only in fields where undesirable winter annuals mature before all subsurface moisture is exhausted, leaving some available for the summer weeds.

Admitting the importance of increasing drought resistance and improving screening procedures, perhaps these are not of the most immediate urgency. Even more urgent now is the need to create a more favorable environment for the adapted plants already available. The way to create this more favorable environment is by the application of agronomic principles of crop production to range improvement. Consider the complex of range species as a crop (with weeds, to be sure) and learn how to harvest this crop by livestock. Manage the area to encourage the crop and discourage the weeds. Love and Sumner (45) defined this agronomic aspect of range improvement as "the process of replacing a relatively undesirable population of plants with a more desirable type of forage."

In the last decade, particularly, men trained in fields other than ecology have taken an increasing interest in range improvement. New concepts are being developed. A typical purely ecological definition is that of Sampson (1952): "Range management is the science and art of procuring maximum sustained use of the forage crop without jeopardy to other resources or uses of the land."

Sampson goes on to say: "A knowledge of agronomy and animal husbandry, however, is highly useful to the range manager, though these subjects apply less directly to the understanding and solution of range problems than such subjects as plant physiology, ecology, and taxonomic botany." Evaluating the range in terms of its climax status presupposes that the climax vegetation is the most productive or most economical (64). It is encouraging to see different ideas expressed by some workers in America (40, 45, 48), New Zealand (49), and Uruguay (57).

How Can We Develop a Program of Revegetation?

This question may have been directed to the broad program after basic research information is available. It will be discussed in two parts: research and development.

Avenues of Research

There are several aspects to revegetation, any one of which is more applicable to some land than to others. On some ranches a combination may be used with great benefit to the whole operation. These aspects are fertilization, use of competitive plants, seeding of long-lived species, and special problems.

1. *Fertilization of Otherwise Unimproved Range.* Research in California has shown two ways that fertilization can be used to improve forage yields: first, the use of phosphorus or sulfur to increase the yield of resident legumes (2, 9, 10, 38); second, the use of nitrogenous fertilizers alone or in combination with phosphorus and sulfur to increase total production and also to provide feed earlier in the season (25, 33, 38, 46). In extensive tests Martin and Berry found that yields of meat could be increased two- to fivefold, the better soils providing the lower increases and the poorer soils, the higher increases. Conrad (10) has developed an "exploratory" test method for this purpose (Figure 1).

2. *Fertilization of Improved Seeded Range.* This will be discussed in the following paragraphs.

Use of competitive plants. The fact that on many soils annual legumes respond to phosphorus or sulfur fertilization makes possible an important development in range improvement. A dense

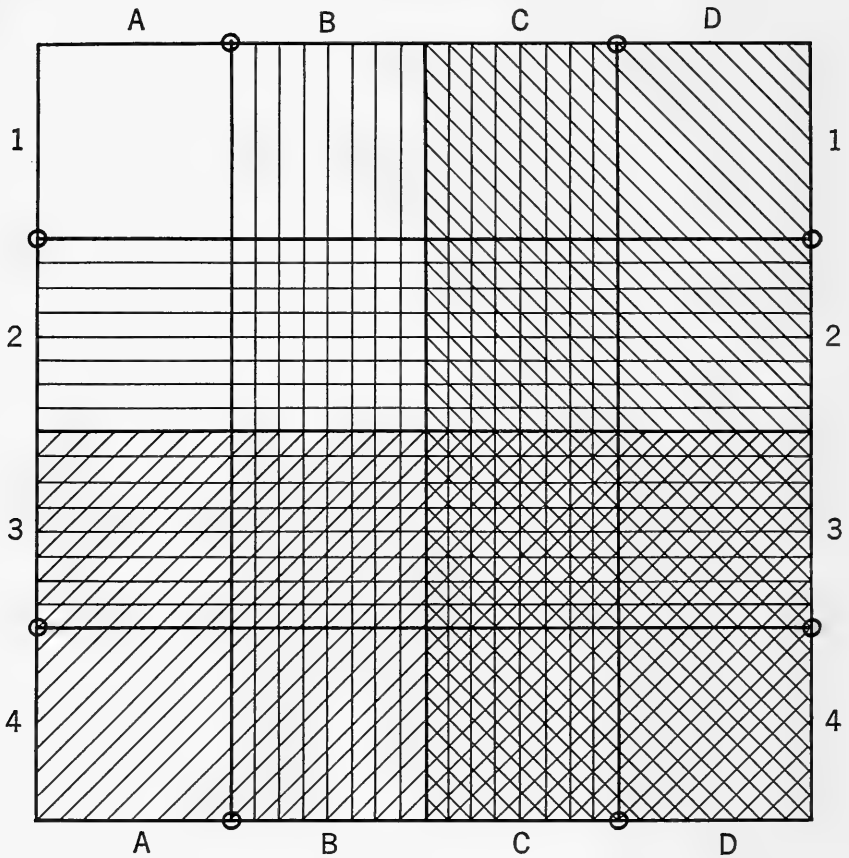


Figure 1. Exploratory layout to determine nutrient deficiencies on the range by plant response.

The following materials and amounts are suggested for each 60-by-80-foot strip:

Horizontal strips: 1-1, nothing applied horizontally. 2-2, 8 pounds treble superphosphate. 3-3, 8 pounds treble superphosphate and 8 pounds muriate of potash in turn applied uniformly. 4-4, 8 pounds muriate of potash.

Vertical strips: A-A, nothing applied vertically. B-B, 16 pound, gypsum. C-C, 16 pounds gypsum and 4 to 8 pounds ammonium nitrate. D-D, 4 to 8 pounds ammonium nitrate.

Just before the stakes are pulled if two or three handfuls of borax are spread in a circle of about 2 feet diameter around each stake as indicated by an open circle, the killed growth makes the plot easy to find later.

population of annual legumes, together with concentrated grazing, will reduce the population of undesirable annual grasses and summer weeds to a remarkable extent. Therefore, fertilizers and soil amendments should be tried along with the annual legumes.

Annual legumes are perhaps the most promising species for improving and increasing returns per acre in arid areas. They are more nutritious than annual grasses, whether green or mature, and they provide more flexibility to the year-long livestock operation. In some instances seed can even be broadcast into resident sod without seedbed preparation (69).

Seeding of long-lived species. Begin tests on arable land, if at all possible, and use the best agronomic methods to establish a stand (42, 43). We have found that a summer crop such as sudan-grass (*Sorghum vulgare* var. *sudanensis*) is ideal preparation for a dryland pasture seeding. The sudan provides some summer feed, and the grass and legume seeds can be planted directly into sudan stubble without further seedbed preparation. Actual seedling counts at the University of California's Hopland Field Station indicated that 19 times as many seedlings of *Phalaris tuberosa* var. *stenoptera* were established following sudan as following wheat. This is primarily due to the reduction in competition of resident species by the sudan crop.

Adapted perennial grasses are worth striving for since they have a much longer season of use than annual forage (33, 34, 38, 40, 51). Again, fertilization together with judicious grazing increases yields of perennials. In an experiment at the University of California's Hopland Range Field Station 400 pounds per acre of ammonium-phosphate-sulfate fertilizer increased perennial forage production four times over the 200 pounds per acre application. Fertilization the second year after seeding yielded two-tenths pound per day of sheep weight gains compared with one-tenth pound unimproved, unfertilized range at the Station.

Fertilization, combined with controlled grazing, not only increases forage production but may also improve its quality by creating a more favorable environment for the desirable species. Many of the species on lands of low fertility are "invaders" which by their very nature are the least desirable plants from the standpoint of livestock production. They may be highly desirable from the standpoint of soil conservation, but man cannot afford to wait for the successional trends that over the centuries will result in an improved cover.

A rotational system of grazing should be designed to harvest

A	B	C
Water "O"	Water "O"	Water "O"
Early Close Grazing First Year	Early Close Grazing Second Year	Early Close Grazing Third Year

Figure 2. Standard seasonal grazing rotation plan.

the crop when most advantageous. This calls for at least three subdivisions of the range. Each subdivision is grazed heavily one year out of three at the time of maximum flush of growth to control the undesirable species as outlined by Jones and Love (33). This system has been further discussed by Love (40) and Murphy *et al.* (52) (see Figure 2). Jones (formerly Extension Agronomist) and Love made a survey of hundreds of test plots in California in 1942 and 1943. They had been seeded in the years 1937 to 1942 by the Agricultural Extension Service under a program designed by B. A. Madson and Jones. (It is a pleasure here to pay tribute to these two men who started to teach Californians that there are differences in grasses). This survey showed that many more failures could be attributed to exclusion of livestock (i.e., protection) than to excessive grazing. In the protected plots the weeds gained control. These observations have been amply verified since.

Special problems. In California, as in some other regions, brush is an undesirable plant that reduces forage yields. Fire, herbicides, and mechanical equipment may be used alone or in combination to get rid of the brush in preparation for revegetation by desirable grasses and legumes (41).

Development of Program of Revegetation

Two aspects of a development program are private and public. The individual owner must decide on the program to be de-

veloped on his property. This will be determined by his needs and opportunities, and of course will have to fit in with other farm operations such as grain growing and irrigated pastures. Incidentally, experience has shown that in California about ten acres of unimproved range are required to supplement each acre of irrigated pasture (33).

Non-arable land may be fertilized to provide early feed. Arable land that cannot be irrigated may be seeded to legumes to provide late green feed or feed during the dry season (44). The better soils may be seeded to mixtures of perennial grasses and legumes to extend the green feed period.

Governments may assist in a number of ways. More money put into research programs would undoubtedly pay dividends. At the farm level, such programs as the U. S. Department of Agriculture's Agricultural Conservation Program is helpful in assisting farmers financially.

What Are the Economic Possibilities?

A few examples will be given from California experience.

In 1950 when the first farmer began his project of converting poor land to annual clovers his cost for land preparation, fertilizing, and seeding were about \$20.00 an acre. Carrying capacity the first spring following seeding was trebled, returning at grazing rental rates \$15.00 an acre. Aftermath grazing added another \$5.00 an acre to the returns. By 1952 his costs were down to about \$15.00, primarily because the new clover seeds were more abundant and cheaper. Another farmer seeded and phosphated 350 acres in 1953 at a cost of \$8.00 per acre. His net return (based on cattle gains) was about \$10.00 an acre the first year. A herd of 700 animals had access to the 350 acres for 50 days in the spring and averaged 46 pounds more than a comparable herd on unimproved range throughout the season.

A perennial grass-annual clover mixture produced 79.3 pounds of beef per acre July 12 to October 3, 1953, in addition to a grazing period in the spring and about 120 sheep-days per acre cleanup later that same fall. The gross return that year alone was well over \$20.00 per acre. With trial plots as a guide, there is no ques-

tion of economic returns resulting from fertilization of unimproved ranges.

What Are the Possibilities of Maintaining Larger Human Populations in Arid Areas?

The answer to this question seems to follow directly from the preceding discussion. It has been shown that arid lands in a Mediterranean type climate can be made from two to ten times more productive by improved agricultural practices. This makes the livestock economy a more efficient one, and if one acre can be made to produce what now takes two to ten acres, a larger human population can be supported.

It was pointed out, above, that one of the difficult problems confronting the range manager is efficient harvesting of the forage crop. Because animals are "selective" in their grazing habits, that is, when they have a choice they will first graze the most palatable plants. On a so-called overgrazed range, reducing livestock numbers for the season is of little avail since the animals can still select the most palatable plants first. Such a policy will result only in continuing the trend of range depletion.

A three-field, three-year rotation grazing plan for California foothill ranges has been described earlier in this paper.

The California Forest and Range Experiment Station conducted five years of research on a five-field, five-year rotation grazing plan at their Burgess Spring Experimental Range on the Lassen National Forest in Northeastern California (A. L. Hormay, unpublished). This is in the Great Basin zone where the grazing season is June 1 to September 30.

The California Region, V, of the U. S. Forest Service has put this plan into operation on a 32,352-acre allotment, of which 20,645 acres are usable as range. The allotment is fenced into five fields of approximately equal carrying capacity. During the 5-year period each of the range units receives a different grazing treatment. The timing of heavy grazing and resting is based on the growth requirements of *Festuca idahoensis* (Idaho fescue)—the key species in this allotment. This plan has been put into effect with no reduction in livestock numbers, and it is confidently expected that grazing capacity will be increased in later years.

This additional example has been given to encourage others to plan similar rotational grazing systems based on the growth requirements of the key species. Intensive grazing at appropriate periods, followed by resting, will assuredly result in more efficient use of the range resource.

Conclusions

Everyone interested in the development of higher producing grasslands and the more efficient utilization and conversion of the feed grown should read C. P. McMeekan's talk presented at a plenary session of the Sixth International Grassland Congress (49). He presented the philosophy underlying the interdependence of grassland and livestock. He concluded: "The most effective use of grassland frequently involves the temporary abuse of both pasture and animals, and [I] make a plea for the clear recognition of this by those interested primarily in the pasture itself. Grassland improvers must also never forget that pasture is useless unless usable. I believe the recognition of these two facts is essential if further development of our grasslands is to result in healthy, productive swards in terms of animal use."

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Animals and Arid Conditions: Physiological Aspects of Productivity and Management

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The rapidly increasing amount of scientific information about animals in arid climates now permits some general conclusions which can provide a fruitful basis for further research on the practical aspects of animal management and production.

From results obtained in recent research emerge principles which could be easily applied to the thinking and the projects of the practical research worker, and also by those concerned with planning the future of arid lands and their populations. It is evident that no more can the fate of man be left to chance. The scientist's responsibility is to make his conclusions available so that his hypothesis can be put to the hard and rigorous test of practical use. This paper is presented in the hope that it may clarify how simple reasoning may transform scientific facts into practical considerations.

How Can Animal Production Be Increased?

The yield of animal products can be increased in a number of different ways, well known, but not always well practiced where

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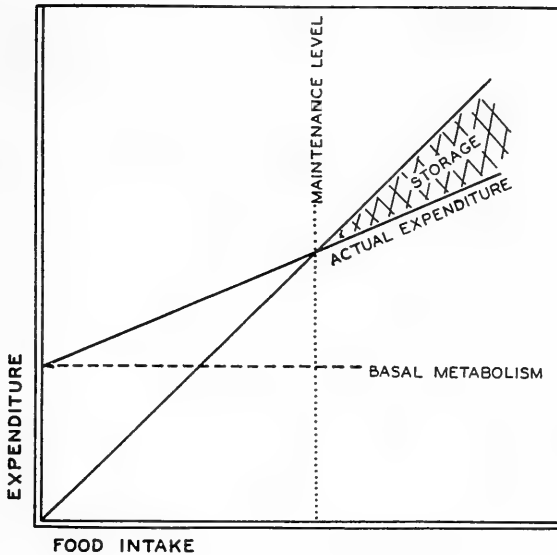


Figure 1. Production of animal tissue (cross-hatched area, labeled "Storage") can take place only when the level of feeding exceeds the maintenance level. The line labeled "Basal Metabolism" refers to the metabolic level when no food is taken in. Food intake raises the metabolism, and the quantity of food required for maintenance will therefore exceed the basic metabolic level. With increasing food intake, the energy expenditure increases steadily as indicated by the line "Actual Expenditure." The "Maintenance Level" is where the "Food Intake" equals the "Actual Expenditure."

This is a simplified illustration and does not refer to any specific data. The slope of the curve "Actual Expenditure" includes expenditures for obtaining the food, for digestive processes, and waste. If the vegetation is scattered, more work is expended to obtain it, and production is decreased.

they are most needed. Production (which in the following refers to production of consumable animal foodstuffs) can be increased in two ways, either by increasing the amount of feed or by a better utilization of the feed available. The first problem, increasing the feed, is a problem for hydrologists in irrigation, for agriculturists in selection and improvement of plants, and in fertilization, etc. In this paper I shall mainly concern myself with the second problem, that of utilizing the feed available as natural vegetation on

lands where agricultural improvements cannot easily be made. However, I shall return to the question of increasing the amount of available feed in a somewhat different way, with stress on the word "available."

Colonel Draz, in his paper in this symposium, has pointed out the importance of raising the level of nutrition of the animals for increased production. It is obvious that when animals are fed just enough for maintenance, no production can take place. By cutting down on the number of animals, the same amount of feed will serve for production as well as maintenance for the rest of the animals. How production increases with increasing level of feeding, but only above a certain level, is shown in Figure 1.

One desirable way to increase actual production on a limited feed supply would be to indoctrinate the animal owners in this very simple fact of production physiology.

In Norway, as a young student, I tried to convince a country woman of the poor economy of keeping chickens too long. She was unwilling to kill any hen that was still producing some eggs and was unable to see that they consumed an ever increasing amount of feed as compared to her return in eggs. It must be equally difficult to teach principles of production economy to populations where wealth and social prestige is proportional to the number of livestock.

It is well known that overstocking reduces productivity also in another way, which has more serious proportions because of its more far-reaching effects. I am referring to the effects of overgrazing on depletion of vegetation, and the consequential reduction of plant production, soil erosion, increased aridity, etc. It may prove less difficult to inform people of this chain of events than of the more subtle arguments of production economy.

The Physiological Role of Water

In arid lands feed is not the only limiting factor; water is a precarious commodity that in the hotter part of the year takes on the role of a limiting factor of all-encompassing importance. Here also there are two ways out: providing more water or being more economical with the available water.

Obtaining more water is not always simple. Large scale drilling for water has been practiced in the southwestern United States with effects on the water table that have been described as disastrous. A similar decrease in the water table in some Old World arid areas would involve a much more precarious situation if wells in villages and oases were starting to dry up. Obviously, large scale irrigation cannot be started without careful consideration of long range effects, but when found possible, it is a most efficient way of handling the production problem.

The other possibility is that of using the available water to better advantage. In the following I shall present some general considerations of this problem, and in order to illustrate principles I shall simplify matters as much as possible.

In winter, the water content of the vegetation is high. At the same time the animals need relatively small amounts of water because the temperature is low and water is not used for heat regulation. Animals do not return frequently to the wells, and may therefore graze over large areas. They can utilize well the vegetation which is at its maximum productivity. The range of the animals is restricted by management and herding problems, and a nomadic (or semi-nomadic) management seems more advantageous because it will permit the utilization of areas far away from human settlements.

The amount of water in the plants may be so high that at least the camel becomes completely independent of drinking water in the winter time. We have offered water to camels that had been without it for two months, and they would not drink. Subsequent examination of blood, tissues, stomach, etc., showed them normally hydrated. In the summer the situation is different. The vegetation dries up, and at the same time the animals need water for heat regulation.

In all deserts one finds some mammals, mostly small rodents, that seem completely independent of water. The American kangaroo rats and the Old World jerboas, for example, do not drink water and can thrive indefinitely on only dry food.

Even the driest seeds contain some absorbed water, but a larger quantity is formed by the oxidation of the food in the body.

On oxidation one gram of starch yields 0.6 gram of water and one gram of fat yields almost 1.1 grams of water. By exercising the greatest physiological economy with water expended for urine and feces and for evaporation (which cannot be completely avoided because the expired air is saturated with water vapor), those small rodents can just manage on the oxidation water, being independent of intake of free water.

These small animals do not use water for heat regulation. They are nocturnal and remain in their underground burrows throughout the hottest part of the day. They are an ecological paradox, living in the desert without being exposed to the rigor of desert heat.

The large animals cannot escape the desert heat by hiding underground. To avoid undue rise in the body temperature they evaporate water from the surface of the skin (sweating) or from the moist respiratory surfaces (panting).

The oxidation water which goes a long way for the small rodents would not go far in the water economy of an animal using water for heat regulation. The amount of oxidation water formed in man is about one-quarter liter per day (on a metabolism of 2,000 kcal) and is insignificant when sweating rates may be over 1 liter per hour or 10 to 15 liters or more per day.

Water and the Camel's Hump

This seems to be the place to discuss a widespread misconception with respect to the role of oxidation water in the water balance of the camel. It has been said that since oxidation of fat yields more than its weight in water (1.07 grams of water per gram fat), a camel that walks into the desert with a hump with 40 kg fat actually carries a potential water supply of more than 40 liters. This, of course, is true, and has led to the deceptive idea of "water from the hump." What was forgotten is that oxygen is required to oxidize the fat. This involves ventilation of the lungs and loss of water in the expired air. The amount of evaporation from the lungs is of the same magnitude as the quantity of water formed. In very dry air it would exceed the oxidation water, and even in moderately dry air there will be no appreciable gain.

TABLE 1
Comparison of Foodstuff Used, Oxygen Taken up, and Water Formed
Metabolic level 10,000 kcal

	Foodstuff used kg	Oxygen Used for Oxidation of Food liter	Oxidation Water Formed kg	Approx. Water Evap. from Lungs in Dry Air kg
Fat	1.06	2130	1.13	1.8
Starch	2.39	1980	1.33	1.7

One further and rather striking fact is that fat yields almost twice as much oxidation water as starch. Seemingly fat is more advantageous to the water economy than starch. However, fat also yields more calories. This means that when the water yield is related to metabolic rate, the apparent advantage disappears.

Let us make a simple calculation: A camel has a metabolic level of, say, 10,000 kcal, and if he uses exclusively fat or exclusively carbohydrate we can use the comparison presented in Table 1.

For a given metabolic level one finds that more water is formed if starch is metabolized, than would be formed by metabolism of fat. Also, the evaporation from the lungs, which is proportional to the oxygen consumption, is higher when fat is burned. Although water is formed in the oxidation of fat, the conclusions must be that: (a) incidentally to the necessary oxygen uptake water is evaporated from the lungs in an amount similar to that formed in the oxidation process, (b) the evaporation from the lungs is slightly higher when fat is metabolized, and (c) at a given metabolic level starch would yield more water than fat. The biological truth is that fat is the most widespread form of energy storage in the animal kingdom, and in this sense the camel is no different from other animals. Fat gives more energy per weight unit than other foodstuffs, and the economy in carrying the reserves as lightly as possible is indeed very useful, particularly to an animal that may be deprived of an adequate food supply for extended periods of time. The water economy of the camel, then,

is not located in the fat of the hump. Strict economy in water expenditure is the all important factor.

Water Economy of the Camel

It was mentioned before that the sweating rates of man in the hot desert may be as high as 15 liters per day or more. Compared with this quantity, the water lost in urine is quite insignificant. The minimum urine output in man is about 300 ml per day, and if the kidney were more efficient and could produce twice as concentrated urine, it would be possible to save 150 ml of water, or one per cent of the amount evaporated. While such an efficient kidney is essential to the kangaroo rat, the relative saving is unimportant in a large animal that uses water for heat regulation. The quantity of water used for evaporation may be tremendous, and if some economy could be accomplished in this amount it would be of great significance.

When the temperature of the environment rises above that of the animal (more precisely, that of the skin surface) heat will be conducted to the animal from the hot surroundings by conduction from the air and by radiation from the sun and the hot ground. Body temperature can be kept from rising only by evaporation of water.

It is a consequence of the simplest physical laws that less heat will reach the animal surface if there is an insulating layer between the heat source and the body. There is a great deal of physiological truth in the old saying that the Arab wears so many garments to exclude the desert heat. The woolly coat of the camel has a similar function in the summer. In our recent experimentation we showed that the camel's fur was an efficient factor in reducing water loss in the summer. Of course, the fur is also an efficient insulation against loss of body heat in the winter.

Another and major factor in the water economy of the camel is the variation in his body temperature. In the summer a camel may have a morning temperature of 34° and an afternoon maximum of 40.6° to 40.7° . Man, when exposed to a hot environment, will, by evaporation of water, maintain a practically constant body temperature of about 37° . The variability of the camel's

body temperature has a double advantage. In hot environments the camel, instead of evaporating water, permits the body temperature to increase to a maximum of about 40.6° . This increase can be regarded as a storage of heat in the body, heat which can be dissipated in the cooler night without expense of water. But there is one further important advantage to the high body temperature. The difference in temperature between the hot environment and the body will be smaller, and since the movement of heat is proportional to the temperature difference, less heat reaches the body and less water is required to prevent a further increase in body temperature.

This reaction, which is a well-regulated physiological mechanism, effects a very considerable economy with water in the two ways just mentioned.

Length of Time Without Drinking

The time an animal can tolerate lack of water in the desert depends on the rate of water loss, and the limit to which actual desiccation of the body can be tolerated. We have just seen some of the physiological mechanisms which result in an exceptionally low rate of water loss in the camel. They are so efficient that the rate of water loss in this animal in the summer is less than one-third that of the donkey, which is also well adapted to the desert climate.

The camel can also withstand an exceptional degree of dehydration of the body. In one case a camel had lost more than 40% of its body water before it was allowed to drink. This should be compared with the situation in man and other mammals which die from explosive heat rise when 15-20% of the body water have been lost in hot surroundings. However, the donkey can tolerate as much depletion of the body water as the camel, showing that this animal too is exceptionally well adapted to desert life.

The camel, since it has a low rate of water loss and tolerates considerable depletion of the body water, can go for a long time without drinking. How long he can go without water depends not only on external conditions of air temperature, wind, solar radiation, etc., but also on how much he works, how far he has

to walk and at what speed, what load he carries, what feed he eats and its water content, what grazing he can do, etc. It is therefore meaningless to discuss whether a camel can go for 5 days or 10 days without water; as we have seen he can go entirely without water in the winter.

Drinking Capacity

When the camel drinks he fills up with water in a short time. On one occasion a camel that weighed 325 kg (when dehydrated) drank 103 liters of water in less than 10 minutes. The water becomes evenly distributed in the body in less than two days. The blood and tissue fluids become rapidly diluted to an extent that would not be tolerated by other mammals, which would die from water intoxication at a much lower water intake. This difference poses a number of important physiological questions that are being further investigated.

One important observation is that the camel, as well as the donkey, drinks an amount of water corresponding to the amount of water depletion, but they do not drink more than that needed to bring the water content of the body back to normal. In other words, there is no extra intake of water that could be regarded as a storage, or a supply to be drawn on when need arises.

The legendary structure of the camel's stomach, which as early as in Pliny's *Historia Naturalis* was interpreted as serving water storage, serves no such purpose. When carefully examined it is clear that such a function would be extremely unlikely. The glandular rumen sacs that are supposed to hold the water, could not possibly store a significant amount. Furthermore, they contain more solid food than the major part of the rumen, and the fluid which can be obtained from them has the same salt concentration as the general body fluids. However, this does not contradict the widespread tale that an Arab in an emergency will kill his camel and drink the fluid in the stomach. The fluid would serve well in an emergency, and one finds abundant amounts of fluid in the rumen of the camel, just as in other ruminants. The mistake is made in implying that it is stored water.

Nitrogen Utilization on Low Grade Feed

The rumen, however, serves another important function in the camel. Investigations on the physiology of renal function in the camel revealed an extremely low excretion of urea when the feed was low in protein. In one particular camel fed on dry dates and hay, the total urea excretion was less than 1 gram per day, corresponding to the metabolism of about 2.5 grams protein per day. There is no reason to believe that the actual protein metabolism would be that low in such a large animal. If one remembers that urea (or ammonium compounds) when fed to cattle is synthesized into amino acids by the bacterial flora of the rumen, and that cattle can be fed a major part of their "protein" supply in the form of urea, one sees what may happen in the camel. Urea retained from secretion in the urine may be re-used as protein via bacterial synthesis in the rumen.

When urea was injected in large amounts in a camel, less than one-tenth was recovered in the urine. Stomach samples showed an increased urea and ammonia content, and it is reasonable to conclude that protein was synthesized in the rumen as it is in cattle fed urea.

The value of this ability to re-use the protein nitrogen is obvious to any animal husbandry man who works with low grade pastures. It is not unlikely that other ruminants would behave like the camel, and we are now in the process of investigating whether the sheep can utilize a similar "urea cycle" when fed an extremely low protein diet.

Role of Physiology in Production Considerations

If one summarizes the physiology of the camel the following features stand out:

1. The camel can withstand an unusually high degree of water depletion, and it also has a very low rate of water loss; in combination, these two factors mean that the camel can go for exceptionally long periods without drinking.
2. The camel (as well as the donkey) has a very unusual drinking capacity, which means that, when water is available, it can fill up in a very short time.

3. The camel (and the donkey) maintains its appetite in spite of dehydration. While other animals will lose their appetites when deprived of drinking water, the camel continues to eat until the water depletion becomes severe.

The value of maintaining the appetite will be clear when one considers that tolerance to water deprivation permits the animal to graze over a large area, and continued food intake is the essential to the utilization of the available grazing.

The effect of the range of the animal on the area available for grazing is illustrated by the diagram in Figure 2. The areas that can be covered by different animals are encircled, using as radii the number of days the animals can go without water in the severe desert summer (Sahara). (The figure for sheep is only an estimate because we lack sufficient data.) In reality, the animals do not remain away from water until the limit of endurance. In the western parts of the Grand Erg Occidental of the Sahara, the sheep are returned to the wells for watering every day in the summer. The camels stay away for several days but will return on their own initiative within four days. This is in the same proportion as the maximal endurance, as indicated in the diagram by the numbers on the radii.

(The actual areas covered may be even more to the advantage of the camel because of the much greater speed of this animal.)

I would like to discuss separately the meaning of this diagram to maintenance and to production.

In summer, vegetation and water supply are at a minimum, and an important problem is to maintain an animal stock sufficiently large so that later the winter grazing can be efficiently utilized. In this case the problem is one of maintenance rather than production. Assuming that the vegetation density is uniform over the areas represented in the diagram, one can calculate the approximate relative numbers of animals that can be maintained, and likewise, as given in the diagram, the total weight of meat maintained.

When the time of abundant feed comes, production is resumed. At this time one might prefer a rapidly reproducing and growing animal in order to utilize maximally the food available. However, this reasoning is fallacious. It is true that production is more

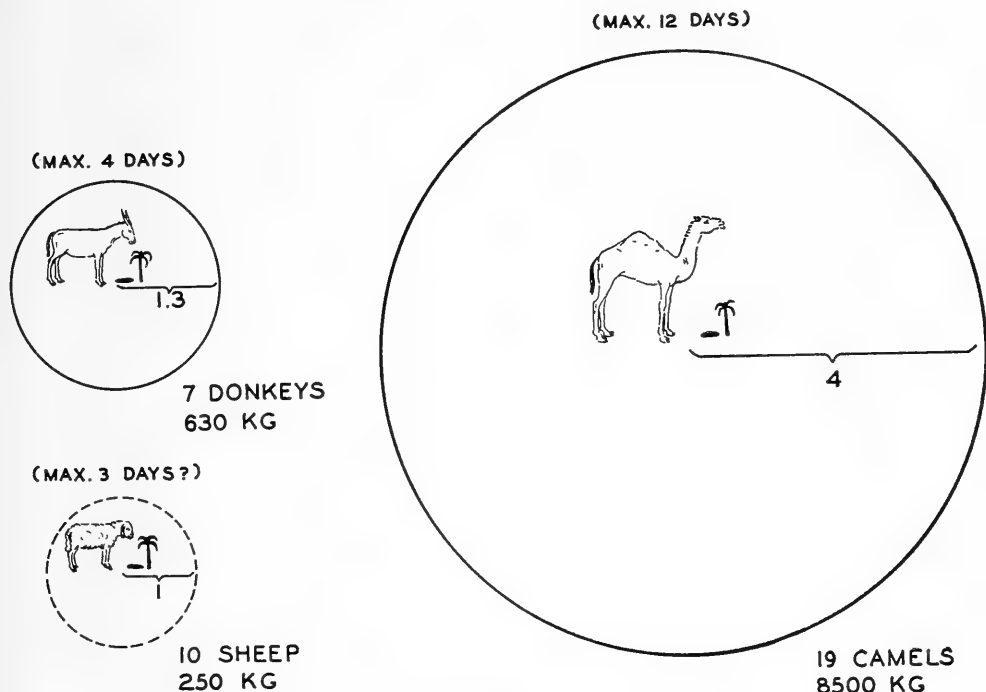


Figure 2. Relative grazing areas for camel, donkey, and sheep. The radii of the circles are in the same proportions as the number of days (approximate) that the animals can go without water.

The relative numbers of animals that could be maintained on these areas with a given constant vegetation density throughout the area, have been calculated. For this calculation only maintenance requirements have been considered (and not growth or meat production), since during the summer time satisfactory maintenance of a relatively large stock is more important in order to have a large size herd for production when vegetation is more easily available in the winter. (In this consideration the question of overgrazing has been disregarded.) It is in the summer that the grazing area is restricted by the access to water, and this coincides in time with the lowest availability of vegetation in the same area. In winter the grazing area of the camel is not limited by water supply, and its range will then be determined by the practical limitations of the human herders.

rapid in a small animal (sheep compared to camel), but the maintenance expense per kilogram is also higher. It has been shown that the production per unit feed is approximately independent of body size of the animal; in other words, for a given amount of

feed, camels should produce approximately the same amount of meat as sheep. Due to the larger grazing area, more feed is available to the camel and productivity should be correspondingly higher.

It therefore seems that from the standpoint of production as well as maintenance the camel would be far superior to the sheep. (The donkey, now used only in small numbers, can be left out of consideration because its meat, for religious reasons, usually is not eaten.) The tremendously higher estimated production of the camel is a point I would like to emphasize as a most important subject for future practical research in order to test the validity of the ideas presented here. From the theoretical considerations it seems amazingly clear that the camel offers a most obvious solution to increased meat production in arid zones with a low natural vegetation density that cannot easily be increased. On this point practical research is urgently needed.

Human and Social Factors in Management

The possible success of practical attempts to utilize the principles just outlined for increased production will depend entirely on the management of the herds with respect to avoidance of overstocking. Some further human and social factors are also of great importance.

In the areas I know from personal experience, camels are of great importance for meat production. At the present time camels are butchered when they are very old or when, for other reasons, they cannot be kept without difficulties (for example, vicious males or sick animals may be butchered young). When meat production is the main purpose nothing is gained from maintaining fully grown animals. It would be better economy to butcher the animals young and maintain only the still productive animals. For this purpose, of course, all reproducing females are productive, and it would seem most efficient to maintain a herd of females with a sufficient number of mature (but young) males for breeding. Other males should be regarded as having completed the role of production. It may require much thoughtful educational work before such viewpoints gain general acceptance in these areas.

The following can be used as illustrative examples. I have seen a vigorous and well-fed young male camel butchered because it was too vicious to be handled. It brought the owner a price of nearly 50,000 francs. I have also seen a very old scraggly female camel being brought to butchery by its owner because unexpectedly it became pregnant and was not expected to survive it. It brought 18,000 francs, probably half of what it could have brought a few years earlier.

It would also be important to investigate the effect of castration of the males on the final yield of meat and fat, and whether castration should be done in the very young animal or, for example, a year before butchering.

Where low grade pasture cannot be readily improved, it can be utilized to advantage along the principles outlined above only in connection with nomadic or semi-nomadic life. The availability of cheap labor for herding is a requisite condition for this type of production.

It has often been said that modern means of transport, in particular the automobile, are rapidly making the camel superfluous. This is true for long distance transport, where now even the Sahara is crossed by a network of roads with rather regular bus and truck traffic. On a smaller scale the camel still maintains great importance in transport, but its use may in the future yield more to the truck. However, in meat production on vast areas of low grade arid lands the camel may maintain its role. In production of meat the truck can never complete.

The truck may, however, depose the camel in this field, too, in an indirect way. As a representative of the mechanized culture the truck represents higher wages, fostering settlement and abandonment of primitive nomadic life. The situation is not unlike the migration of the rural population to the big cities in so many Western countries.

Many oases, at least in the Sahara, depend on the nomads for meat production. Areas inaccessible to the settled populations can be used for production by the nomads. Settlement leads to overgrazing of the area immediately surrounding the settlement, unless means and resources are available for adequate irrigation. One of the great dangers in planning the future of arid lands is the belief

that the Western way of life and a mechanized culture are always a step forward to peoples now living close to a marginal existence.

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The Locust and Grasshopper Problem in Relation to the Development of Arid Lands

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Grasshoppers and their larger swarming relations, the locusts, are the oldest and most serious enemies of agriculture. Since their depredations are particularly great and persistent in the regions with arid or semi-arid climate, it should be of interest to present a brief outline of the locust and grasshopper problem as it already exists in arid lands, and as it may be affected by accelerated development of them.

Mosaic Vegetative Cover

An essential feature of the ecology of grasshoppers is that different stages of their life are passed in different environments. Eggs are laid in the ground, usually in bare spots, whereas the young hoppers and adults require abundant vegetation for food and shelter. Therefore, a complete environment must include two kinds of habitat: oviposition habitat and food-shelter habitat. This implies that a patchy, mosaic vegetative cover is more favorable to these insects than uniform vegetation.

The mosaic type of vegetation is most typically met with where two major vegetation zones are in contact, e.g., forest and grassland, prairie and semi-desert, or savanna and desert. It is in fact in such transitional belts that grasshoppers and locusts generally reach their maximum economic importance. Thus, in

Siberia, the species of grasshoppers which occur commonly over the steppe zone, become persistent pests mainly on its northern fringe where it comes in contact with forests and a mosaic of grassland and forest is formed. In Australia, the areas particularly favorable to grasshoppers are characterized by a transitional mosaic of low shrubs and bunchgrasses.

In Central Asia and in tropical Africa, the migratory locust thrives on the edges of river flood-plains overgrown with dense tall reeds and grasses but bordering on semi-desert grassland with sandy bare patches. The mosaic structure of vegetation is, on the other hand, often directly due to human activities, or very much accentuated by them.

In Siberia, the clearance of forests for settlement and cultivation has created favorable conditions for the extension of steppe grasshoppers into the former forest zone, while the fallow system of agriculture, with disturbed land lying idle for several years, has produced a mosaic of weeds, grass, and bare patches eminently suitable for mass outbreaks of these pests.

In the dry hill pastures of Mediterranean countries, excessive grazing and destruction of perennial shrubs for fuel and by goats have resulted in a cover of short bunchgrasses, with abundant bare spots, and here the Moroccan locust is enabled to thrive. Similar examples of human activities favoring grasshoppers and locusts are found in South Africa, Australia, and North America. In the Philippines and Indonesia, deforestation and seasonal burning have resulted in forest-grassland mosaic, enabling the migratory locust to live and multiply where it could not even exist before. In the Sudan, mechanized cultivation in the transition zone between the tall grass and short grass savanna has caused several native grasshoppers to become important pests.

Effects of Human Activities

In all these cases, the general effect of human interference has been to destroy the original uniform structure of vegetation and to create a mosaic in which the more arid habitat was particularly encouraged to expand, together with its grasshopper population. The importance of such increase in the ecological aridity

of the area lies in the fact that outbreaks of grasshoppers are usually associated with a series of dry years. The effects of dryness in favoring grasshoppers are, naturally, greater in an environment which is partly arid naturally, or made so by man. A feature of mosaic habitats, particularly those created by man, is their instability, as the relative extent of their arid and more humid parts is likely to vary from year to year. This has an important effect on grasshoppers, which are very mobile insects. Even in most equable conditions, they move from the food-shelter habitat to the oviposition sites, but when the contrasts are very strong such movements extend and become migrations, leading to a concentration of the insects in crops.

The result of migrations is especially striking in the case of locusts. A relatively favorable season may cause a great increase in a local population of locusts; if this is followed by drought, this population would move and concentrate in the most favorable places. This creates crowding, to which locusts respond in a most characteristic way—they acquire gregarious habits and travel in dense masses. As the direction of flight of locust swarms is largely dependent on winds, the swarms arising in one area may travel great distances and invade fertile lands far from their birthplace. An extreme case of this kind is offered by the desert locust of Africa and western Asia. The home of this species is in deserts which are generally extremely arid, but are liable to localized rainstorms. Such rains bring forth abundant ephemeral vegetation, on which locusts can multiply rapidly. In a few weeks, however, the plants wither away and the locusts, if they have had time to grow up, must migrate elsewhere or perish.

Swarm flights follow seasonal winds and generally end in an area where such winds bring rain, so that locusts can produce a new generation many hundreds of miles away from the previous one. The survival of such nomadic insects is clearly dependent on the chance of swarms reaching an area where they can feed and reproduce. In this respect also, man is already beginning to make their life less hazardous; some areas in the Sudan and Arabia, where natural vegetation is green for only a few months in the year and that only if rain happens to fall, have been irri-

gated for cultivation, and they now harbor locust populations which otherwise would not have been able to survive without migration. Irrigated crops in the southern United States, Argentina, and Central Asia suffer from grasshoppers whose existence in these arid lands was made much easier by man.

Development of Semi-Arid Lands

This much too brief survey of the problem should be sufficient to show, first, how erroneous was the old belief that grasshopper and locust plagues are a feature of undeveloped lands and almost belong to the past. On the contrary, there is no doubt that the grasshopper plagues in semi-arid lands have been created by their much too rapid and thoughtless development, in the same way as the deterioration of soil and its erosion. Moreover, even now and even in the better developed semi-arid countries, the problem tends to become more and more acute, and ever increasing efforts and expenditure are required to reduce losses from grasshoppers by chemical methods, which alone will never provide a satisfactory solution. This experience of the already developed semi-arid countries should serve as a warning to others where schemes for the opening of vast new semi-arid lands are being considered.

Development of Arid Lands

The development of the truly arid lands is only beginning, but we have seen that it is almost certain to benefit such inhabitants of the desert as locusts. Their life is full of hazards at present, but should the "islands" of cultivation in the desert become large and numerous, they would save many a nomadic swarm from starvation and provide conditions in which local populations of locusts could multiply.

Even apart from encouraging locusts directly, cultivation of desert lands is certain to increase the risk of crop losses as a consequence of making more crops exposed to locust attack.

All this does not mean, of course, that development of arid and semi-arid lands should be discouraged. My object is merely to draw attention to the need for taking into account its possible

hazards, among which locusts and grasshoppers have already proved to be outstanding. These particular hazards can be avoided if they are carefully studied before it is too late. One hopes that the future development of arid lands will not follow the pattern of the semi-arid ones, where a rapidly expanding exploitation of the land preceded an understanding of its long-range consequences. In the typical semi-arid country of North Africa, the Moroccan locust is called in Arabic *djerad-el-adami*—man's locust. This name is appropriate to most locusts and grasshoppers, as it has been man who has encouraged and continues to encourage them by short-sighted land usage.

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Desert Agriculture: Problems and Results in Israel

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Phytogeographically and climatically, 36% (9,468 km²) of the area of Israel belongs to the Mediterranean, 16.3% (4,288 km²) to the Irano-Turanian, and 45% (11,835 km²) to the Saharo-Sindian territory (17, 18). This means that even the best agricultural region of Israel, the Mediterranean region, is semi-arid, and the rest of the country is classified as either arid or very arid. Consequently, our agriculture had, from the very beginning, to deal with arid zone problems, and we can consider the whole country as a large-scale experiment in problems of aridoculture.

The ever increasing population of Israel has prohibited the limitation of our agriculture to the best regions, and forced its extension into our Irano-Turanian steppes and Saharo-Sindian deserts.

That this was really done is clearly seen from the figures for the Negev* (Table 1).

Whereas in the northwestern part of the Negev agriculture is based on supplementary irrigation with water piped there from northern Israel, it was decided that in the rest of the arable Negev all agricultural practice will be based primarily on the use of local

* The Negev is the southern part of Israel and roughly comprises the Irano-Turanian steppe region in the north and the Saharo-Sindian desert region in the south. The whole region receives only winter rainfall. The yearly average for the Irano-Turanian region fluctuates between ca. 150 and 300 mm, for the Saharo-Sindian between ca. 25 and 125 mm. As in all desert regions, rainfall is very uncertain as to amount and season.

TABLE 1
Number of Agricultural Settlements in the Negev between 1945 and 1955

Phytogeographical region	1945	1950	1955
Irano-Turanian	11	38	46
Saharo-Sindian	2	8	15

rain water. The latter is what we call "desert agriculture" in the following pages.

The reason for using only the natural precipitation is twofold:

1. The relative scarcity of one of the most important natural resources of Israel, i.e., water, necessitates its more rational use.
2. Irrigation water from the north cannot economically be raised the necessary 500 meters and conducted over great distances to the few arable patches scattered here and there in the Negev.

The whole project aims at trying to collect information about the possibility of maintaining a larger population in an extremely arid area, by the sole use of its natural water resources, and is, therefore, highly experimental. The results which this project would achieve may be of universal importance in similar arid zones elsewhere.

The first results of five years of experimental desert agriculture carried out by a large team of research workers* will be summed

* The main cooperating agencies are:

1. The Israeli Ministry of Agriculture (Departments of Water Utilisation, Soil Conservation and Ecology).
2. The Israeli Ministry of Development.
3. The Israeli Government Department of Antiquities.
4. The Israeli Government Meteorological Service.
5. United States Operations Mission in Israel, Sections of Range Development and Water Spreading.
6. The Hebrew University of Jerusalem and its Departments of Botany, Geology, Geography, Archaeology and Agriculture.
7. The Technion in Haifa (Divisions of Hydraulics, Agricultural Engineering, and Soil Conservation).
8. The Weizmann Institute of Science in Rehovot.
9. The Agricultural Experiment Station in Rehovot, especially its departments of Soil Science and Field Crops.

(Footnote continued on page 392.)

up here. Special stress will be laid on the problems. Most of these could not be seen at the start, and evolved only during the course of the work. Based on the experience gained during this work, it will be possible to evaluate more realistically the future possibilities of desert agriculture and its contribution to the solution of the human food problems.

The first lesson to be learned—important in the past and even more so for future work—was that desert agriculture is possible only when preceded by planned, thorough, scientific fact finding about the area involved. Geological, pedological, biological (especially phytogeographical, phytosociological, and plant physiological), meteorological, and archaeological surveys must be carried out. These surveys have to be done cooperatively. Vital meteorological data, for example, which could not, in our case, be based on decades of records, could be worked out only on the evaluation of ecological and phytosociological observations. For this purpose the method of “shifts in amplitude,” using the IE-amplitude of certain indicator plants (7–11) or the distribution and limits of distribution of certain plant associations (9–11, 42, 45, 46, 48) are very useful. We may point out here that ecology, phytogeography, and phytosociology are very important auxiliary disciplines for all surveys in general. Thus, for instance, no pedological survey is complete without the distribution map of the main plant associations (42, 48), and the most important demarcation of the borderlines of arable zones can be done only by observing the yearly fluctuations of the annual vegetation (10, 47). These surveys should, therefore, never be an *ad hoc* compilation of facts but an integrated product of scientific teamwork, without emphasizing only immediate practical needs.

10. The agricultural settlements of Sde Boker (in the Negev Highlands), Mashabei Sade, and Revivim (on the loess plains), Yotvata and Ein Yahav (in Nahal Arava).

Special thanks are due to the Ford Foundation. A great part of the work reported here could be carried out only with the help of the generous grant given us by the Ford Foundation. By doing so the Ford Foundation has greatly furthered our knowledge of desert agriculture with all the practical consequences thereof.

As a result of these surveys we possess today, *inter alia*, a sound geological knowledge, a detailed phytogeographical, phytosociological, and pedological map of the Negev, transforming an area, which twenty years ago was largely terra incognita to science, into a scientifically better known area than even certain parts of Europe.

One may be astonished to find archaeology in the above-mentioned list of necessary surveys. As will be shown later, the archaeological survey has made a most valuable contribution to the solution of practical agricultural problems. The study of archaeology should, therefore, never be neglected in regions where previous civilizations existed in desert areas.

The practical importance of these integrated surveys as the first essential in desert agriculture cannot be overemphasized. Whenever we tried to jump ahead and to find empirical solutions without possessing the necessary data, we were faced with costly failures that could have been avoided had necessary scientific information been collected and analyzed before taking the first practical step.

The second essential, we learned, was that any team working on a project of desert agriculture has to be extremely versatile and elastic. Some of the main practical problems could not be foreseen when the working plan was made. They emerged, sometimes in the most unexpected way, only during the course of the practical work. The research team, therefore, has to be ready and scientifically capable of dealing with all kinds of unexpected problems by either tackling them themselves or by enlarging the circle of cooperating agencies. Since most of the problems which have to be solved are scientifically fascinating as, for instance, the problem of germination, it is sometimes difficult to remember that practical results are the goal and that we cannot allow ourselves to get lost in most interesting, purely scientific research.

In the following pages we shall deal with some of the main problems of desert agriculture. Emphasis will always be laid, in accordance with the main theme of this conference, on the lesson to be learned from it for future work and not so much on the results achieved.

Germination and Vegetative Propagation (27, 28)

It became clear, when we started, that for all reseeding work a thorough research on the germination conditions of the seeds involved is of paramount importance. We can state today with certainty that any reseeding project in desert areas is doomed to failure when it does not provide for a special systematic research on germination and propagation problems. We should like to illustrate this point by citing a few examples.

In the course of an investigation on the use of the wild growing plants of the Negev for industrial purposes it was found that *Juncus maritimus*, a perennial hydrohalophyte, produces excellent raw material for the paper industry. In order to propagate this plant, seeds were collected, and field sowing was carried out in the Negev. It failed completely, as the seeds did not germinate. The problem was then handed over to our germination laboratory where it was found that *J. maritimus* is an obligatory light germinator (between 20° and 30°C). Treatments with thiourea and potassium nitrate, which are known to promote dark germination in light-requiring seeds, did not abolish this need for light. It was concluded that *J. maritimus* could be propagated by seed only by means of surface sowing, in spite of the agrotechnical difficulties involved.

A method was therefore worked out to sow the seeds in shallow ditches on top of continually moistened soil. This was carried out in Yotvata (Nahal Arava) with very satisfactory results.

It is interesting to note that a chloride content of ca. 4,800 ppm in the water did not affect germination. In sodium chloride solutions containing 7,000 ppm chloride, germination percentages decreased, but the germinated seedlings were not injured, although the chloride concentration had eventually increased twice to threefold by evaporation during the tests.

During the search for good native pasture plants it was found that *Colutea istria*, a perennial legume growing wild in the dry stream beds (wadis) of the Negev highlands, is an excellent pasture plant. Its germination is, however, inhibited in two ways: the seed coats are impermeable to water and they also contain a water-soluble growth inhibitor which considerably retards seed-

ling growth. This retardation of growth is a very important factor, as germination and seedling growth have to be very rapid in order to establish this plant in its climatically unstable natural surroundings. A practical method had, therefore, to be developed for the removal of the coats before sowing the seeds.

Oryzopsis miliacea is a perennial grass, valuable both for pasture and soil conservation, various ecotypes of which are native to nearly all regions of Israel. In the northern part of the country reseeded of the plant in fall was practiced. The seeds germinated gradually during early spring. For reseeded under desert conditions, where soil moisture is available for much shorter periods, such prolonged germination is, however, out of the question. A method for hastening germination had to be worked out. It was found that the seeds contain a water-soluble germination inhibitor which is removed by treating the seeds with sulfuric acid. Seeds thus pretreated may be dried without impairing their germinability. This is important, as after the acid treatment the seeds are wet and cannot be sown by mechanical means.

In addition, it was found that the acid-treated seeds need for optimal germination either a daily alternating temperature of 20° and 30°C, independently of light, or a constant temperature of 20°C with the addition of light. This would have meant that, under constant temperature conditions, the seeds should be sowed very superficially with all the resulting hazards. However, it was found that dark germination could be increased to nearly 100% when the dark is interrupted by a short period of illumination at any time after the first day. A method was then developed by which the seeds were illuminated for five minutes after twenty-four hours of imbibition in the dark, and then dried. Seeds thus treated germinated well in darkness under all temperature conditions, and our germination problem was solved.

Many more such examples could be cited all of which would prove the one point already made, namely that no desert agriculture is possible without collaboration of a germination laboratory where the germination conditions of the seeds involved may be investigated. The reasons are obvious. The seeds of most desert

plants contain different mechanisms which regulate germination by means of inhibition. Under natural conditions this results in inhibited germination which either fractionates germination over many years or limits it to coincide with the infrequent suitable conditions for the species. These are modifications of survival value for the species insuring it against extinction in a year in which incipient good germination conditions are followed by a period of drought. But in agricultural practice we must attain just the opposite, i.e., very rapid, simultaneous germination at the time of sowing. As the time of sowing has to be chosen very carefully—and the question of when to sow is one of the main problems confronting desert agriculture—one has to be absolutely sure that germination is rapid and uniform. This can be achieved only when the germination of a given seed has been carefully studied, its germination mechanisms explored, and its requirements for external germination conditions are known.

The establishment of a germination laboratory in connection with each local project for desert agricultural research is not enough. There must be a central international organization where all the information obtained about germination of desert seeds in different regions of the world is collected and correlated. The reasons for this suggestion are obvious. The local germination laboratories must serve a practical need and, as pointed out before, should not get lost in the purely scientific research problems involved. On the other hand, usually, only part of the work done there on different seeds is published in scientific journals. This information should also be fed into a central collecting agency and stored there where it can be available to everybody.

The propagation of species suitable for desert agriculture is concerned not only with reseedling but also with vegetative propagation.

When the vegetative propagation of the important pasture plants *Hordeum bulbosum* and *Phalaris bulbosa* by transplanting of bulbs was tried, it was found that bulbs removed from the soil at the end of the growing season lose their viability completely after four to seven days. This makes their storage impossible. An investigation was undertaken, therefore, to find out if there are

developmental stages where the bulbs keep their viability during longer periods of storage.

Another problem arose with *Atriplex halimus*, an excellent pasture plant. After extensive research it was found that this plant can be propagated by seeds after proper pretreatment, but cuttings can be used as well. The problem here was to see if there is any periodicity in the rooting response of cuttings. In this field, too, the lesson learned was that only by physiological research can the proper methods for vegetative propagation be found. This can be done only through the cooperation of a laboratory of plant physiology.

Selection of Plants

Here, naturally, the main problem is the finding of suitable pasture and other economically important species for reseeding purposes. The greatest part of our efforts was concentrated on local species and arid ecotypes, which are able to withstand prolonged periods of drought.

Selection of Pasture Plants (12, 13)

In the selection of pasture plants for desert agriculture considerations other than those for moister climates have to be taken into account:

(a) Grasses utilize soil moisture up to a depth of 120–150 cm. In some of the main wadis in the Negev, moisture penetrates 300 to 400 cm. This deep lying moisture may be utilized if deep-rooting pasture shrubs are found. Such a mixed grass-shrub pasture would afford a more rational utilization of available soil moisture.

(b) In the desert the growing seasons for most grasses coincide with each other and last throughout late winter and spring. This limited grazing season may be extended by reseeding with ever-green shrubs like *Atriplex halimus*.

(c) Legumes in general are essential for nitrogen-deficient desert pastures and for providing high-protein pasture.

Consequently, great advantage may be gained from a mixed pasture consisting of grasses (perennials and annuals), deep-

rooted pasture-shrubs, and legumes. The most promising species were found to be:

Local perennial grasses: *Hordeum bulbosum*, *Oryzopsis miliacea*, *Cynodon dactylon*.

Perennial grasses introduced from neighboring regions in Israel: *Phalaris bulbosa*, *Oryzopsis holciformis*, *Agropyrum junceum*.

Annual grasses: *Avena sterilis*.

Annual broad-leaved herbs: *Medicago* spp., *Trifolium* spp. *Malva* spp.

The extremely drought-resistant *Panicum turgidum* deserves special mention as it is at the same time an excellent binder of shifting sands and a recognized pasture plant.

Of the shrubs suitable for pastures we mention *Atriplex halimus*, an omni-Mediterranean meso-halophyte, well eaten by all animals. It may also be used for human consumption as a boiled vegetable or salad. The bush branches out profusely from its base, and can be used well in soil conservation and for the prevention of flash-flood damage. Large-scale reseeding with this species has already been successfully attempted (especially for reinforcement of dykes and terraces).

Calligonum comosum is a Saharo-Sindian species which, together with *Haloxylon persicum*, forms the climax vegetation of sandy soils situated on the borders between steppe and desert (9). It is apparently a good prospect as a pasture plant. Experimental reseeding has already given promising results.

Colutea istria, a Saharo-Sindian leguminous species, is considered an excellent pasture shrub, and has already been used for reseeding of depleted desert pastures.

From pasture plants introduced from abroad we mention: *Panicum antidotale* and various *Atriplex* species like *Atriplex semibaccata*, *A. spongiosa*, *A. vesicaria*. Our *A. halimus* seems, however, to be more suitable under local conditions.

Oryzopsis miliacea and *Phalaris bulbosa* strains, which originated in the Mediterranean area, were improved upon in the United States, and then were reintroduced to Israel. As far as desert agriculture is concerned our own local ecotypes seem to be superior.

Selection of Industrial and Pharmaceutical Plants

Mention has already been made of *Juncus maritimus* as raw material for our paper industry. Israel possesses a modern paper mill which uses imported raw material. *Juncus maritimus* has been investigated thoroughly from a technical point of view and first class paper has been produced from it (29). Its planting and sowing in salt marshes of the Negev is still in the experimental stage.

As regards pharmaceutical desert plants, we are carrying out a systematic survey of our desert flora, searching for plants which contain pharmaceutically important substances. At the same time, plants known to contain drugs are being investigated as regards the amounts of the active constituents and their seasonal fluctuations (37, 38). With the exception of *Hyoscyamus muticus*, large-scale culture of these plants has not yet been attempted. Our main prospects are:

Hyoscyamus muticus for atropine.

Anabasis haussknechtii for anabasine.

Artemisia herba-alba and *Artemisia monosperma* possess anthelmintic properties. From the essential oils of *A. monosperma* a new substance, furoartemone, was isolated, a furan compound possibly of great importance.

Peganum harmala for harmine and harmaline.

Periploca aphylla, *Daemia tomentosa*, *Leptadenia pyrotechnica* for various glucosides.

Gypsophila rokejeka for sapogenin.

Capparis spinosa for heart alkaloids.

Achillea fragrantissima and *A. santolina* for essential oils.

Agave sisalana, introduced as an industrial fiber plant, contains in the unused parts of its leaves hecogenin, which can be used as a starting material for the synthesis of steroidal hormones.

Special mention has to be made of *Citrullus colocynthis*. This belongs to the Saharo-Sindian area, but penetrates into the Mediterranean territory and grows on sandy soils. Its fruit contains the well-known and long-used colocynthin, and its seeds contain 20 per cent oil. This interesting drought-resistant plant could be

used for the breeding of either perennial or drought-resistant watermelons, or both.

Selection of Woody Desert Plants for Various Purposes. (25)

Woody species find their uses in deserts: (a) for shade, which is so essential to the well-being of livestock in the scorching noon-day desert sun; (b) for permanent dune fixation by plants which resist oversanding and blowing out; (c) for shade and beauty wherever human beings settle.

A good local candidate, but not yet used on a practical scale, is *Haloxylon persicum* which is to be found as remnants of former larger "desert-forests" in Nahal Arava. It is a good "fodder-tree" and represents the dominant plant of a climax association. "Large-scale artificial reestablishment in its original area of distribution is highly recommended" (9).

The local *Tamarix* species represented a special problem. This is one instance where considerable financial loss was experienced when trying to proceed empirically without proper scientific preparation. In the earliest stages of this work *Tamarix* was planted indiscriminately on a large scale. It was found that the species used was ecologically the wrong one, and the whole plantation failed in one year's time. Nine species with widely diverse ecological requirements are to be found in Israel, but their taxonomy is most difficult, as everybody knows who ever tried to identify the different closely related species. The thorough taxonomic survey, which is the first precondition for their proper use in desert afforestation, is now being undertaken.

Local *Retama* and *Pistacia* species are at present also being studied taxonomically as only after determining the subspecies and varieties which differ much in their respective ecological amplitude can they be profitably propagated.

Of the introduced species, *Eucalyptus rostrata* may be important. Fourteen years ago a big plantation was made in the Negev on a locality with 100 mm yearly rainfall. Only few specimens survived, apparently representing a drought-resistant strain. They are now being propagated.

Selection of Plants for Sand Dune Fixation (12)

Great areas of the Negev lands are composed of shifting and semi-mobile sand dunes. In order to fix those dunes and at the same time derive some economic profit from the plants which are being used for the fixation, the ecology and economic value of all the plant communities growing naturally on sand dunes of our area were studied.

Testing their resistance against blowing out, oversanding, and salinity, the following plants were found to be most useful: *Fucus maritimus*, *F. acutus*, *Scirpus holoschoenus*, and *Eragrostis bipinnata*, which can all be used in paper manufacture. *Artemisia monosperma* as a pharmaceutical plant, *Agropyrum junceum*, *Convolvulus secundus*, *C. lanatus*, and *Calligonum comosum* as fodder plants. Here, too, the absolute necessity for close cooperation with a laboratory for plant physiology was experienced, especially in questions of germination and propagation, and with a technological laboratory for the testing of the respective plants for their usefulness as raw material for paper manufacture or for pharmaceutical value.

In summing up the results obtained regarding the selection of suitable plants for desert agriculture, it is important to point out that we relied nearly exclusively on the selection of pre-adapted ecotypes either of the region to be developed or of neighboring phytogeographical territories of Israel. The approach to the problem was—with success—an empirical one. Here much has to be done in the future—and is now being done—based on very long-range scientific planning which has to be not only regional but also international. The various ecotypes have to be tested for their different qualities under constant controlled conditions. Genetic strains of these ecotypes have to be developed and hybridization experiments to be carried out.

All this necessitates, again, a well organized international clearing house for systematic exchange of information and its correlation. In addition, it is obvious that a small country like Israel cannot afford installations which are expensive to build and expensive to maintain—where genetic strains developed from local

ecotypes can be tested under controlled conditions like those available in the Earhart greenhouses in Pasadena. The old methods of testing under natural conditions are much too laborious and slow for the rapid tempo needed in a progressive desert agriculture.

Use of Natural Precipitation (6, 30, 31, 40)

As already mentioned, the only source of irrigation for our desert agriculture is the natural precipitation, and the runoff water derived thereof. We learned how to utilize this, mainly by studying the remnants of the ancient agricultural systems of the Nabataeans and Byzantines who once populated the central and southern Negev. There are today six dead cities (1) which were once thought to have thrived on caravan trade only. After an archaeological survey we know that they practiced a highly developed desert agriculture and possessed a very elaborate system of utilizing practically every drop of precipitation for agricultural purposes.* After the destruction of these desert cities in the seventh century A.D. (they were founded in the second century B.C.) the intricate system of perfectly and laboriously constructed dams, spillways, and terraces slowly crumbled, and for many centuries they were maintained very amateurishly by desert nomads. Today we partly use the same reconstructed dams and terraces, the same rock-hewn cisterns which the Nabataeans had built over 2,000 years ago. It is thrilling to see time and time again how the present day dispositions of highly complex irrigation systems, calculated by trained specialists, with the latest technical aids, coincide with remnants of ancient irrigation systems on the same spot.

There is today a consensus that in historical times there was no fundamental change of climate in our region (31) and that the Nabataean and Byzantine agriculture in the Negev faced essentially the same problems we are facing today.

* Similar agricultural systems are known from ancient civilizations in the desert areas of southern Arabia and North Africa. A comparative study of such systems all over the world might provide valuable practical and historical information.

The first problem in the utilization of rain water in the desert is how to deal with desert floods and transform them from a destructive force into a creative agent. Even though the rainfall in our deserts is very scant, the limited percolation of water in our desert soils, and the resulting excessive runoff, cause sudden tremendous flash floods in the wadis. After a rainfall of as few as 10 mm on the watershed, for instance, it is no rarity to see a flood of 30,000 m³/hr crashing through a wadi draining a 50-sq km catchment basin for four to five hours. These great quantities of water are practically the only source of irrigation water. But unless they are harnessed, they are lost, and all they cause is extensive soil erosion. Various types of dams, dykes, terraces, and spillways were, and still are, the answer to this problem. Topographical considerations are the decisive factor in the choice of the system to be employed.

After ten years of observation we have reached the conclusion that this type of flood causes a rainfall of a few millimeters to increase soil moisture in the wadis to the equivalent of several hundred millimeters of precipitation. This transforms the wadis and the catchment basins, however small, into productive soil, especially when the natural moistening by floods is augmented by various flood control measures, as described later.

The second problem is an edaphic one. Real soil in our desert area is rare. Most of our terrain cannot be used at all for lack of soil (21). Only where loess, sandy loess, or sand is to be found, or can be induced to deposit by flood control, is agriculture possible. This again means that desert agriculture is possible in strips and patches found only in the above-mentioned wadis and catchment basins, or in sandy plains.

The utilization of water and the agricultural technique are very different in tributary wadis, in the major drainage channels, and in flood plains. Accordingly, we shall treat each one separately.

Tributary Wadis

The first consideration with this type of wadi is that, owing to its narrowness and steepness, a tributary wadi has to be controlled as a unit from the watershed down. Only thus may the destructive

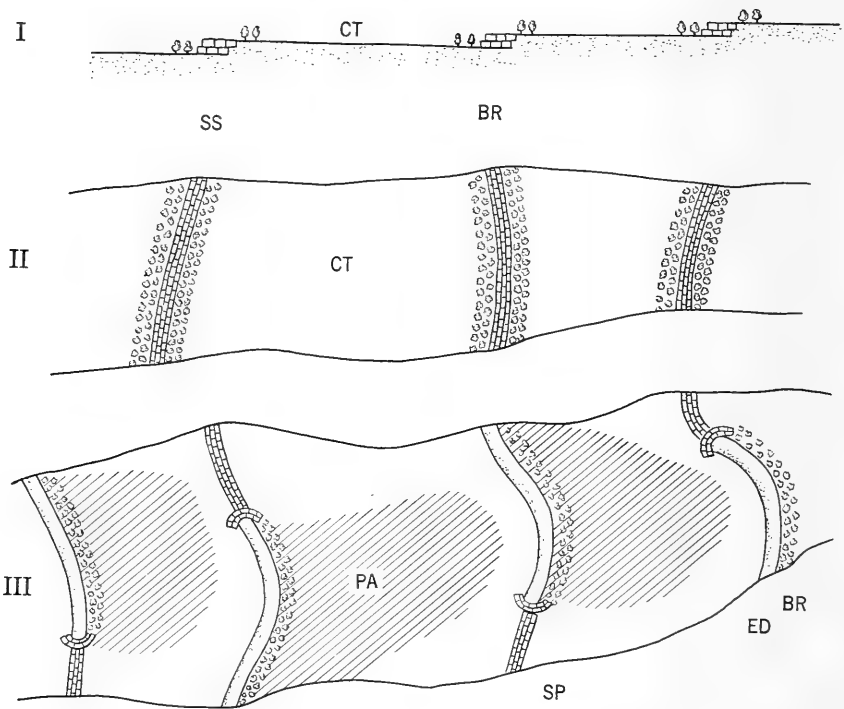


Figure 1. Flood water irrigation. I. Tributary wadis (Schematic). II. Tributary wadis (Plane view). III. Broad flat wadis (Plane view). (Direction of flow is from right to left.)

SS—Stone shelves on contour lines; BR—Bush reinforcement; CT—Cultivated terrace in water course; PA—Ponded area in water course; ED—Earth dyke on contour lines; SP—Stone spillway with reinforcement of dyke tip.

force of the flood be harnessed so that the work done in the lower part of the wadi may not be totally demolished. The total length of the wadi is terraced by a series of broad masonry shelves into level plots, each lower than the preceding one—like the stairs of a staircase. These shelves are quite low (25–50 cm). The wadi is thus completely transformed into a series of terraces, narrow (a few meters wide) in the upper parts of the wadi and broader in its lower parts (Figure 2).

The velocity of the water is thus considerably reduced, the

percentage of percolating water is increased, and greater depth of water penetration is achieved (Figure 3).

Soil particles brought by the run off water from the slopes are deposited on the terraces, the soil quality and topography of which are thus slowly improved, and the terraces further leveled.

The stone dams can be reinforced by the planting of bushy plants like edible *Atriplex halimus*, on inedible *Thymelaea hirsuta*, etc., in front of each dam. A "bush-dam" alone may be sufficient and at times even better than a stone dam. The considerations are: (a) The bush-dam is pliable and may be better able to withstand the force of the flood than solid stone or earth dams. (b) The dam would grow in size concurrently with the silting processes. (c) The bush-dam filters the flood water, thus enriching the soil with organic matter. (d) The costs of construction are lower. (e) Consequently, more dams may be planted per unit area. (f) The plants themselves may provide grazing, but as this may prove detrimental for the dam, inedible species may have to be used to replace the edible ones.

Main Wadis

Floods in main wadis are very strong and cannot be completely stopped by any sort of dam. They can, however, be slowed down. Thus floods cannot be prevented but have to be brought under control in some other way.

According to the quality of the beds of the main wadis, they are agriculturally treated in different ways.

(a) Broad, flat beds are covered by a deep layer of loess. An earthen dyke is built across the wadi on the contour. The dyke does not, however, reach across the wadi, but terminates a few meters before reaching the opposite bank, and is terminated by a broad spillway. The next dyke downstream is built just the other way around with its spillway on the opposite bank. The threshold of the spillway is constructed several decimeters higher than the wadi bed. The water is thus forced to follow a much longer zigzag course down the wadi, instead of running straight down it, and a shallow pond forms behind each dyke. This artificially creates a much gentler slope and slows down the velocity of the water con-

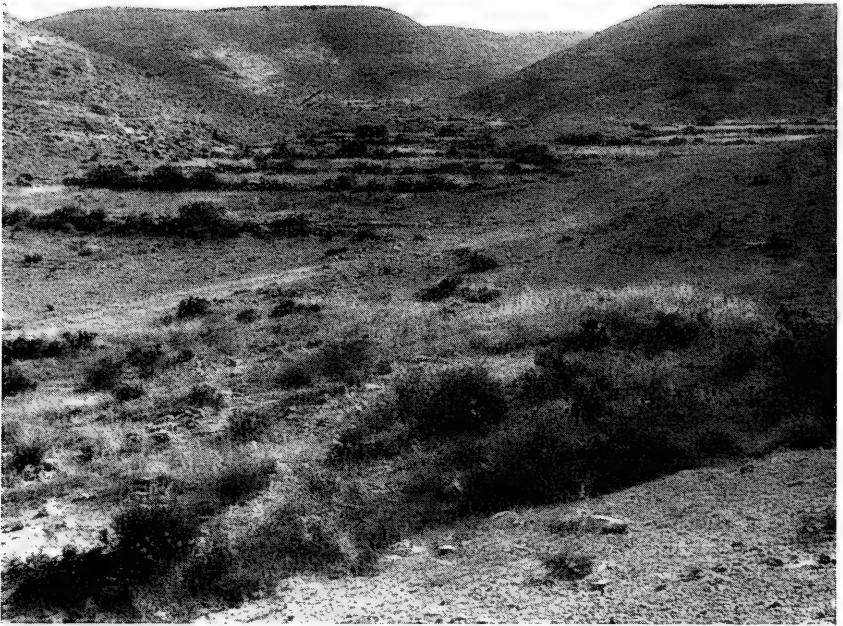


Figure 2. Flood water irrigation in tributary wadis in the Negev Highlands. Two tributaries, completely terraced up to the watershed, stone shelves reinforced with inedible bushes (*Thymelaea hirsuta*, *Haloxylon articulatum*, etc.).

siderably. Danger of erosion is thus reduced, and at the same time, the water has more time to percolate and moisten deeper layers of the ground. The design of these structures is planned on topographic maps (Figure 1, III).

(b) Broad loess wadis are longitudinally dissected by a steep stony watercourse. In this case the shape of the watercourse prevents any flood control. However, it may be, and has been in ancient times, utilized by diversion and spreading on the loess banks, and on higher lying fields on the slopes. That the Nabataeans and Byzantines were masters in this type of agriculture is proved by the very extensive system of terraces left by them and by the excellent, solid quality of the stone walls built round the terraced fields. These fields, which accompany the wadi bed on both sides along its course, are leveled and their edges are protected by low stone walls. The main terrace wall runs perpendicular to the course

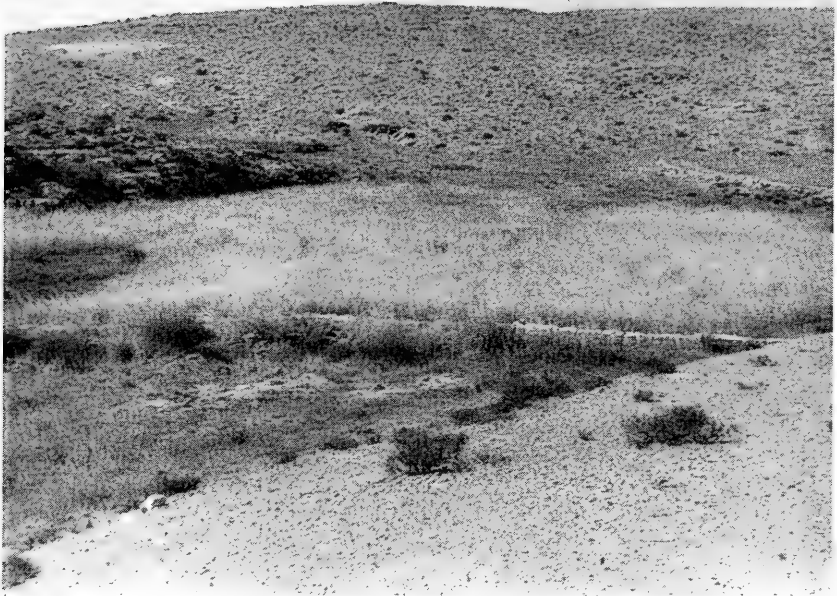


Figure 3. Dense plant cover obtained by efficient water spreading. Terrace thickly covered by *Avena sterilis*; slopes carry *Zygophyllum dumosi*. Uncovered patches on terraces received insufficient water (drought year!).

of the wadi. At the side of the field adjoining the wadi bed a stone wall protects the plot from erosion by the flood water. The terraces thus formed are very broad, completely level, and one only slightly lower than the next. Onto these terraces water is diverted and spread by channels running obliquely from the watercourse.

However, the force of the water often demolishes these channels. The ancient civilizations overcame this difficulty by constructing a solid low stone dam, a few meters thick, at a point below the opening of the channel. The height of this dam controlled the height of the flood water at the mouth of the channel, all excess water flowing over the dam. The force and amount of water entering the channel were controlled by the shape and size of its opening.

We have developed a type of detention dam at a point above the channel calculated to catch most of the flow. The dam is pierced by a large diameter pipe, which permits the flow of a

limited volume of water (about 10,000 m³/hr). This serves a double purpose. First, this controls the maximal pressure of water reaching the channel, and secondly, this constantly reduces the water pressure on the detention dam, and thus helps to preserve it. The earth dam is built sufficiently strong to detain the total flow until it is completely drained off by the outlet pipe at a controlled rate.

Flood Plains

In many places in the Negev small or large level plots of land can be found surrounded on all sides by gently inclined slopes. After a rainfall, the runoff water of these slopes is collected on the flood plain, where it slowly sinks into deeper soil layers. Small, stone-reinforced channels, built obliquely on the surrounding slopes, greatly increase the amount of catchment water.

Before concluding, we should like to emphasize that all our experience so far bears out the well-known truth that there is no soil conservation or flood control without permanent plant cover on the water-spreaded lands.

Agrotechnical Problems (6)

There are a great number of agrotechnical problems involved in desert agriculture. One of the main agrotechnical difficulties encountered in desert agriculture is the rapid formation of a hard crust on the upper surface of the loess soil, whenever the soil has been wetted and starts to dry out. This crust greatly obstructs reseedling by preventing seedling emergence, except from cracks formed in the drying out crust, and by tearing of roots when the crust separates from the subsoil. This problem is being attacked by trying to prevent crust formation by adding soil conditioners (Kryllium and other artificial soil conditioners specially developed in Israel (26) and natural soil conditioners like straw and sand) to the soils. Another type of attack is made via germination. The study of the germination mechanisms of each seed often leads to methods of greatly accelerating germination, so that uniform seedling emergence is obtained before crust formation starts. This is another example of the need for close cooperation between various research agencies, as under these extreme conditions it is

sometimes of vital importance to hasten germination and seedling growth even by a few hours.

The time of sowing is another problem. It is technically easier to sow before the first rain or flood, but there are reasons for not doing so: (1) crust formation; (2) the danger of the seeds being washed away with the top-soil by the first flood; (3) danger of germination after a small rainfall sufficient to bring about germination but insufficient to maintain further growth; (4) on account of the rather erratic occurrence of effective rainfall, the impossibility of deciding on the species to plant until the rain has actually fallen.

All these considerations lead to the conclusion that it is practicable to sow only after the soil has been wetted by flood. This raises the basic agrotechnical problem of methods of sowing in wet clay. This has to be done rapidly, and not be delayed even for one day as the drying of the topsoil is very rapid.

Utilization of Available Saline Water

Most of the available ground water is highly saline. There are, however, a number of plants which thrive on saline water. To cite only a few of the many species on which such work is being done: (1) *Juncus maritimus* as mentioned above; (2) *Phoenix dactylifera*, which is planted extensively at Revivim and along the salt marshes in Nahal Arava, between Yotvata and Elath on the Red Sea shore; (3) vegetables, such as beets and spinach; (4) salt-resistant strains of forage crops, such as alfalfa.

Dew

A yearly water balance of certain desert plants shows that they do not rely only on the water taken up from the soil (20, 22, 23). On the other hand, it seems today a well-established fact that dew is taken up by leaves, and may even be transported from the leaves to the roots where it can be secreted into the soil (16, 35). At the same time it seems to be certain that plants growing under arid conditions benefit decisively by the uptake of dew (16). Are there any practical conclusions to be drawn for desert agriculture from those facts?

Based on ten years' measurements of dew, made with Duvde-

vani's dew gage (14), we possess today figures about the average number of dewy nights per month, and about the amounts of dew formed in different topographical localities and at different heights above the soil surface (3, 12, 24). It will perhaps be possible in the future to choose special localities, rich in dew, for certain crops profiting especially from dew, and to create artificially better microclimatic conditions for the formation of dew on plants and in soils.

In addition, the application of limited quantities of additional moisture in the form of artificial dew might prove useful in conservation of irrigation water resources, especially when performed at night, when plant growth is at a maximum and loss of water by evaporation is at a minimum.

Conclusions and Outlook for the Future

Desert agriculture is definitely one of the many different ways of increasing populations in arid areas. It can be successful only under three conditions:

1. Prior to any practical work, a broad, thorough scientific survey of the area has to be carried out.
2. The surveying and practical work has to be done by a closely knit cooperating team of scientists of all branches of the natural sciences. This teamwork has to be very elastic as constantly new problems arise, necessitating the cooperation of new agencies.
3. The practical work in its pilot plant stage has to center around experimental settlements situated inside that desert area where desert agriculture is being tried out.

It is felt that the establishment of an international center for the storage and exchange of information on desert research is urgently needed. At the same time this center could refer major research projects, which cannot be carried out by small nations for lack of the needed equipment and scientific manpower, to the few specialized, well-equipped, experimental research institutions. It is much too early to discuss the purely economic side of desert agriculture, as we do not yet possess the necessary data. But when taking Israel as an example, it can be said that by using the methods described here, 3 to 5% of our desert area, which up

to now produced nothing, can be converted into productive agricultural land.

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Problems in the Development and Utilization of Arid Land Plants

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Native plants of the desert region of the southwestern United States and northern Mexico, in addition to contributing much to the health and well-being of the inhabitants, have long held the attention of chemists and biologists as potential sources of industrial raw materials. Although attention has been directed to many of the species as containing exploitable quantities of essential oils, medicinal alkaloids, gums, fibers, rubber, tannin and other products (4, 5), very few of them have been studied thoroughly to determine their chemical constituents. An even smaller number, represented by guayule (*Parthenium argentatum*) for rubber (7), and canaigre (*Rumex hymenosepalus*) for tannin (6), have been investigated by chemists, plant breeders, and engineers attempting to improve the plants and the methods of processing to the point where they can be utilized in commerce, either as wild plants or cultivated crops.

Conditions of Commercial Use

Unless the plant product involved is scarce or has unique properties demanded by a particular industry, it must be produced on a competitive cost basis with similar products from other sources. Furthermore, it must be available in sufficient quantity to furnish a fairly continuous supply to commercial users. Candelilla wax, from species of *Euphorbia* and *Pedilanthus*, is an example of a desert plant product which has been in com-

mercial use for many years. The continuous utilization of candelilla wax is based in part on distinctive properties not present in other materials and in part on its price in relation to other similar waxes, such as carnauba (2). The introduction into commerce of any new product from arid land plants will be difficult unless such information is known.

Natural stands of some potentially valuable desert plants, such as canaigre and jojoba (*Simmondsia chinensis*) (3), are not extensive enough to furnish material for commercial utilization. Other species are sufficiently abundant to provide an adequate and perpetuating supply only if they are managed on a sustained yield basis. For example, excessive harvesting of candelilla plants in Mexico without proper provision for regeneration of the plants after cutting, has resulted in depletion of natural stands which appeared to be inexhaustible (2).

Means of Improvement

Cultivation of arid land plants, either for the purpose of supplementing supplies from natural sources or for furnishing the entire supply, offers promise in many cases. Certain species may be adapted to low-cost operations, carried on in conjunction with water conservation practices where sufficient water is not available for crops with high water requirements. The work of various public agencies in reseeding deteriorated areas of range land suggests methods that may be used. Species that can be readily adapted to cultivation, such as canaigre, guayule, and plantago (1), have definite promise as crops in irrigated areas or in areas with marginal supplies of irrigation water. The ability of arid land plants to survive under conditions of extreme water stress makes it possible to grow them under a much wider range of conditions than can be done with other crop plants.

Any program for developing desert plants for commercial utilization should also include thorough investigation of the possibility of developing superior strains through selection and breeding. Substantial improvement in the yield of a desired constituent can often be made simply by selecting desirable plants from natural populations. Investigations carried on with guayule (7) and

plantago (1) have indicated great promise of improvement by means of interspecific hybridization.

Canaigre: An Example

Recent experimental work with canaigre (*Rumex hymenosepalus*) by the Special Crops Project, Agricultural Research Service, Department of Agriculture, may be used to illustrate briefly some of the points mentioned.

Canaigre, a distinctive species of *Rumex*, with tuberous, tannin-bearing roots, grows in scattered stands from west Texas to California and from Colorado and Utah to northern Mexico. In many locations the plants are not sufficiently concentrated to furnish roots for commercial exploitation. Furthermore, roots from plants in the extensive and accessible stands in eastern Arizona, New Mexico, and Texas are relatively low in tannin and difficult to extract. Any industrial use of canaigre for tannin will, therefore, necessarily depend upon roots from cultivated plants to maintain an adequate supply.

Distinct variations in root, leaf, and seedstalk characteristics have been found in strains collected in various locations. Roots from different locations varied in tannin content from less than 20 to more than 40% (dry weight basis). Similar wide variations between strains were found in non-tannin extractives which affect processing quality. When all the collections were grown under the same environmental conditions in southern Arizona, many distinctive characteristics were found to be heritable.

The range of variation in the wild material is so great that practically every characteristic needed in a cultivated crop appears to be available. Some selected lines consistently produce high yields of roots containing more than 35% of readily extractable tannin. Other lines are characterized by desirable root shapes for mechanical harvesting, abundant seed production, and disease resistance. It appears that through the use of appropriate breeding procedures, varieties can be produced that are distinctly superior to the wild types and productive enough for use as a cultivated crop. The use of F_1 hybrids for commercial production also appears to be a promising possibility.

The development of effective methods of production also has an important bearing on the success of any program for converting wild plants into cultivated crops. Early experiments with canaigre indicated that two full growing seasons were necessary to produce economic yields of roots with satisfactory quality. In recent experiments, 15 tons of roots per acre, equivalent to approximately 1,800 pounds of 100% tannin, has been produced in one 10-month growing season. Other results indicate that even higher yields may be obtained from improved strains, using either seed or crowns for planting stock.

Soil moisture is the major factor which regulates the volume of roots produced by wild canaigre plants. The storage roots survive long periods of extremely low soil moisture, increasing in size and number only during favorable seasons. As a cultivated crop in southern Arizona, canaigre requires a limited amount of irrigation to produce satisfactory yields. Adequate soil moisture must be available during October and November to establish the plants, and during March and April to promote root growth and tannin storage. Further study of the seasonal development of canaigre in relation to soil moisture may be expected to lead to more effective methods of using limited supplies of irrigation water.

The processing of canaigre roots into high quality tanning extracts presented several major problems because of the presence of sugar and starch in the roots. Research on processing, conducted concurrently with the breeding and production investigations, has resulted in the development of methods for producing tanning extracts which compare favorably with commercial extracts in tannin content and tanning properties (6). Tonnage lots of canaigre extract will be available in the near future for use in semi-commercial tanning tests.

The progress that has been made in developing canaigre for a source of vegetable tannin for industry illustrates one method of attacking the problem of utilizing arid land plants. Such progress can be achieved only through expensive research on the part of chemists, plant breeders, agronomists, and engineers. Ideally, it should be a cooperative enterprise involving appropriate public

agencies and industries interested in the product to be obtained. Without such a concentrated effort in which scientists of several disciplines cooperate, many potentially useful arid land plants (1, 3, 6) will not become crops or even be extensively utilized.

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Plants, Animals, and Humans in Arid Areas

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Gambling on the climate may be possible in semiarid regions, but the dweller in an arid region has to play safe or perish.—
R. W. Bailey. *Yearbook of Agriculture*, 1941.

In discussing the possibility of improving conditions for production and the standard of living in arid zones, major emphasis is usually placed on bettering and propagating domestic plants and animals.

This is, without doubt, especially important, but I believe that within the whole it is necessary to fit the *arid zone-wild plants and animals-human population-domestic plants and animals* complex. Taking into consideration the four components of this complex, one should try to discover the elements which may serve to balance them from a desirable economic and social viewpoint.

Arid Zone

This is the basic element, the stage on which the drama is set, and its principal characters will be largely determined by the degree of aridity surrounding them. This element does not noticeably change throughout history.*

* I do not forget the profound change which may take place in an arid zone if it is supplied with water; but, in that case, it takes on new characteristics and, therefore, it is no longer necessary to consider it an "arid zone."

Wild Plants and Animals

In the above-mentioned setting, the flora and fauna which naturally live there have become adjusted to the hostile environment and get along reasonably well. The variety of species and the number of individuals which can exist in arid zones is remarkable.

Human Population

In a strictly biological sense, the human race is only one more animal species and, to a certain extent, it thrives in arid zones. But, given man's capacity to act upon his environment, it is necessary to reserve a separate place for him and to consider him as a new element which will fundamentally modify the ones already mentioned.

Domestic Plants and Animals

Man partly maintains himself from the wild plants and animals which exist in arid zones. However, as soon as he establishes himself, he introduces domestic types which constitute a new element, altering the zone's natural dynamic equilibrium, that is, the equilibrium existing when the impact of human action is not felt.

Balance of the Four Components

Undoubtedly, there are many possible ways to improve the domestic plants and animals in arid zones by applying scientific methods of selection, breeding, and cultivation. Nonetheless, the attainment of these possibilities is generally accompanied by an increase in the local population, making new demands on a naturally feeble environment and further altering the native flora and fauna.

It must be considered that the prevailing conditions in arid zones are really borderline for organic life, and even though it is possible to improve them somewhat by human action, it is still easier, by the same token, to increase its unfavorable conditions until they are not adequate for human existence.

Therefore, in the question "What are the possibilities of main-

taining larger human populations in arid zones?" there is implied a great potential danger, since an immoderate increase in the population of such zones may be encouraged, with all the risks that this may involve.

Conditions exist in Mexico which make it necessary to consider this point very carefully. It has been estimated that between 50% and 80% of the country's national territory are arid and semi-arid zones, depending on the criterion used, and it has been roughly calculated that, in spite of adverse conditions, those zones support about fifteen million inhabitants, representing more than half of the Republic's total.

This population has traditionally been sustained by the desert it lives in, either availing itself of the native animal and vegetable elements or supplementing their possibilities by means of uncertain farm crops and an extremely limited livestock. The meagerness of the products obtained gives rise to extremely poor living conditions for the inhabitants, above all in zones of greater water scarcity. And what happens in Mexico is repeated in many other regions of the world.

With the aid of modern science and technology, it will be possible to improve the living standards of such communities, especially if the effort is directed toward balancing the utilization of native resources with what may be obtained from crop plants and domestic animals, improved as much as possible.

But it would be dangerous to apply to those zones a demographic policy of maximum increase in local population or of transportation from other areas in an attempt to benefit them or to solve resettlement problems.

It is evident that many arid zones could materially increase their yields in order to achieve a substantial improvement in the living standards of the groups living there at present. But if the population density goes beyond a certain maximum, which cannot be very high, not only will it have a greater impact on the feeble environment which supports it, but the existing living standards will surely fall.

Since the time available does not permit a fuller or more detailed discussion, the basic aim of this brief explanation is to

emphasize the following points, which I feel should be clearly established.

1. Arid zones offer intrinsic conditions which necessitate the greatest caution in considering any project affecting them.

2. The rise in local living standards should not depend exclusively on the improvement of domestic animals and plants nor on the introduction of new ones; it should also be based, as far as possible, on the rational ecological utilization of the elements native to the region.

3. Any tendency to a substantial increase in the population should be carefully examined before encouraging it, for it could have disastrous results. As Bailey states so well in the words which preface these comments, the margin of tolerance in arid regions is so small that any error may have fatal consequences.

By always bearing in mind the existence of the *arid zone-wild plants and animals-human population-domestic plants and animals* complex, one may get a general view of the problems relative to the improvement of those regions. In order to ensure permanent yields, it is essential to base any action on sound ecological grounds, with a clear conservationist orientation.

Perhaps the preceding observations may appear pessimistic, although in reality they are not. Basically, they tend to guarantee a high living standard to the desert population groups by preventing the feeble environment which supports them from further deterioration as the result of an intensive misguided exploitation producing only temporarily favorable yields.

Nor do we state categorically that an increase in the human population of those zones is impossible. We only point out the obvious potential danger, that an immoderate increase in population may provoke a real catastrophe in a naturally adverse environment.

If we accept, and we believe it is impossible not to do so, the existence of the *arid zone-wild plants and animals-human population-domestic plants and animals* complex, it is evident that it will be necessary to seek a reasonable ecological equilibrium among those four components. Any omission of one of these, or the mis-

taken assumption that one may be independent of the rest, might cause an irreparable maladjustment.

Any intensification of the utilization of wild plants and animals or any increase in the cultivation and breeding of domestic plants and animals, beyond the natural or improved possibilities of the environment, can be dangerous. In turn, any unplanned population increase will immediately make greater demands on the natural resources, which can be satisfied only at the risk of grave consequences.

Summary Statement

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The authors have adequately summarized the major points in their own papers. This summary by the Chairman will consist in brief statements in answer to the six basic questions used by the participants in the development of their subject.

What screening procedures would lead to the selection of more productive plant and animal species for arid regions?

1. Selection in natural environments of preadapted types.
2. Introduction and reselection in environments to be served.
3. Basic research on biotic factors influencing plant response.
4. Laboratory for basic studies under controlled environments of (*a*) salinity, (*b*) climate, (*c*) diseases and other pests, (*d*) nutrition, (*e*) heredity, (*f*) etc.
5. International cooperation on a coordinated testing program.
6. Regional technical conferences to screen ideas, as well as methods and procedures, and to promote new lines of reasearch.

What are the genetic and physiological bases for drought resistance in plants and animals?

1. Physiological. Basic research on water and irrigation requirements.
2. Morphological. Characters that will not interfere with utilization.
3. Habitats. (*a*) Escape of critical climatic periods. (*b*) Association with other species.

4. Growth patterns and cycles of development adjusted to climatic limitations.
5. Cultural patterns and management.

What are the prospects of increasing drought resistance through genetic research?

1. Improvements in drought resistance can be made but will be limited to inherited potentialities of available species, native or introduced.

- (a) Evaluation of indigenous material.
- (b) Mode of inheritance of important characters.
- (c) Intensive genetic and extensive breeding programs in arid environments.
- (d) Development of controlled selective environments for testing and evaluation.
- (e) Selection of adapted superior plants under field conditions.
- (f) Ability to survive natural conditions and special treatments.

How can we develop a program of revegetation?

1. Historical study of practices, past and present, and causes of failures.

2. Analyze limiting micro-climatic factors in environment at representative stations.

3. Collect preadapted races and evaluate basic adapted material.

4. Introduce adapted foreign species and varieties.

5. Determine cultural requirements of promising species and association of species.

6. Use vegetative cover for increasing ground water recharge.

7. Develop establishment procedures for revegetation with improved species and strains.

8. Control grazing adjusted to plant requirements.

9. Determine number and kind of livestock.

10. Develop feed reserves for use during critical periods.

11. Manage vegetation and livestock to balance forage with livestock requirements.
12. Explore new patterns of land use and management.

What are the economic possibilities in the development and utilization of arid land plants and animals?

Excellent with basic program of research, teaching, and extension.

1. Increase in knowledge and understanding of basic principles involved.
2. Intensification of education and extension programs: (*a*) translating knowledge at hand into action, (*b*) expansion of demonstration areas of improved practices, (*c*) cooperation of public and private agencies.
3. Modify land tenure and credit systems to meet needs of a sound program of production and use.
4. Establish objectives and needs of programs on a national basis.
5. Promote culture of food trees: olive, almond, carob, pistachio, fig, and date.
6. Regional understanding and agreements on management and use.
7. Agreements on relative values of competitive uses of water.
8. Classify and control livestock for more efficient land use.

What are the possibilities of maintaining larger human populations in arid areas?

1. Possibilities will vary according to present population numbers, resources, and possibilities for development. Some areas already have population and resources out of balance.
2. Some areas are favorable for expansion but improved standards are more important as a first step.
3. Demineralization of water for human and livestock watering will permit more efficient utilization of vegetation in some areas.
4. Stabilize population through integration of social and economic factors.

Recommendations by the Socorro Conference

Following the symposium at which the foregoing papers were presented, 71 participants joined in the field trip and then met at the New Mexico Institute of Mining and Technology at Socorro to examine the implications of these findings for new research. In an informal atmosphere the group sought to identify the major gaps in knowledge and possible ways of closing them. Stress was placed upon lines of research that appeared to require cooperation across national or disciplinary frontiers.

The first day was devoted to a review and evaluation of the problems and development of the Rio Grande Valley as a typical arid area and of problems and procedures involved in planning and conducting integrated surveys of semi-arid and arid zones.

On the second day, the conference separated into three working groups with the following general assignments: new approaches needed in meteorology and applied climatology; the concept of the water budget and its areal application; and closing the gap between scientific knowledge and its application to arid lands development. Each group formulated a series of recommendations to be considered by the conference as a whole on the final day. The conference considered each recommendation, combined, modified, and clarified some, and approved those that follow.

Anthropology, Archaeology, and Geography

1. A bibliography of our present knowledge of biological adaptations of man and the cultural patterns in arid climates, past and present, is needed to promote specific research in these areas. Such research would contribute to the betterment of living conditions and to planning for greater safe use of arid areas.

2. Further research, in addition to the diffusion of information,

is needed concerning the history of land use, especially agriculture, in arid and semi-arid regions. Information in this field has practical applications in land-use planning, and our present knowledge is very sketchy. The UNESCO Advisory Committee on Arid Zone Research is urged to consider means of furthering research on this subject and to consider the publication of a volume dealing with agriculture of the past in the arid and semi-arid lands of the world.

3. Exploration is needed of possible new patterns of resource use and practice with local participation in the studies to insure the public understanding so necessary for achieving any change, even on a gradual basis. There is a tendency to encourage the maintenance of existing patterns, even when it is realized that existing patterns have been inherited from conditions quite dissimilar to those of the present. Land-use histories may be valuable in dramatizing climatic hazards; there is need for long-term improvement in management; and even statistical data on climatic change can be effectively and convincingly presented if they are properly organized.

Meteorology and Climatology

4. The conference notes with satisfaction the recent action of the UNESCO Advisory Committee on Arid Zone Research in planning to devote the next arid lands symposium to climatological problems of arid lands and urges sponsorship of continued research on arid land climatology by the committee.

5. It is recommended that the program of the International Geophysical Year, which previously emphasized polar observations, be extended in 1957-58 to include, to the maximum extent possible, the arid belt of the world, and, in addition, that arid zone countries involved be asked to participate in this program. Although the original plan of the International Geophysical Year has been expanded, the vast arid and semi-arid areas of Africa, Asia, Australia, North America, and South America—30°N to 30°S principally—are still poorly represented in the list of longitudinal and latitudinal sections fixed for intensive observations.

The observations of solar radiation and of other meteorological

elements on the surface and in the upper atmosphere in the arid countries, and specifically along a parallel of latitude through as many as possible of the world's deserts, should be useful in the solution of arid and semi-arid zone problems. Intensification of observations at the national level will enable arid zone countries to benefit even more from the international aspects of the International Geophysical Year.

6. More effective climatic studies require an increase in density and improvement in representativeness of meteorological stations (both at sea level and at higher elevations) for surface and upper air observations in all arid areas.

7. Careful attention should be paid to current research studies concerning relationships of solar emanations and terrestrial weather patterns, with particular attention to the effects that may bear on arid land problems.

8. Synoptic and dynamic climatological studies, in different arid and semi-arid regions, are essential. Emphasis should be placed on interrelationships between the general circulation of the atmosphere at upper levels as well as at the surface and the precipitation in different parts of the areas and at different times of the year. With such studies as a basis for the development of understanding, prediction of precipitation within the area in question may follow.

9. Inasmuch as the matter of the evaluation of the results following attempts to modify weather and weather processes is recognized as offering great possibilities for the peoples of arid lands, every effort should be made to develop improved techniques for statistical evaluation of weather modification experiments and to use the best available present techniques and data in the analysis of the results of such experiments.

10. An international cooperative program of synoptic observations should be instituted to determine the concentration of ice-forming nuclei throughout the world, especially during periods of the earth's passage through meteoritic streams. These observations should be supplemented by measurements, synoptic if possible, of the concentration of naturally and industrially induced

condensation nuclei (including giant hygroscopic nuclei) by studies of the chemical composition of precipitation and by the conduct of cloud surveys.

11. A more vigorous study of all possible aspects of periodic cloud seeding is imperative.

12. Present knowledge of nucleation properties of silver iodide as affected by the methods of generation and dispersal is inadequate. Further studies, with particular reference to the decay of the nucleating activity of silver iodide with increasing time of exposure in the atmosphere, are recommended.

13. Closer integration of the sciences of climatology and hydrology can be fostered through better exchange of information and collaborative analyses aimed at improving joint methodology. The lack of such collaboration between climatologists and hydrologists has contributed in the past to inadequate estimation of available water resources in some arid-zone projects.

Recommendations 17, 19, 25, and 29 are also applicable.

Hydrology, Geology, and Soils

14. The importance of ground water in arid zones calls for continued research on the following aspects of this subject: (i) methods of exploration and estimation of the volume of ground water bodies; (ii) methods of increasing ground water recharge and of estimating rates of recharge; (iii) the relation of vegetation and other biological factors to ground water recharge; (iv) the geomorphological aspects of the occurrence and chemistry of ground water.

15. The precipitation occurring on drainage basins should not be regarded in terms of utilization for irrigation alone, and more consideration should be given to planning for the beneficial use of water that is not reaching points of downstream use.

16. Continued study is needed of the factors and practices modifying soil structure under various land-use practices, such as grazing, dry land farming, and irrigation farming, recognizing the importance of soil structure and its maintenance in relation to permeability and to prevention and abatement of erosion.

17. The work of hydrologists and climatologists would benefit

greatly by the fullest possible use of vegetation studies, specifically by the consideration of the role of vegetation as a factor in the hydrology of dry lands and plant species and communities as indicators of climates, past and present.

18. Further attention should be given to the study of the geomorphic dynamics of landscapes for application to regional and land-type appraisal and land-use planning.

Also see recommendations 13, 21, 25, 28, and 30(ii).

Biology, Ecology, and Conservation

19. Intensive studies of the microclimatic environments of plants and animals should be encouraged and pursued. The relationships between the data usually recorded by meteorological stations and the microclimatic effects of these phenomena in different sections of typical arid environments should be subjected to intensive study.

20. Research on plant and animal ecology, improvement, and management in arid areas should be intensified. Emphasis should be placed on preadapted species and races, on understanding of the physiological factors in the selection of characteristics desired in breeding, on water requirements of the various species and breeds as related to production, and on utilization of available soil and climatic resources by plants and of available vegetation by various species and breeds of animals.

21. Additional research is needed on the methods of determination and the estimation of the water requirements of plants in arid regions, especially on the efficiency of transpiration, the relationship between transpiration and photosynthesis, and the regulation of transpiration. The suggestion is made to the UNESCO Advisory Committee on Arid Zone Research that it compile a review of information and research studies currently available on this subject.

22. Intensified research should be undertaken, and research results should be applied in the management of grazing, because of the paramount importance of grazing management in the conservation and improvement of arid grasslands.

23. A thorough investigation should be made of indigenous

plants of arid and semi-arid regions with a view toward determining their usefulness and adaptability to grazing and cultivation.

24. There is reason to believe that studies of pharmaceutical and industrial uses of desert plants would be justified.

25. Intensified studies should be made on the formation, measurement, and utilization of dew to determine its potentialities as a supplement to rainfall in arid regions. Such studies should encompass the utilization of dew by plants and the selection of plants most efficient in such use; the relationship of dew to soil moisture; and the establishment of physical relationships for extracting dew from the atmosphere.

26. Natural arid land ecological communities of indigenous animals and plants in their original habitats are essential for educational and scientific purposes. Areas of adequate size should be acquired and preserved in the various arid land countries.

Also see recommendations 1, 2, 3, 14, 16, 17, 18, and 30(i, ii).

Organization, Communication, and Interdisciplinary Programs

27. The UNESCO Advisory Committee on Arid Zone Research is urged to revise and reissue its list of national and international scientific institutions concerned with arid land problems. The revised list should be as comprehensive and as up to date as possible and should include addresses and fields of interest in order to serve effectively for intercommunication among workers in various disciplines.

28. Permanent cooperation in connection with studies on the demineralization of salty and brackish water should be maintained among the UNESCO Advisory Committee on Arid Zone Research, the U.S. Saline Water Conversion Program, and Working Party No. 8 on demineralization of salt and brackish waters of the Organization for European Economic Cooperation (OEEC) with the objective of adapting technical possibilities to local needs and economic resources.

29. Interdisciplinary studies should be promoted in order to sharpen the concepts used in defining, delimiting, and classifying

arid and semi-arid lands, with special emphasis on the variability of precipitation.

30. A demand for the application of scientific and scholarly knowledge in arid areas should be created by means such as those indicated in items i-iv. It should be noted that in many situations the driving force necessary for getting available knowledge applied to improvement of land and water utilization is lacking. This driving force is essentially public demand or social pressure. Creating such demand is the most effective method of attaining the desired end. (i) Expansion of demonstration areas, even though they have some disadvantages. They stress management by practical operators, such as commercial or family farmers, where demonstration of practical value are sought. However, demonstrations designed for the promotion of specific understanding of resource problems and techniques by business and political leaders, and even by technical men themselves, should be maintained. Cooperative interdisciplinary demonstrations on single resource management problems are useful. They have been successfully extended to include treatment of the entire resource pattern in areas of some size. Complex demonstrations of integrated resource management on a scientific basis not only are proved but also deserve more intensive use. Demonstrations may be supported entirely by public funds, partly by public funds, and entirely by private funds. The possibility of extending the usefulness of the demonstration technique under private auspices is a relatively new subject that deserves further attention. (ii) Research in the social sciences, exploring limiting factors that have tended to keep knowledge from application. Much more knowledge is needed concerning the social and economic factors that influence the development and application of science, and concerning the art of persuading people to take action in resource development to their own and their community's long-term benefit. Special attention should be paid to economic and social studies that can throw light on the relative values of competitive uses of water. However, the cooperation of engineering and natural sciences in such investigations will be essential, together with the

collaboration of geographers and anthropologists. (iii) Enlistment of local leadership and local interests in support of both basic research and practical studies designed to advance present knowledge and to transfer such knowledge into a form for direct application. Local groups will profit by taking an active part in and by supporting these programs. In many fields in some parts of the world institutes have developed techniques for enlisting the aid of private industry in some broad public programs. These techniques may be applicable in areas other than the limited ones where they have been applied up to the present, but applications will vary with cultures and local conditions. (iv) Greater attention by scientists to their relations with the press, radio, television, and other channels of public information. Such relations involve an opportunity and a dual responsibility—responsibility to science for the presentation of an accurate and complete report and to the particular audience for framing scientific material in a form that will most effectively reach the public whose interest in resource development they hope to arouse and to inform. Also, more attention should be paid to the art of communication and its demands in the training of scientists.

31. More effective interdisciplinary pooling and dissemination of information should be developed for the purposes of advancing science, as well as public understanding of scientific matters, by the following. (i) Establishment of local and national committees on arid zone problems to enlist public interest in support of studies of arid lands and the dissemination of information on results of such studies in each country. The nature of such committees and their method of formation ought to be locally determined in order to meet special conditions in each country, but it is strongly urged that they be broad in scientific disciplines and in representation from both private and public agencies. These committees should operate in a manner best suited to the interests and possibilities of each country and should be aimed at encouraging research and spreading information, utilizing UNESCO as a clearing-house in this field. (ii) Creation of a preliminary project to explore the feasibility of an abstracting service on arid zone literature. A periodical, patterned after existing successful ab-

stracting journals, would include, as soon after original publication as possible, abstracts of technical economic, and social literature related to arid zone problems and research. Consideration should be given to the desired business and production organization, the volume of material to be included, the subject matter divisions, the availability of abstractors, the cost of publication, the required subscription price, and so forth. A target date for the report on this feasibility study should be 1 year from the adoption of this recommendation by some agency capable of committing funds. (iii) Encouragement of the formation of research organizations, comprehensive in discipline and concerned with the best use of specific limited resources. Such organizations should be encouraged in all arid lands through adequate and broadly based financial support and through organized community interest.

Also see recommendations 2, 3, 4, 5, 10, 13, 18, and 21.

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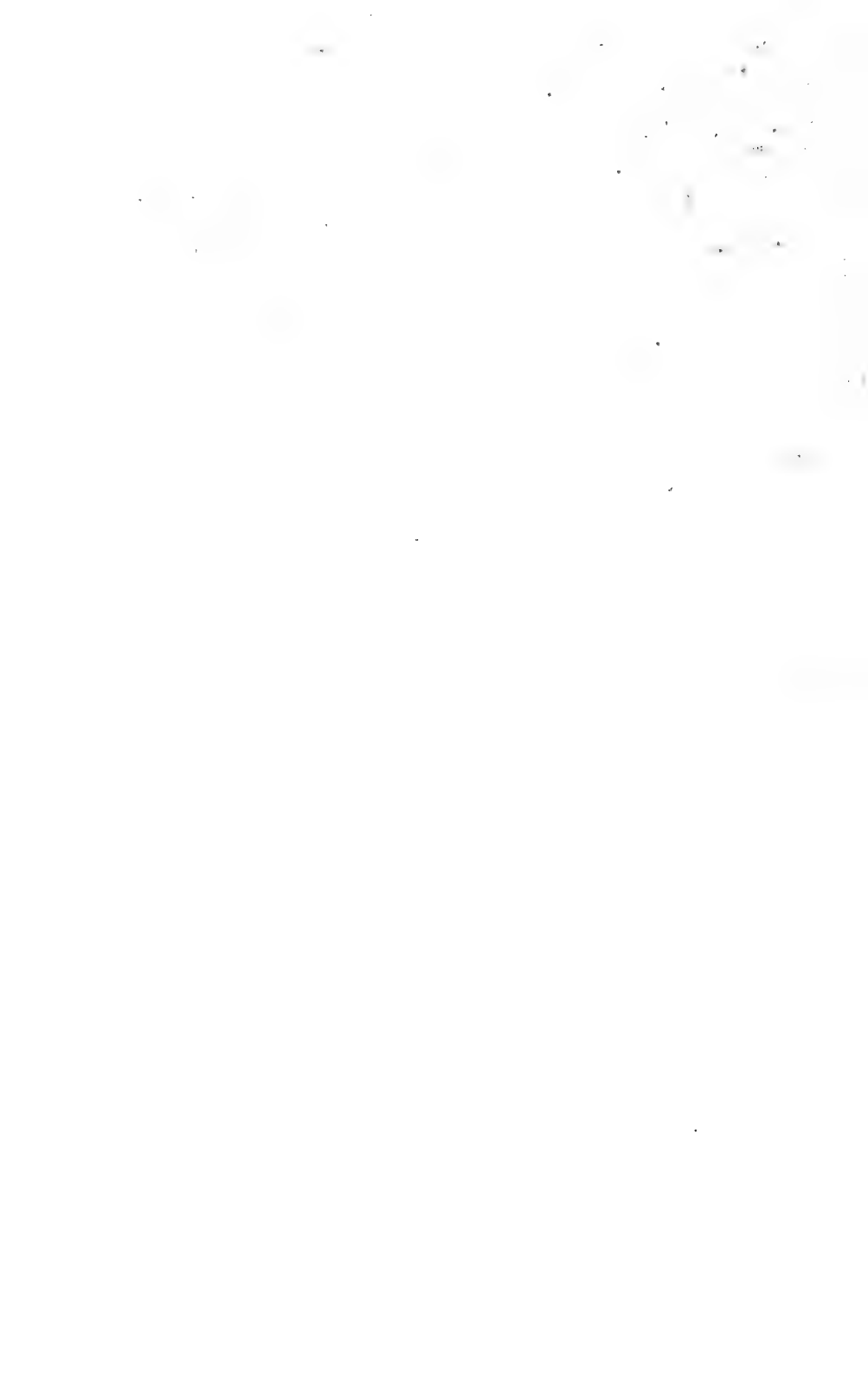
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ARID LANDS

-  Extremely arid
-  Arid
-  Semiarid

