STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES

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USE OF WATER BY NATIVE VEGETATION

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LETTER OF TRANSMITTAL

Mr. Edward Hyatt,
State Engineer,
Sacramento, California.

Dear Sir:

Transmitted herewith for publication is a cooperative report "Use of Water by Native Vegetation."

The report, prepared by Arthur A. Young and Harry F. Blaney, is a comprehensive presentation of available research data dealing with the consumptive use of water by various non-crop plants native to California and the Southwest in general. Its analyses are of economic and practical importance in shaping the effective conservation and use of water in this wide region.

The greater part of the investigations on which the report is largely based was supported, and the report was prepared, under cooperative agreement between the Division of Water Resources of the California State Department of Public Works and the Division of Irrigation of the Soil Conservation Service, United States Department of Agriculture.

Respectfully submitted,

W. W. McLaughlin

Chief, Division of Irrigation,
Soil Conservation Service,
United States Department of Agriculture

Berkeley, California,
July 31, 1942.

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The advice and assistance of Harold Conkling, Deputy State Engineer, is recognized. Credit for specific data is indicated at appropriate places throughout the report to individual investigators or agencies, the results of whose investigations were pertinent to the authors' analyses.

ORGANIZATION

STATE DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES

Frank W. Clark ------------------------ Director of Public Works

Edward Hyatt ------------------------------------ State Engineer

Results of cooperative research as to evapo-transpiration losses in California summarized herein were a part of general investigations on water supply and utilization conducted by the State of California under the direct supervision of

Harold Conkling
Deputy State Engineer

ORGANIZATION

UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
DIVISION OF IRRIGATION

Cooperating in

Studies on Use of Water in Irrigation

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USE OF WATER BY NATIVE VEGETATION

By

Arthur A. Young 1/
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CHAPTER 1

INTRODUCTION

The purpose of this bulletin is to bring together conveniently in a single report the results of studies of consumptive use of water by a number of species of native vegetation, as determined by the Division of Irrigation for various western climatic conditions, and some of the results of similar investigations by other agencies. Such studies have been carried on for many years.

It is not the intention of the authors to minimize the value of vegetation as its growth on mountain watersheds, as elsewhere, constitutes a very necessary protection to the soil. Water consumed by most native vegetation is used beneficially and is not considered as wasted. The moisture requirements of the natural ground cover are satisfied before water becomes available for other purposes. In considering the water supply of a region, therefore, the difference between precipitation and run-off plus deep percolation constitutes the consumptive use by the native growth. It is for those concerned with the natural resources of soil and water that these data on use of water by native vegetation are presented.

The usefulness of such data are recognized by administrators and investigators in regions where water rights are in dispute locally, or where interstate water supply and water use are not in balance. Valley or basin investigations to determine a

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1/ Associate Irrigation Engineer and Irrigation Engineer, respectively, Division of Irrigation, Soil Conservation Service, U. S. Department of Agriculture.

proper division of the supply between contending uses need first of all a knowledge of the amounts consumed by crops and native vegetation; without such data there is little likelihood that results of investigations can be final. Moreover, in planning new irrigation projects, consideration must often be given to differences in amounts of water used by irrigated crops and those used by the native vegetation replaced by the crops. These differences largely determine the extent of the available water supply and show how much must be obtained from other sources.

By "Use of Water," the title of this report, "consumptive use" is principally intended. Consumptive use, sometimes called "evapo-transpiration," is the sum of the volumes of water used by the vegetative growth of a given area in transpiration or building of plant tissue and that evaporated from adjacent soil, snow, or intercepted precipitation on the area in any specified time. If the unit of time is small, such as a day or week, the consumptive use may be expressed in acre-inches per acre or depth in inches; whereas, if the unit of time is large, such as a crop-growing season or a 12-month year, the consumptive use may be expressed in acre-feet or depth in feet. Such terms as "irrigation requirement" and "water requirement," sometimes used to designate, respectively, the quantity of irrigation water applied to crops, or the total quantity including rainfall required for their normal and profitable production under field conditions, include some unavoidable losses by deep percolation. Such losses are not included in the definition of consumptive use, which designates only the unrecoverable portion of the water supply.

Investigations by which consumptive use is ascertained do not involve the determination of amounts of water "evaporated from adjacent soil, snow, or intercepted precipitation on the area," since such evaporation is difficult -- often impossible -- to ascertain and of no particular interest as a separate element in the total unrecoverable portion of the water supply. On the other hand, the relation of consumptive use to evaporation from water in a Weather Bureau pan is of some significance, as both are influenced by the same factors of temperature, wind, and humidity; and whereas consumptive use determinations are available to represent a strictly limited number of localities, evaporation records are available for many and can be established quite readily for more. When estimates of consumptive use are needed for localities where determinations have not been made, available evaporation results are therefore useful if both evaporation records and consumptive use results are also available from other areas having comparable characteristics. A discussion of such opportunities is found in the chapter headed "Relation of Consumptive Use to Evaporation."

Extensive work in regard to native vegetation has been carried on by the Division of Irrigation, United States Department of Agriculture, in cooperation with the Division of Water Resources, Department of Public Works, State of California, and most of the results of the investigations have been published in previous reports of the latter office. In this bulletin these previously published data are assembled and analyzed in association with the results of similar studies by the Division of Irrigation 1/ in other sections of the West. These studies specifically included those undertaken by the Division of Irrigation in the Upper Rio Grande Basin in cooperation with the States of Colorado, New Mexico, and Texas under an agreement with the National Resources Committee. In Colorado, the Division cooperated with the Colorado Agricultural Experiment Station with regard to grasses, sedge, sweetclover, tules, sunflowers, and weeds. Likewise, it cooperated with the Oregon Agricultural Experiment Station in determination of water consumed by grasses and native meadow lands in south-central Oregon.

The cooperative field work in southern California had been carried on under the general supervision of Harry F. Blaney, by

1/ The Soil Conservation Service on July 1, 1939 took over most of the irrigation investigations formerly conducted by the Bureau of Agricultural Engineering.

Colin A. Taylor and Arthur A. Young, assisted by Dean W. Bloodgood, Dean C. Muckel, and Harry G. Nickle. In the Sacramento-San Joaquin Delta, field work was under the supervision of the late O. V. P. Stout, assisted by Lloyd N. Brown.

Obviously, it has been possible to study only a few of the many species native to the West, partly on account of the difficulties of transplanting or growing the larger types in tanks. There are, however, a number of western moist-land species about which a great deal has been learned, especially with regard to their water habits and the quantity of water each will consume under specified conditions. Plants growing in unusually moist soil consume annually more than an average amount of water. In desert areas, on the other hand, typical vegetation is adapted to an extreme economy in its use of water. Between these two types are many species that consume variable quantities depending upon the supply available. It is apparent that there is seldom a definite water requirement for most native vegetation.

CHAPTER 2

RELATION OF PLANT COMMUNITIES TO MOISTURE SUPPLY

The relation of plant communities to moisture supply is one of the outstanding characteristics of the growth of natural vegetation. While individual species are largely restricted to favorable physical environments, the principal condition that governs the distribution of vegetative groups is the amount of available moisture. Each species responds to individual water conditions for its most favorable growth and its widest distribution. As expressed by Shantz (25),[1/] "One of the most successful correlations yet attempted is that between plant associations and the water content of the soil. This correlation ..... has been accepted and modified by leading ecologists and has proved one of the most useful generalizations in the study of vegetation."

Temperatures, moisture, and the chemical and physical properties of the soil are contributing factors in the distribution of natural vegetation. However, the quantity of water available for plant use and the effect of plant growth on supply, are of great interest to the hydrologist. Soil texture and salinity, as well as moisture content, have been correlated with distribution of native growth as indicators of the adaptability of uncropped land to agricultural possibilities; but to those interested in water supplies, rather than soil, the consumptive use of water by natural vegetation and the residual water available for recovery are of greater economic importance than other characteristics.

Bowman (6) has said: "It is found that each species of plant requires its own specific water supply for most favorable condition of growth and that the quantity of water in the soil has a greater influence than any other condition on the distribution of plant species." In the absence of ground water, then, the

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1/ Numbers in parentheses refer to Literature Cited, p. 147.

distribution of the great regional types of desert vegetation is determined by the limited amount of precipitation which falls in a given region.

The effect of environment on the distribution of plants is well recognized, those best adapted to resist the unfavorable conditions of a region being the most successful in surviving. As stated by Weaver (37) "The natural vegetation, for many centuries, has been sorted out by climate as well as by soil in the process of development. The various species of plants have usually inhabited a region so long that they are now quite definitely distributed with relation to the environmental complex, species well adapted to a given environment now occurring in abundance. Thus, the growth of native vegetation becomes a measure of the effects of all the conditions which are favorable or unfavorable for plant production." This is particularly true in arid regions where high rates of evaporation and transpiration, and a very limited water supply, have reduced vegetation to a veritable struggle for existence.

Again, according to Warming (36), "No other influence expresses its mark to such a degree upon the internal and external structures of the plant as does the amount of water present in the air and soil." It appears, then, that authorities are in accord on the soil-moisture plant distribution relation. Contributing factors, as temperature, altitude, humidity, and evaporation also must be considered, but these are so interrelated with water supply that the effects are not always discernible.

Natural vegetation grows under moisture conditions that are always changing. Plants that do not subsist on ground water but depend upon moisture held by the soil particles may have an abundant supply at one time and suffer a scarcity at another. Ground water fluctuates and roots in contact with it are alternately wet and dry. Soil moisture is dependent upon precipitation, but evaporation, transpiration, percolation, and run-off cause its uneven distribution in the soil.

In arid areas moisture is retained in the upper soil horizon, and the vegetation is confined to those species which are adapted to extreme economy of water. In areas of greater precipitation, deeper penetration results in plant roots drawing upon a greater volume of soil moisture. In low places a concentration of moisture takes place and ground-water areas support those plants which use more water than dry-land plants. Finally the water-loving plants, living with their roots in water, are large consumers of water.

DROUGHT-RESISTANT PLANTS

Certain plants are qualified to inhabit desert areas where temperatures are high and precipitation is low. These plants have guarded themselves against excessive transpiration in order that they may conserve the limited supply of moisture available. This economy is accomplished, in part, by reducing the area of the transpiring surface through size of the leaf or in limiting the amount of foliage. In some instances the plant lives through the dormant season by storage of moisture in succulent tissues. In others, modifications, as hairs on the leaves, waxy surfaces, or closing or concealing of stomata are employed to prevent excessive transpiration.

Investigations of desert growth by Cannon (9), have shown three different systems of roots developed by perennials in their struggle for survival under arid conditions. First, the spreading type of lateral roots which are common to many cacti; second, the long tap root which not only helps to anchor the plant against winds, but draws moisture from depths below the surface; and third, a generalized type which combines the other two, enabling the plant to take advantage of all the moisture in the soil to a depth of several feet. The creosote bush (Covillea glutinosa) is an example of the generalized systems which probably accounts for its rather wide distribution under varying conditions of moisture.

Desert growth includes many plants having varying water requirements, but generally one dominant species is best adapted to the prevailing conditions of rainfall. Generally these species will be found in widely scattered regions where much the same condition of rainfall exists. In other areas, the dominant species may be in association with others which in turn will dominate as moisture conditions become more favorable to their growth. Changes such as these are shown in Table 1, which indicates the relation of temperatures and rainfall to some of the prevailing types.

Although rainfall is a matter of record in most localities, but little is known regarding the limits of soil moisture upon which the flora of the desert survive. Statements of the moisture percentages in a given soil are of little value unless the physical properties of the soil are likewise known, as the percentage alone does not indicate the quantity of water available for plant use. For this purpose moisture in excess of the wilting percentage is a better indicator of the quantity that the plant may extract from the soil. "Permanent wilting percentage" has been defined by Veihmeyer and Hendrickson (35) as "the lower limit of readily available soil moisture." In agriculture this is the soil-moisture condition that limits the activities of plants. In the case of desert growth, the plant survives, but remains dormant during long periods of deficiency and resumes growth when new moisture is received.

Limited investigations in the Coachella Valley, Calif., (26) found creosote bush, chamiso (<u>Atriplex canescens</u>) and desert sage growing in areas having extremely little available moisture. In the spring, moisture in the soil ranged from 2.2 per cent below the wilting point to 3.5 per cent above, but by the following autumn these amounts had decreased to as much as 8.0 per cent below the wilting point. In the Gila Valley, Ariz., (26) much the same conditions were observed. Investigations in the Tooele Valley, Utah, (15) showed big sagebrush (<u>Artemisia tridentata</u>), shadscale (<u>Atriplex confertifolia</u>), kochia (<u>Kochia vestita</u>), and

TABLE 1

RELATION OF TEMPERATURE AND PRECIPITATION TO SOME PREVAILING TYPES OF SOUTHWESTERN DESERT VEGETATION[1]

Prevailing type of natural vegetation	Locality	Elevation[2]	Mean annual temperature	Annual precipitation[3]
		Feet	°F.	Inches
Desert sage (*Atriplex polycarpa*)	Death Valley, Calif.	-178	75	1.45
	Indio, Calif.	- 20	73	3.00
	Calexico, Calif.	0	71	3.18
	Mecca, Calif.	-185	71	3.27
	Salton, Calif.	-263	--	3.36
	Mohawk, Ariz.	538	74	3.57
	Las Vegas, Nev.	2033	64	4.51
Desert sage and creosote bush (*Atriplex polycarpa* and *Covillea glutinosa*)	Bagdad, Calif.	784	72	2.28
	Yuma, Ariz.	141	72	3.33
	Barstow, Calif.	2105	63	4.10
	Sentinel, Ariz.	685	71	4.57
	Aztec, Ariz.	492	70	4.81
	Gila Bend, Ariz.	737	72	5.90
	Casa Grande, Ariz.	1400	72	6.89
	Maricopa, Ariz.	1186	71	7.03
	Phoenix, Ariz.	1108	70	7.43
	Mesa, Ariz.	1245	68	8.65
	Tempe, Ariz.	1165	67	9.31
Creosote bush (*Covillea glutinosa*)	Needles, Calif.	477	72	4.45
	Mojave, Calif.	2751	64	4.84
	Parker, Ariz.	350	69	5.07
	Logandale, Nev.	1400	65	5.42
	Lone Pine, Calif.	3728	56	5.69
	El Paso, Tex.	3778	64	9.05
Desert grass and creosote bush (*Covillea glutinosa*)	Sierra Blanca, Tex.	4512	--	9.45
	Lordsburg, N. Mex.	4245	61	9.54
	Deming, N. Mex.	4331	60	9.66
	Socorro, N. Mex.	4600	57	10.13
	Alamogordo, N. Mex.	4250	61	10.92
	Willcox, Ariz.	4200	60	11.21
	Carlsbad, N. Mex.	3120	63	13.03
	Douglas, Ariz.	3939	62	13.71
Creosote bush and Yucca-cactus (*Covillea glutinosa* and *Yucca mohavensis* - *Ferocactus* and *Opuntia bigelovii*)	Florence, Ariz.	1500	69	10.04
	Tucson, Ariz.	2423	67	11.50
Desert grass	Wickenburg, Ariz.	2072	65	10.55
Short grass	Congress, Ariz.	3688	67	13.55
Chaparral	Cabazon, Calif.	1779	--	10.96

1/ After Shantz and Piemeisel (26).
2/ Minus sign denotes below sea level.
3/ Rainfall taken from Climatic Summaries of the United States containing climatic data from the establishment of stations to 1930, inclusive.

big greasewood (Sarcobatus vermiculatus) growing under similar conditions.

The extensive primitive grassland communities of the Great Plains did not support a uniform vegetation. The rainfall of the eastern portion moistens the ground to a depth of several feet, promoting a distinctive cover of prairie grasses 1 to 5 feet in height. Characteristic of the region, as listed by Weaver (37), are the bluestem grasses (Andropogon) which supply the bulk of the wild prairie hay, the tall panic grass (Panicum virgatum), tall marsh grass (Spartina michauxiana) which also furnishes an abundant foliage, and other plants.

There is likewise a distinction between ground-water plants that feed upon fresh water and those that are tolerant of water slightly alkaline. Plants of this type are more or less salt-resistant. Saltgrass (Distichlis spicata) is an important unit in this group. It is found often in areas of shallow water table, the limit of depth from which the roots may draw moisture depending upon soil type. Being a salt-resistant plant it is not an excessive user of water, and unless the water table is within 24 to 30 inches of the ground surface the water transpired will probably be less than that required by most cultivated crops.

In many localities succulents are identified with alkaline conditions resulting from areas of high ground water.

Riparian vegetation, as alders, sycamores, and cottonwoods, growing in canyon bottoms where the roots are fed by percolation from the stream bed, uses large amounts of water. Seepage from irrigation canals often feeds the roots of willows, cottonwoods, sweetclover (Melilotus sp.), and other ditchbank vegetation. Such growth is sometimes troublesome in canal management.

INDICATOR VALUE OF GROUND-WATER PLANTS

The value of many species of arid land vegetation as indicators of ground water has long been recognized in the geological and botanical investigations of southwestern desert areas, yet literature on the subject deals inadequately with the problems of plant growth, root systems, transpiration losses, soil types, alkali conditions, and their relation to underground waters. Such literature as exists is fragmentary and treats of these subjects, if at all, more or less individually. Meinzer (19) and other investigators, however, have assembled from various sources much information in relation to ground-water plants and the depths at which they seek moisture. Many desert plants have been listed by them as indicators of ground water.

The opportunity for such growth to send its roots to water is naturally limited, as ground water in the desert is usually beyond the reach of the root systems of plants. Nevertheless, certain areas exist where it may be found. These are mostly in the vicinity of surface lakes or desert playas (dry lakes) where water is reasonably close to the surface. Because of soil evaporation, areas overlying high ground water are likely to be strongly alkaline and the vegetation which they support is of the salt-resistant type.

Ground-water areas are generally in the lowest portion of a region. As the terrain rises towards the surrounding hills and distance to water table increases, vegetation changes from the salt-resistant succulents to the more bushy and woody types which have roots developed for obtaining water from greater depths. This arrangement inevitably results in irregular zones of vegetation arranged in the order of the ability of the roots to reach the ground-water levels. Exceptions occur, however, where percolating water from springs or occasional flows in normally dry channels furnish a somewhat inadequate water supply for a precarious growth.

In the absence of comprehensive field studies relating to the subject, a complete catalog of ground-water plants and the depths to which their roots may go to secure water becomes impossible. Nevertheless, the relation of certain plant species to water levels in the soil have been more or less adequately determined in various localities and for different soils. For a more complete description of these the reader is referred to the various publications relating to this subject. Only a generalized list is here possible as the complete range of depth to which roots extend has not been sufficiently determined, the same species having more extensive root systems under some soil and moisture conditions than under others. The texture of soil, its capacity for capillary moisture, its permeability to rainfall as affected by soil type, slope, and surface conditions (12) in addition to the amount of precipitation, are important factors in determining the limits of depth to which roots may extend.

Studies of the relation of mesquite (Prosopis) to ground water, by Brown (8) and others, have definitely placed it as a ground-water plant that grows within a wide range of depth limits. The normal habitat of mesquite growth is the lowlands of southwestern deserts, but it grows well also in other regions having altitudes of from 2,000 to 3,500 feet. It is sometimes found in upland draws at some distance from the lowland areas where the water table is not too far below the surface.

Mesquite thickets occupy the lowest valleys where ground water is most readily available and such conditions may produce trees from 10 to 40 feet in height. As depth to water increases the mesquite gradually diminishes in size until usually it ceases to exist where depth to ground water exceeds 40 to 50 feet. Such depths are unusual for ground-water plants. Of it, as a desert plant, Spalding has written: (28) "It (the mesquite) is commonly armed with spines, and its coriaceous leaves are well protected against excessive transpiration. It is a plant requiring a better water supply than many of its associates, yet well adapted to the low relative humidity of the desert air, and its occurrence beyond its own special area, ... corresponds with this peculiarity. Thus it is, in a sense, a desert plant, yet one of high water requirement -- characteristics which it shares with various other species."

Saltgrass is another plant found in many regions where it is recognized as evidence of shallow depth to water table. In light sandy soils saltgrass grows where the depth to water does not exceed 6 feet and in heavier soils 11 feet. It is sometimes found in pure communities but more often in association with other ground-water vegetation. Investigations in the Owens Valley, Calif., by Lee (16) showed the first scanty appearance of saltgrass to be where the depth to ground water was 8 feet, with more luxuriant growths in areas of shallower depths. White (38) reports saltgrass meadows in the Escalante Valley, Utah, where water is within 4 feet of the surface; the growth is thin and in association with greasewood, rabbitbrush (Chrysothamnus graveolens) or pickleweed where the depth ranges between 4 and 10 feet. In the Santa Ana Valley, Calif., it grows where the ground water is from 3 to 12 feet below the surface, depending upon soil type and drainage conditions.

The distribution of saltgrass depends not only upon adequate soil moisture reasonably near the surface but also upon soil conditions favorable to its growth. It is seldom observed where the soil does not contain a moderate amount of alkali. Where the salts become excessive, however, white spots appear in what are otherwise saltgrass meadows, the grass being killed by salt accumulation.

The plant spreads by means of a thick creeping rootstalk within the upper few inches of soil, from which finer roots extend downward in search of moisture. The stiff, light green leaves rise from each joint of the rootstalk and often spread to form a dense sod. The grass has a distinctly salty taste although it is often used for pasturage of stock or dairy cattle. The growing period in southern California is from February to December, and although the grass dies or becomes dormant during the other months there is some discharge from the water table throughout the year. Saltgrass is not an excessive user of water, as its habit of growth in alkali soils has caused it to protect itself against the toxic effects of alkali by a decreased rate of transpiration.

While the alkali condition of the soil which supports saltgrass is sometimes excessive, nevertheless drainage has reclaimed numerous areas which it formerly covered.

The big greasewood found on subirrigated lands from the Canadian to the Mexican borders is also recognized as an indicator of ground water. As with other ground-water plants, the more luxuriant growth occurs where the zone of saturation is within a few feet of the surface, but according to Meinzer (19) it is, like the mesquite, sometimes able through its large deeply penetrating taproot, to extract moisture from the soil to depths of 40 feet or more. It is an indicator also of alkali in the soil, but under proper systems of irrigation and drainage greasewood areas have good possibilities of becoming agricultural districts.

Mesquite, saltgrass, and greasewood are but a few of the many ground-water plants common to western regions, and it is neither necessary nor possible to describe all such growth within the limits of this report. Data on the relation of plants to ground water have been listed by Meinzer (19) as a basis for further investigation, realizing, however, that such generalizations may be questioned.

Marsh Vegetation

Chief of this group are plants, the roots of which ordinarily grow in water or in very wet soil. Typical examples are the cattail (*Typha* sp.), tule (*Scirpus acutus*), and sedges (*Carex* sp.) which belong to that group of water-loving plants known as hydrophytes. These and others of similar habits, through transpiration, dispose of large quantities of water from the surfaces of ponds, lakes, marshes, and running streams, and probably have a greater effect upon the water supply of streams than any other group of plants of equal area.

Both tules and cattails are common in many regions. Prior to the reclamation of the delta lands of the Sacramento and San Joaquin Rivers in California there were approximately 180,000 acres of tules, cattails, and sedges growing in dense formation and transpiring heavily. Much of this area is now farmed, and the remaining growth is chiefly along stream channels and in other unreclaimed places.

Tules also are products of undrained agricultural districts which have developed swamp areas through overirrigation. They soon appear in the shallow water of marshy places, and are particularly undesirable in drainage ditches. However, it has been learned by investigation (4) that large areas of tules do not use as much water per unit of area as those in the relatively narrow ribbons of growth along ditches and other stream channels.

Ditchbank vegetation is subject to exposure from sun and wind with little protection from surrounding growth and transpires freely. It is well known that such vegetation is of the water-loving type, the use of water by a few species having been investigated. Where such studies have been undertaken, individual plants or groups of plants have been grown in tanks and the water requirements measured. Attempts have been made also to determine the quantity of water consumed by mixed growths of willows, tules, cottonwoods, and other wet-land vegetation growing under natural conditions, but these have been limited in scope.

CHAPTER 3

METHODS OF DETERMINING CONSUMPTIVE USE

Limited investigations of the use of water by natural vegetation have been made by various methods. Vegetative types, ranging from grasses to trees, have been studied, but owing to the inherent differences in aerial and root growth, different methods of approach are necessary. The source of water consumed by the vegetation, whether from a high water table or from rainfall and soil moisture, is an additional factor influencing the selection.

The principal methods used are: (1) by tank investigations; (2) soil-moisture studies; (3) stream-flow measurements; and (4) interpretations of water-table fluctuations.

(1) Tank investigations are conducted under artificial conditions. The growth in the tanks may be the original product of an undisturbed soil although more often perennial shrubs or grasses are transplanted into the tanks before water measurements are begun. With annuals, seed must be planted each year and new root systems developed. Artificial conditions are caused by the limitations of soil, size and depth of tank, or regulation of water supply, and by the very important factor of environment. In consequence, the resulting tank growth lives under conditions somewhat different from those affecting similar plants in their native habitat, and it is usually necessary to apply correction factors to tank results.

The natural vegetation most often grown in tanks is of two classes: plants which grow with their roots in water, and those which use capillary moisture. Although a number of tank investigations have been made in recent years, the plants occupying the tanks have been limited to a few species. Of these, cattails and tules grow in water, while saltgrass, greasewood, sweetclover, and red willow (<u>Salix</u> <u>laevigata</u>) draw moisture from a water table below the ground surface. In tank experiments the amounts of water used are determined by quantitative measurements. The principal tank investigations of natural vegetation have been made in California, Colorado, Idaho, New Mexico, Oregon, and Utah.

(2) Soil-moisture studies are generally conducted in areas where the water table is some distance below the root zone. The amount of precipitation retained in the soil is measured by means of soil samples taken from definite depths, before and after each rainstorm, and the moisture content of the sample is determined. In clay, loam, or sandy soils the soil tube is used in collecting the samples, but in rocky or gravelly places samples are taken from open pits.

This method is suitable for areas of deep-rooted natural vegetation. It may be used for weeds, native brush and grass, trees, and agricultural crops. The principal soil-moisture investigations of native growth have been in California.

(3) Consumptive use of water by alders, cottonwoods, sycamores, and other riparian growth common to small streams has been found by measurement of the stream flow at two or more control points where the underflow is forced to the surface, the decrease in flow between controls representing use of water by the vegetation affected. The danger of nonmeasurable inflow to the stream from the canyon sides is a factor not to be overlooked, and this difficulty makes many canyons undesirable for such investigation. However, where conditions appeared stable, this method has been used by the Division of Irrigation in southern California. Literature, with a few exceptions, (2, 4) appears to have given the subject little attention, yet there is a field for this type of study in many localities.

(4) Approximate measurements of ground-water discharge by plant growth may be made by translating the daily rise and fall of the water table into inches of depth of water consumed by the overlying vegetation. This requires a knowledge of the specific yield of the soil from which the water is withdrawn, specific yield being the amount of water which will drain from

a previously saturated soil by gravity, measured as a percentage of the total volume. Fluctuations of the water table, caused by transpiration losses, show a decline by day when transpiration is greatest, and a recovery by night when it is least. Measurement of the fluctuations by continuous recorders provides a basis for calculating the consumptive use. Investigations have shown that the daily fluctuations usually do not occur unless there is vegetative discharge. They respond directly to weather conditions, increasing in amplitude with sunshine, temperature, and a clear sky, and decreasing with lower temperature, greater humidity, and increasing cloudiness.

This method was first proposed by Dr. G. E. P. Smith of the University of Arizona in an unpublished paper read before the Geological Society of Washington, November 22, 1922. It has been successfully used by White (38) in the Escalante Valley, Utah, and by Troxell (33) in the Santa Ana Valley, Calif. It is an ingenious method of translating a natural phenomenon into vegetative discharge, having the distinct advantages of using soil that has never been disturbed and of measuring consumptive use by vegetation in its native habitat. On the other hand it involves the obvious difficulty of obtaining average specific yield of a large nonuniform soil mass underlying a given basin.

TANK MEASUREMENTS

Metal tanks have been used extensively in plant investigations for many years. Those best adapted for consumptive use of water studies are of the double type having an annular space for water between the inner and outer walls, with perforations through the inner wall to insure a thorough distribution of water throughout the soil mass. Tanks of this design usually are from 24 to 36 inches in diameter by 4 to 6 feet deep. They should be of heavy galvanized iron to withstand corrosion. In acid or alkali soils the metal should be treated with a protective coating.

The Mariotte Tank

It is often desirable to make investigations in which the water table in the soil tank does not fluctuate with the demands of the plants. For this purpose the Mariotte supply tank is of practical use. Inverted bottles having connections to the water surface have been used on occasion, but more elaborate arrangements embodying the same principles, have been designed by the Division of Irrigation (2, 20, 21). This equipment has given general satisfaction by maintaining a fixed water level in the annular space and in the soil, as well as providing a means of measuring the daily rate of extraction of moisture by the plants.

In the Santa Ana, Calif., (2) investigations a battery of Mariotte tanks was used. The following description indicates the relation of supply tank to soil tank and outlines the theory under which operation proceeds: The Mariotte tank, a 12- by 36-inch galvanized-iron range boiler, was chosen because of its solid construction, the rigidity of its connections, and the practicability of keeping it airtight (fig. 1). Mounted on the side of the tank is a vertical length of glass tubing, each end of which is fitted with a rubber stopper perforated to admit a small connecting pipe. The lower pipe connects with the supply pipe between the Mariotte tank and the soil tank, while the upper pipe connects with the top of the supply tank. A graduated scale mounted beside the glass tube shows the depth of water in the supply tank. A valve in the connecting pipe makes it possible to shut off the flow of water when the supply tank is refilled. A waste pipe in the connecting pipe discharges excess water from the soil tank into a receiving vessel. The lip of the waste pipe is set at the level of the water in the soil tank.

A small vent tube passes through the rubber stopper at the top of the glass gage. This tube is open at both ends (the lower end in water and the upper in air) and the level of the soil water is determined by the elevation of the bottom end of the vent. In

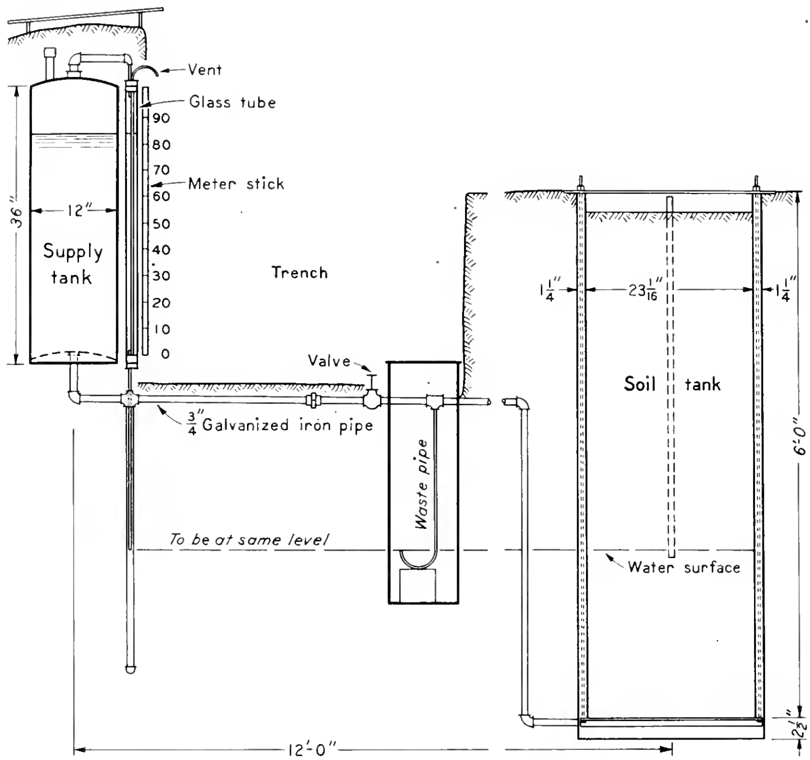

FIGURE 1.--Mariotte tank connected to soil tank to maintain a constant water level in the soil and supply water evaporated or transpired. Santa Ana station, 1929-32.

Figure 1 the water table in the soil tank is at such a depth that it is necessary to extend the vent tube downward into a well below the level of the connecting pipe.

Experience has determined that variations in temperature cause changes in vapor pressure in the Mariotte tank, resulting in fluctuations of the water level. Thorough insulation is therefore necessary. Tanks at Santa Ana were completely buried in the ground except for a small entrance provided with a narrow doorway which opened upon the graduated scale. Protection against changes in soil moisture around the tanks due to rainfall was provided by a section of roof which excluded precipitation while permitting a free circulation of air above the tanks.

The vent tube provides the Mariotte control feature which maintains a constant water level in the connected soil tank. In operation, the Mariotte tank is filled and the valve in the connecting pipe is opened, admitting water to the soil tank. As the water level drops in the supply tank a partial vacuum is formed above the water surface and the water drops in the vent tube from the original level to a point the position of which depends upon the degree of vacuum established. This point is determined by the difference in the pressure heads due to atmospheric pressure and the partial vacuum in the supply tank. Water will continue to fall in the vent tube, but at a greater rate than in the Mariotte tank, until the pressure head corresponding to the atmospheric pressure, minus the pressure head caused by the partial vacuum, is balanced by a column of water equal to the difference in elevation between the water surface in the Mariotte tank and the bottom of the vent. Water will then stand in the vent at the bottom of the tube with the pressure at this point atmospheric.

If the water continues to flow, air will enter the glass gage through the vent tube, bubbling upward through the water and into the top of the supply tank. Water will continue to rise in the soil tank to the level of the lower end of the vent, at which point the atmospheric pressure in the soil tank and in the bottom of the vent tube is the same. As there is no difference in pressure and both points are at the same level, there is no head to cause further flow and bubbling will cease. When the water table in the soil falls below the bottom of the vent, the balance of pressures is again disturbed and flow will once more start from the Mariotte tank, replacing the quantity of water used.

As a partial vacuum must be maintained at all times, pipe connections must be airtight. Air leaks through the many joints of the system disturb the balance of pressure necessary for full automatic control. Thorough insulation against temperature changes has been mentioned. Such changes may cause expansion or contraction of the tank itself, of the water in the tank, and of the air in the chamber above the water. The combined result is change in the vapor pressure with consequent influence upon effective regulation.

Water in the glass tube will fall with an increase in temperature within the Mariotte tank, and readings on the scale, taken at this time, will be erroneous. A test of the effect of temperature on scale readings showed that an increase of 30° F. in outside air temperature caused a drop of 1 centimeter of the water level in the glass gage. As the temperature returned to the starting point, water in the gage came back to its initial position. Early morning is a better time for observations than later in the day when temperatures are higher.

Float Valves

A simple device for maintaining a definite depth of water above the soil surface in tule tanks is an ordinary float valve connected by a feed pipe to a supply tank. The float valve is adjusted to operate at the required water surface. As the water is used the float drops to open a needle valve and admit water from the supply tank. A gage on the side of the tank permits readings of water levels, and the quantity of water released between observations is equal to the consumptive use by tank growth. This equipment has the advantages of fitting into a small space and of maintaining a constant depth of water. It is easily installed and gives satisfactory results. A water-stage recorder with float in the supply tank may be attached to obtain continuous records of consumptive use.

FACTORS AFFECTING THE USE OF WATER BY VEGETATION GROWN IN TANKS

It has already been stated (page 16) that the use of water by tank crops varies in some degree from natural field use, and this difference must be compensated for by applying a reduction factor to tank records. A knowledge of the influencing factors and an effort to carry on an investigation under the most natural conditions will go far to equalize the use of water between tank growth and natural fields. The factors affecting tank investigations are many and are related to soil, water, plants, and environment.

Methods of placing the soil in the tank, density of vegetation, unnatural environment of growth, injury to root systems, limitation of the amount of soil as affecting root growth and soil fertility, aerial spread of foliage, and entrance of rain water, act upon the growth of tank vegetation or the amount of water it consumes. Each of these factors is important, as estimates of field consumptive use by natural cover will be in proportion to the accuracy of the tank determinations.

Experience with the Santa Ana investigation (2) has demonstrated a satisfactory method of filling soil tanks without soil disturbance. The recommended practice is to force the open-bottom inner shell of the double cylinder tank down over a core of undisturbed soil, cutting off the soil column by jacking the bottom plate into place when the shell is filled. (Plate I-A.) This requires an excavation around the tank as the work proceeds. Once the plate is bolted in place the filled tank may be hoisted above ground with tripod and chain-block and lowered into the outer tank previously set in the location selected. This procedure leaves the soil in the tank in its original condition and has the advantage of sometimes capturing a growing crop without serious disturbance to its root system.

The relation of density of tank growth to natural field growth is a contributing factor in determining the reduction

PLATE I

A. Screw jack working against anchored cable, forcing soil tank 6 feet into the ground to capture undisturbed soil.

B. Soil sampling equipment: compressor unit (on truck), pneumatic driving hammer (in operator's hands), ordinary soil tube hammer (on ground) and soil tube jack.

coefficient which must be applied to tank results. Grasses, particularly the original crop of an undisturbed soil, are most likely to have the same density of growth as under field conditions, and the use of water by the tank crop will be approximately the same as by grass in the open field. For native shrubs it is difficult to obtain the same density of growth as under natural conditions, since this type of vegetation does not grow in an orderly manner. The wide spacing of some shrubs and the close growth of others make the correct unit area per plant a matter of conjecture.

Aquatic plants, as tules and cattails, may grow with the same approximate density in tanks as in swamps, although the plants around the edges are more stunted than in the center, owing apparently to greater exposure to sun and wind. The number of stems per unit area is likely to vary in different tanks. A comparison of the density of tules in the Santa Ana investigation (4), showed a tank 6 feet in diameter to have a density of 57 stems per square foot of area and to use 12.43 acre-inches of water in September, while a 2-foot tank having 87 stems per foot used 19.37 acre-inches. Both tanks had the same exposure. Carrying the comparison further, the consumptive use of water per individual stalk was the same regardless of density of growth or the size of tank in which it grew. However, the tank growth was stunted in comparison with normal swamp growth.

The limitations of tank growth, as affected by environment, are extremely important in determining the quantity of water used. It is emphasized that tanks containing vegetation must be surrounded by the same type of growth; otherwise there can be no true comparison of the amount of water used by the tank vegetation and similar growth in the field.

The injury to roots caused by transplanting vegetation into soil tanks, or through cutting the roots, temporarily limits the plant growth and temporarily affects the amount of water consumed. Plants with running roots (saltgrass or brush for example) are subject to shock when their roots are disturbed or partly removed. The size of tanks is a limiting factor in the root distribution of tank growth, especially roots of the spreading type. It has been observed that roots of tules growing in tanks of small diameter become greatly crowded after the first year, and the plant growth becomes more or less stunted as the investigation proceeds.

Limitation of the amount of soil as affecting fertility is likewise important in determining the use of water by tank crops. Investigations running over extended periods in which the relatively small volume of soil is used continuously are likely to result in a stunted growth. The effect of continued cropping of tank soil has been noticed in cotton investigations extending over a 3-year period. Beckett and Dunshee (1) say: "A comparison of the size of plants grown in the tanks with those grown in the field plots under similar irrigation treatments, showed that smaller plants were produced in the tanks each year than were obtained in the plots. These smaller plants, however, used from 40 to 53 per cent more water than the plants growing in the field. This increased use of water might be explained by the probable root concentration in the limited soil mass of the tanks, a higher soil temperature in the tanks, and the higher temperatures and lower humidities surrounding the individual plants in the tanks."

Crop overhang of tank growth also presents a serious question in tank investigations. The aerial portions of some crops, such as tules and cattails, grow naturally stiff and erect and occupy approximately the same horizontal area as the tank. In other growth, such as sweetclover, the stems droop over a much greater area than that occupied by the tank. The interception of insolation under such conditions is greater than the tank intercept, and it is incorrect to compute the water loss on a basis of tank area.

Protection of soil tanks during periods of precipitation to prevent entrance of rain water into the soil has been generally condemned, yet for some purposes prevention of rainfall on the tank surface has advantages. Investigations involving use of water by plants under natural conditions where the ground water fluctuates from day to day and from season to season undoubtedly require that rain be allowed to enter the tank soil. On the other hand, in those investigations which are carried on with a fixed water table, the entrance of rain water into the soil disturbs the normal distribution of capillary moisture. In its natural distribution the largest percentage is immediately above the water table and the least at the ground surface. If rainfall is allowed on the tank, the entire soil mass becomes filled to field capacity, and conditions relative to a fixed water table no longer exist.

In a series of soil tanks having different depths to water table, each with overflow pipes to drain off excess soil water, the soil moisture varies with the depth to the water table. For instance, if the water table is near the surface and rainfall is heavy there will be much overflow from the waste pipe, as the shallow soil is unable to hold all the excess; but if the water table is deep in the tank there will be little overflow as the greater volume of soil holds more rain. Thus all the rain might be retained in a deep tank while but a small portion would be held where the water table was near the surface. Under these conditions the changed moisture distribution resulting from rainfall penetration is different for each tank or for each depth to water table. Hence, while the treatment of a series of tanks may be uniform as regards soil moisture during the dry season, it is far from uniform during the wet season. It is evident, therefore, that the procedure to be followed for tank protection will depend largely on the object in view.

SOIL-MOISTURE STUDIES

It has been shown that the limitations of soil tanks make them inadequate for some types of consumptive use investigations. Tanks are suited to areas of high ground water where studies are to be made with definite water levels but studies in other areas where the water table is beyond reach of root systems may best be carried on through soil sampling. The Division of Irrigation and various agricultural experiment stations have employed soil sampling for agricultural crops and to some extent for natural vegetation.

Soil-moisture studies require systematic collection of many soil samples taken to depth beyond the reach of plant roots. This is done through use of soil tubes of different lengths driven into the soil to known depths. The samples obtained are dried in an electric oven at a temperature of 110° C. Standard laboratory practices are followed.

Collection of soil samples is a laborious process, as the manual effort of driving soil tubes by hand, especially for depths beyond a few feet, is extremely arduous. To lessen the labor and expedite the work a compressed air unit developed by the Division of Irrigation (3) drives the soil tube mechanically. The entire equipment, shown in Plate I-B, consists of an air compressor, a soil tube, and a soil tube jack. The air unit includes a compressor mounted on a truck, a light air hammer, and an air hose. It provides a pressure of 100 pounds per square inch, delivering 2,250 blows per minute to the soil tube.

The soil tubes are of 16-gage seamless steel tubing, from 5 to 25 feet in length, fitted with a suitable driving head and a cutting point. The point is of case-hardened nickel steel with a choke bore to overcome friction within the tube.

A very efficient, light-weight jack shown in the foreground in Plate I-B has been perfected by the Division of Irrigation (31) to draw the soil tube from the ground under difficult conditions.

Withdrawal from depths as great as 25 feet is practicable with this equipment in soil which is neither too wet nor too coarse. In wet clay the soil sticks to the tube and is difficult to dislodge, while saturated soil slips from the tube and is lost before it can be drawn to the surface. Samples of coarse material greater than the diameter of the tube cannot be obtained with this equipment. Most of the valley lands may be sampled with the soil tube, but alluvial fans, gravel areas, and other coarse and rocky places require pits, shafts, or tunnels.

Samples of soil obtained through use of the soil tube weigh 150 to 200 grams, but in rocky soil large samples of the material are more representative. Accordingly, from pits or shafts, 4,000-gram samples are obtained without reference to size of particles. After they have dried, the rocky portions are screened out and classified as rock.

The equivalent depth of water in soil samples may be found from the equation $D = \frac{PVd}{100}$, in which D is the equivalent depth in inches; P, percentage of moisture in the sample; V, apparent specific gravity of the soil in place; and d, depth of soil sample in inches.

The depth to which soil samples are taken depends upon the depth to which roots go in search of moisture. As previously shown, some vegetation is deep-rooted while other species have roots relatively close to the surface. Moisture may percolate to depths beyond the root zone, but root extraction determines the depth to which it is necessary to take soil samples. Beyond this depth percolating water contributes to the underground-water supply. Thus, by sampling, to determine the use of water by deep-rooted shrubs it might sometimes be necessary to drive soil tubes to depths of 25 feet or more, whereas for shallow-rooted grasses 4 to 6 feet would be sufficient.

STREAM-FLOW STUDIES

Because of the increasing scarcity of small water supplies in some parts of the West and the opportunity of obtaining them by diverting canyon streams, there is need to know what happens to the adjacent vegetation when the greater portion of its moisture supply is taken away. For many water-loving trees and shrubs, stream diversion often proves destructive.

In addition to the usual factors of climate affecting the water requirement of canyon-bottom growth there are the environmental factors of type, density and distribution of adjacent vegetation, slope and depth of the soil mantle supporting the vegetative cover, and axial direction and general slope of the canyon bottom as affecting its exposure to sunlight. The density of growth affects the degree of shade and the amount of transpiration, especially that of the under story cover. Slope and depth of the soil mantle control, to a considerable extent, moisture held in the side slopes of the canyon wall.

The cardinal direction of the canyon axis is likewise important, as is also the direction of slope of the mountain side of which the canyon is a unit. In general a canyon stream extending in a northerly and southerly direction has greater exposure to the sun, and its vegetation has greater transpiration opportunity, than one running east and west. This is especially true of the deeper canyons.

Likewise the general direction of the mountain slope influences not only such climatic factors as humidity, rainfall, temperature, wind movement, hours of sunlight, and melting or retarding of snow cover, but also to some extent the variety and density of the vegetation itself. Such differences, on opposite sides of easterly and westerly mountain ranges, are commonly understood. On the southerly side longer and more intense exposure to the sun increases transpiration losses, snow melts more rapidly, and stream flow decreases or dries up at an earlier date than on northerly protected slopes.

Canyon-bottom growth is usually water-loving. It may be a meadow, a swamp, alders, willows, the larger sycamores, cottonwoods or cedars, or a mixture of them. Under certain conditions the use of water by vegetation in any selected section of a given canyon may be determined by the difference in stream measurements at its upper and lower boundaries, particular care being taken to force the underflow to the surface at points of measurement. In some instances natural rock barriers to underflow exist and the stream flows naturally over them, but in other cases artificial controls, such as submerged dams, may be necessary to bring the ground water to the surface. Before an investigation is undertaken, the canyon and its surrounding area should be examined to determine the possibility of stream-bed losses through rock fissures. Where fissures occur or accurate measurements are impossible, the investigation is not feasible. The possibility of side inflow from canyon walls also should be examined. The Division of Irrigation used the method referred to above in determining the consumptive use of water by canyon-bottom vegetation in southern California (see p. 66). (2, 4).

The diurnal fluctuation of flowing streams is of importance as an indicator of the daily withdrawal of water from the soil by plants. It has long been observed that stream flow decreases by day and recovers by night, the plotted daily discharge curves showing a series of alternate low and high points which occur at approximately the same time each day. The daily decline is the result of the action of plants in withdrawing water from the saturated zone, and recovery is due to the nighttime decrease of transpiration. Therefore, as the daily fluctuations of the stream surface depend upon transpiration from plants, the same factors which affect transpiration likewise affect flowing water, but in a reverse order. That is, when bright sunshine, warm weather, or hot winds cause high rates of transpiration the corresponding stream flow will be low; but it will increase in volume when transpiration is low through cloudiness, cool weather, or high humidity.

The use of water-stage recorders at control points provides hydrographic charts that indicate the effect of transpiration upon the flowing stream. The effect may be too small to be visible in the stream itself except in springs and small streams which disappear in the sand by day and flow in the channel by night. Evidence of these daily fluctuations is afforded, however, in Figure 2 which was developed by Troxell (34) to show short-

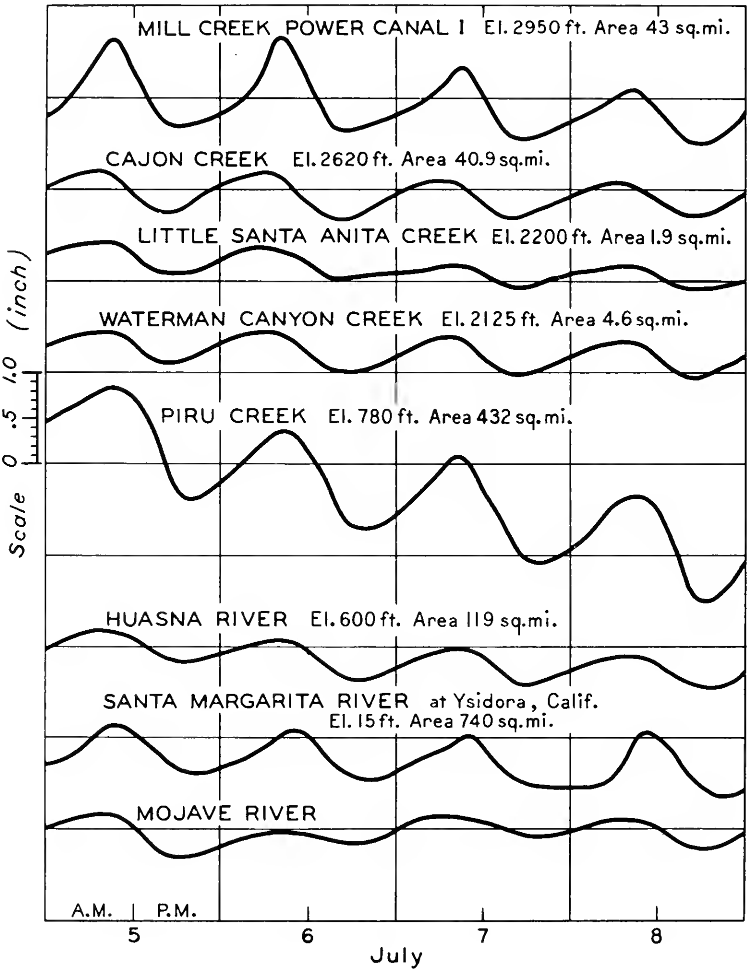

FIGURE 2.--Diurnal fluctuations in southern California streams (after Troxell).

period records of the flow of eight California streams. These were selected to represent a variety of drainage basins varying in length and width as well as in altitude. It will be noted that each hydrograph shows a well-defined daily cycle with rise and fall at approximately the same time each day although not in the same degree of amplitude.

Evaporation from a water surface is an expression of the combined climatic influences affecting both evaporation and transpiration, yet because of the volume of water in an evaporation pan, the solar energy necessary to cause evaporation is greater than that which causes transpiration from plants, and thus evaporation lags behind transpiration. To obtain a more sensitive record of transpiration opportunity, an evaporimeter was designed by Taylor (4). This consisted of a shallow, black pan attached to the weighing mechanism of a recording rain gage. The depth of water in the pan is limited to the maximum evaporation for a single day. The chart scale is exaggerated 9 to 1, making possible the reading of very small amounts of evaporation. With this equipment it is feasible to determine exact hourly evaporation losses. The exposed shallow pan, resting on a sensitive balance, responds readily to wind movement and the resulting pan movements on the chart also record the times of greater wind movement and its relative intensity.

A measuring device much used in California investigations is the Parshall flume (22). The difficulty of measuring, in a single device, both low and high water flows, has been met in a combination Parshall flume and connected V-notch weir or by two connected Parshall flumes of different throat widths, arranged by Taylor (4) to pass the maximum and minimum flows respectively. The difficulty of accurate measurements of low water flow in a flume intended for peak flow is obvious. Design for a double Parshall flume is shown in Figure 3. It should be noted that the combination flume requires two water-stage recorders.

In using the Parshall flume it should be remembered that

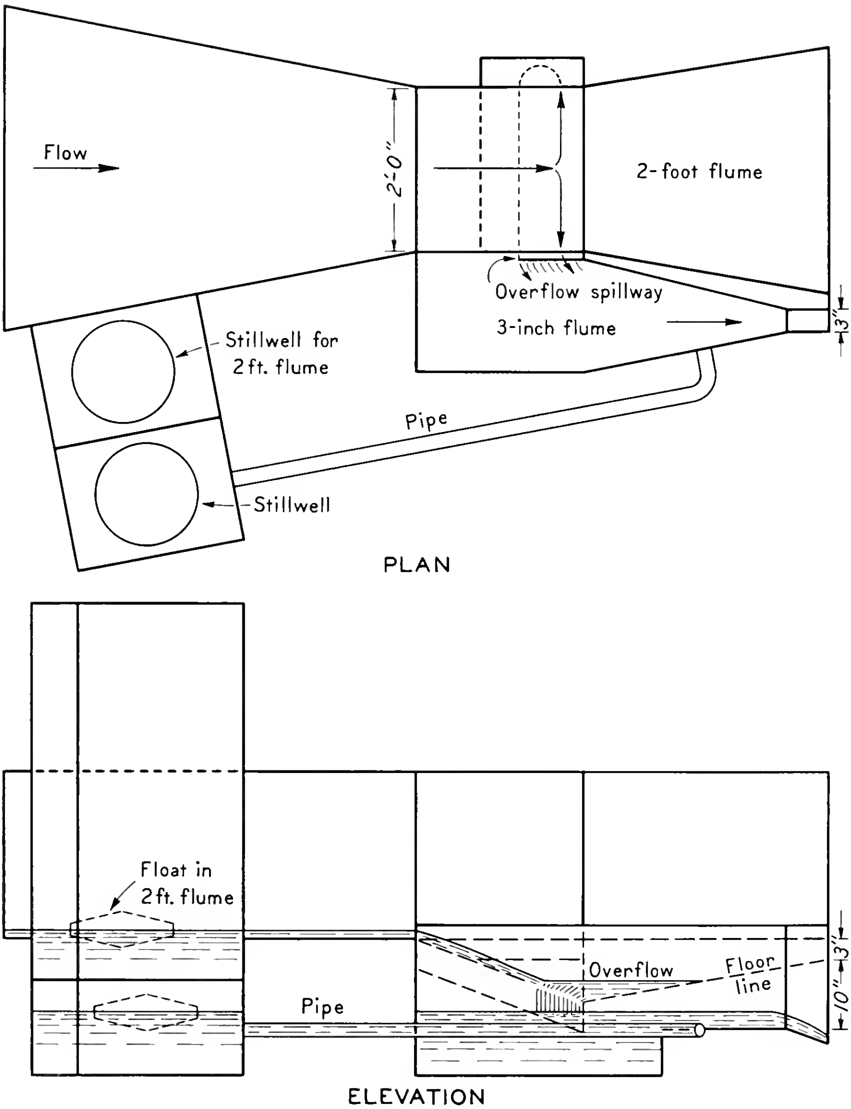

FIGURE 3.--Combination flume for measurement of water at both high and low stages.

this device was designed for irrigation canals carrying water at a relatively low velocity and that it should be used in mountain areas with some caution.

WATER-TABLE FLUCTUATIONS

The three methods of measuring consumptive use of water by vegetation previously discussed - tank, soil moisture, and stream-flow investigations - are applicable to somewhat limited soil-moisture conditions or types of growth. The tank method is suitable for the smaller vegetation, but it is evident that it cannot economically be used for studies of consumptive use of water by large trees. Extensive soil-moisture investigations generally are not undertaken in areas of high ground water, and it is evident also that canyon-bottom investigations are limited. Observations of daily ground-water fluctuation in relation to vegetative discharge has been little used. Beyond its application in Arizona by Smith and in California (33) and Utah (38), it apparently has not received much attention, largely because of the difficulty of determining the specific yield of large areas of soil in place. Water-table fluctuations provide a basis of estimating the consumptive use of water by overlying vegetation but present difficulties in arriving at precise measurements of quantity.

During the early spring, as vegetation is beginning its growth, the daily fluctuations of the water table do not reach the same degree of amplitude that occurs during periods of maximum growth; and conversely, in the fall, as vegetation is maturing and transpiration decreases, the daily fluctuations become progressively smaller. Fluctuations do not occur where there are bare lands or plowed fields under which the ground water is below the reach of plant roots, nor during winter months when plants are either dead or dormant. Lower temperatures, cloudiness, or rainfall decrease the size of the fluctuations; warm sunshine, low humidity, or hot winds increase them. In short, any cause affecting transpiration influences also the diurnal changes of the water table. Fluctuations begin approximately at the same time each day, the surface lowering as the transpiration increases, although the result of the increased transpiration is not immediately apparent and there is a noticeable lag between cause and effect. During the growing season, when demand is greatest, the daytime draw-down generally exceeds the nighttime recovery. The result is a steadily falling water table which continues until transpiration ceases. When plants become dormant the normal recharge of the basin increases ground storage until a resumption of the vegetal demand occurs in the following spring.

Because the water usage of some plants is greater than that of others, the draft of the different species on the ground-water supply varies with the type as well as with density of the natural cover, so that the amplitude of the fluctuations varies with the vegetation. The fluctuations are widest where water-loving vegetation constitutes the dominant growth and are least where drought-resistant or salt-resistant plants occupy the greatest area. Not only does the type and density of plant growth affect the quantity of water withdrawn, but the depth to water affects the total consumed, as is evident from the stunted growth found where the water is at considerable depth.

Interpretation of the ground-water fluctuations in inches of depth of water consumed by vegetation is accomplished by the following method: First, ground-water wells are equipped with water-stage recorders which provide continuous records of changes in water levels. Second, the specific yield of the soil near the wells is determined by driving metal cylinders over columns of undisturbed soil. Third, the ground-water discharge in inches of depth is computed by means of the formula $Q = y(24r + s)$ where Q is the consumptive use of water, y the specific yield of the soil for the area investigated, and r the hourly rate of recharge of the water table during the hours of least transpiration demand. This period is between midnight and 4 a.m. The factor s is the net difference in the height of the water table in 24 hours.

The curve of ground-water fluctuations has the general characteristics of the curve of daily stream fluctuations; that is, there are both a maximum and a minimum period in each 24 hours. These periods do not necessarily occur at the same time. For the purpose of discussion, a representative ground-water curve is shown in Figure 4. It will be shown that this type of curve establishes the daily relation of consumptive use of water to ground-water discharge and recharge.

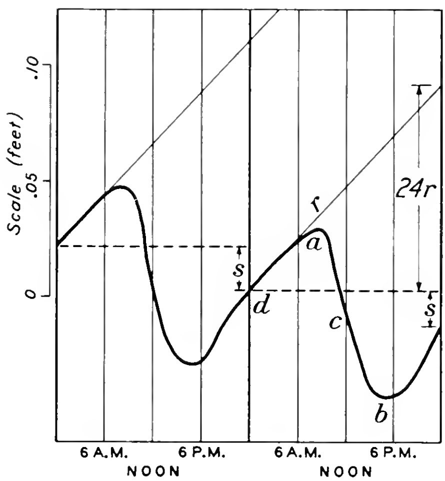

FIGURE 4.-- Representative ground-water curve, showing effect of the daily cycle of transpiration by overlying vegetation (after Troxell).

Assuming that the ground water rises during the night when transpiration is at a minimum, there will approach a time during the morning hours, with increasing transpiration, when the demand of vegetation just balances the inflow. This point is indicated at the top of the daily ground-water curve "a" where the water table starts to fall. On the other hand, at the bottom of the curve "b" in the late afternoon, transpiration losses have decreased to such an extent that they are balanced by the daily recharge and the water table begins to rise. At some point between these two extremes vegetation is not only using all the inflow into the basin, but is also making its maximum demand upon the water held in storage in the soil. This point is indicated by the steepest slope on the falling side at the point "c" between the top and bottom of the curve and represents the maximum daily transpiration. Likewise, the rising side of the curve indicates less transpiration than inflow and consequently an increase in ground-water storage. The steepest slope on the rising side "d", then indicates the point of minimum or no transpiration, and the time of this occurrence lies between the hours of midnight and 4 a.m. At this point, the hourly rate of rise represents the hourly rate of recharge.

Evidence has been advanced by Troxell (34), however, to show that the rate of recharge "r" is not constant throughout the transpiration period, but changes as the rate increases, becoming a maximum at the height of the transpiration season. There is little evidence to show how seriously this will affect estimates of consumptive use. It is not claimed that water-table fluctuations provide a basis for precise measurements; rather, they are considered a foundation for approximate estimates.

CHAPTER 4

INVESTIGATIONS OF THE DIVISION OF IRRIGATION

BASIS AND SCOPE OF STUDIES

Consumptive use of water by noncrop plants has been the subject of investigations by the Division of Irrigation in cooperation with the Division of Water Resources, Department of Public Works, State of California, and other agencies for a number of years. Few native plants have been studied, however, as they are far too numerous for all species to be included in these investigations. Grasses, small shrubs, and swamp vegetation may be grown in tanks, but larger shrubs and trees present problems in consumptive-use measurements that are seldom studied.

As an adjunct of such investigations, records of temperature, precipitation, evaporation, and wind movement are of value. Such records for the Santa Ana station, Calif., appear in Table 2.

Knowledge of consumptive use of water by native growth is most needed for moist areas containing potential water supplies. In closed basins water that may be recoverable amounts to a considerable portion of the annual evaporation and transpiration losses. The natural growth of such areas is usually limited to grasses and water-loving shrubs and trees. Saltgrass, found on moist land, has been grown by the Division of Irrigation and other investigators in tanks having both fixed and fluctuating water tables.

Santa Ana Valley, California [1]

In 1929, the Division of Irrigation in cooperation with the State Division of Water Resources undertook an investigation in the Santa Ana River Valley to measure the consumptive use of

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1/ Field investigations at the Santa Ana, Prado, and San Bernardino stations were made by Arthur A. Young, Associate Irrigation Engineer, Division of Irrigation in cooperation with the Division of Water Resources, Department of Public Works, State of California.

TABLE 2

METEOROLOGICAL DATA AT SANTA ANA STATION, SANTA ANA, CALIF., 1929-32

Month and year	Temperature: Mean maximum	Temperature: Mean minimum	Temperature: Mean	Precipitation	Evaporation from a Weather Bureau pan	Wind movement: Total	Wind movement: Average
1929	°F.	°F.	°F.	Inches	Inches	Miles	Miles per hour
May	74	51	62	0.03	8.39	--	--
June	76	53	64	.11	8.23	--	--
July	81	60	70	--	8.89	--	--
August	85	60	72	--	8.90	--	--
September	79	58	68	.35	5.65	1695	2.4
October	80	52	66	--	6.06	1745	2.3
November	77	41	59	--	5.26	1806	2.5
December	72	41	56	--	3.44	1547	2.1
1930							
January	62	40	51	5.55	2.28	1743	2.3
February	66	44	55	.55	2.87	1682	2.5
March	68	46	57	2.99	4.48	2212	3.0
April	72	47	60	.80	6.05	1970	2.7
May	70	48	59	1.23	6.79	2228	3.0
June	75	55	65	.02	6.95	1871	2.6
July	81	57	69	--	8.54	1671	2.2
August	82	59	70	--	7.39	1518	2.0
September	77	54	66	.02	5.83	1381	1.9
October	80	47	64	.07	5.50	1322	1.8
November	77	43	60	1.47	4.26	1534	2.1
December	70	36	53	--	3.31	1389	1.9
Year	73	48	60	12.70	64.25	20521	2.3
1931							
January	68	40	54	3.82	2.89	1382	1.9
February	68	45	56	2.28	2.74	1378	2.0
March	76	42	59	.03	5.78	1830	2.5
April	76	49	62	2.68	6.02	1736	2.4
May	77	56	66	.67	6.89	1781	2.4
June	81	56	68	.07	8.05	1670	2.3
July	85	64	74	--	8.90	1656	2.2
August	84	62	73	.43	7.46	1415	1.9
September	84	55	70	.29	6.21	1201	1.7
October	79	50	64	.09	4.70	1121	1.5
November	68	42	55	1.69	3.09	1223	1.7
December	63	37	50	4.70	1.99	1136	1.5
Year	76	50	63	16.75	64.72	17529	2.0
1932							
January	61	37	49	2.04	2.38	1335	1.8
February	62	40	51	4.53	2.73	1371	2.0
March	69	41	55	--	4.98	1510	2.0
April	72	42	57	.35	5.86	1659	2.3

water by saltgrass, wire rush, willow, Bermuda grass, tules, and cattails grown in tanks with different depths to ground water.

Study of soils and soil-moisture conditions in the lower Santa Ana River Valley led to selection of a plot in a level 10-acre field 4 miles west of Santa Ana and about 7 miles inland from the Pacific coast. The field was free of windbreaks and shade, and was generally suitable for consumptive-use studies. Soil was of alluvial origin, classified as a fine, sandy loam, grading into a coarse, yellow sand at a depth of 6 to 7 feet. It lacked humus and contained a small amount of alkali. An ample supply of good water for use in the experiment tanks was found at a depth of a few feet. The climatic conditions at this point are representative of the coastal climate of southern California. Summers are warm and dry and winters are moderate and wet. Coastal fogs are frequent, tending to modify evaporation from water surfaces and transpiration by plants. Figure 5 is a sketch of the station showing arrangement of tanks.

Saltgrass.--In all saltgrass tanks water tables were held at definite predetermined depths by means of Mariotte supply tanks. A general outline of the tank set-up is shown in Figure 1, and a description of the Mariotte apparatus is given on page 19. Fifteen soil tanks of the double-shell type, each 23 inches in diameter and 6 feet deep, were filled with a fine sandy loam soil. In 12 tanks the soil was captured in place undisturbed, but in three others it was loosely settled in water. Six tanks of undisturbed soil had an original crop of saltgrass on the soil column with root systems fully developed. Later in the investigation saltgrass was transplanted into all other tanks so that eventually all tanks supported saltgrass growth.

To reduce the hazard of inaccuracies which might occur in a single tank the entire group was divided into sets of three, each set having a different depth to water. In four sets consumptive-use measurements were made with water tables at depths of 1, 2, 3, and 4 feet respectively. A summary of the data obtained from the

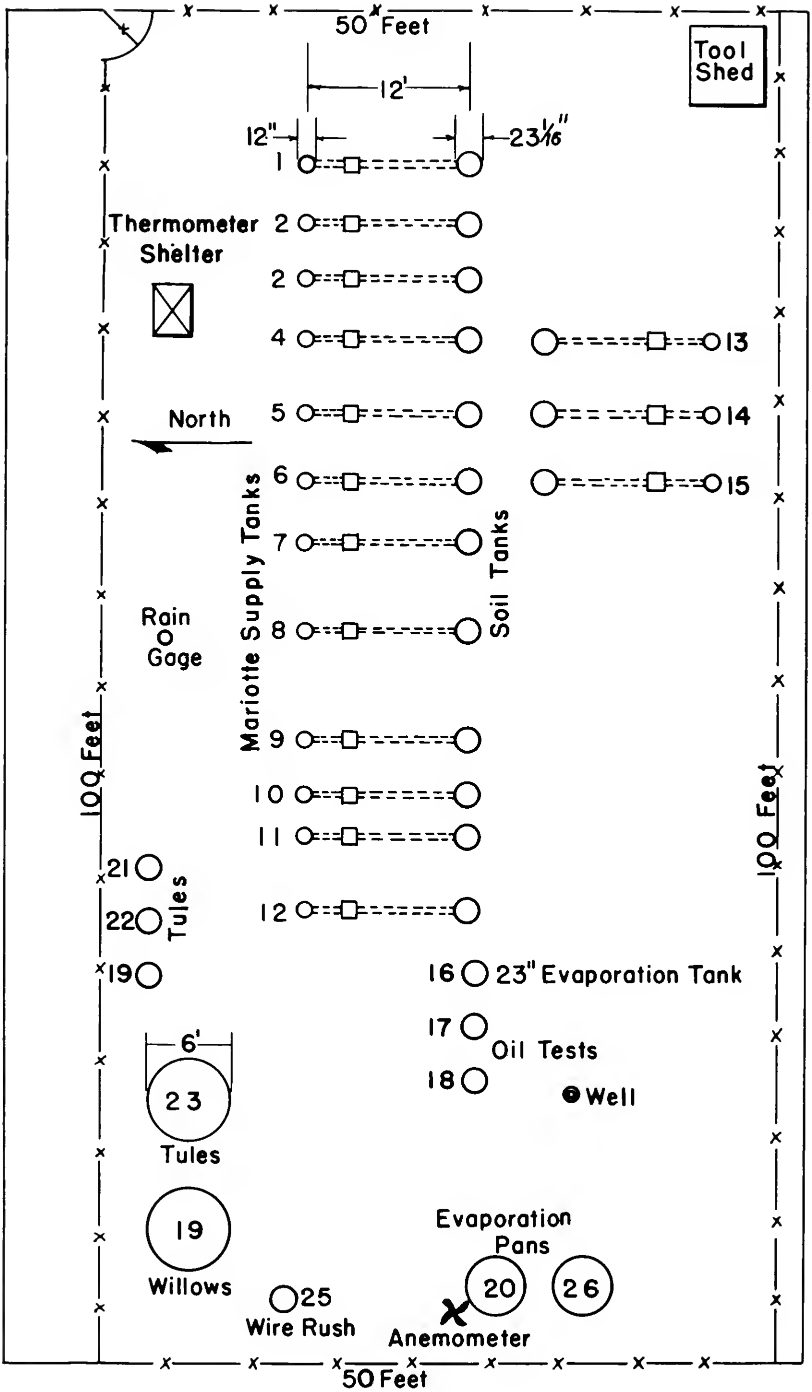


FIGURE 5.-- Plan of evaporation station near Santa Ana, Calif.

four sets appears in the following tabulation, which represents the 3 years 1929-30 to 1931-32:

Average depth to water table	Water used
Inches	Inches
12	42.76
24	35.31
36	1/ 23.79
48	13.37

Saltgrass is an indicator of ground water, but this investigation has demonstrated that its consumptive use is not excessive when compared with water requirements of many other plants. As the depth to water increases consumptive use decreases. Thus, at a depth of 1 foot the quantity of water used in 1 year equalled 42.76 inches; at 2 feet, 35.31 inches; and at 4 feet, 13.37 inches. The depth-use ratio plots almost as a straight line.

In most saltgrass areas in the Santa Ana basin the depth to water table exceeds 4 feet and the average seasonal draft on the ground water is not excessive. Monthly and seasonal data on use of water by saltgrass in the Santa Ana River basin are given in Table 3.

Wire rush.--Wire rush (*Juncus balticus*) was transplanted into a tank in which the water level was held at a depth of 2 feet. With a plentiful water supply close to the roots, growth became dense and the demand for water increased in the second year to a total of 13.75 inches for the month of July. For the 12-month period ending November 30, 1931, the annual consumptive use of water by wire rush was 93.58 inches. Wire rush thus used more than 2.5 times the saltgrass requirement. Monthly use of water by wire rush is shown in Table 4.

Willow.--Investigation of the consumptive use of water by red willow was begun at the Santa Ana station in 1930 and continued for two seasons. During much of the second year, however, the willow was in poor condition and early in the season became partly defoliated. For this period consumptive use data are

1/ For 11 months only; May omitted.

TABLE 3

CONSUMPTIVE USE OF WATER BY SALTGRASS IN TANKS AT SANTA ANA, CALIF., 1929-32 1/

Tank No.	Year	Depth to water table	Water used													Number of months
			May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total	
		Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	
7		12	3.04	5.32	7.55	6.48	4.80	3.20	2.10	2.05	1.63	--	2.58	4.20		11
8	1931-32	12	4.04	6.38	7.68	5.71	4.17	2.77	1.78	1.07	--	1.89	2.21	3.61		11
9		12	3.98	5.64	7.48	6.01	4.42	3.11	1.96	1.19	1.07	1.29	1.74	3.14		12
Mean	1931-32	12	3.69	5.78	7.57	6.07	4.46	3.03	1.95	1.44	1.35	1.59	2.18	3.65	42.76	12
7		24	1.44	4.92	5.53	5.02	3.32	3.41	2.66	1.63	.86	.98	1.29	2.50		12
8	1929-30	24	2.42	3.30	5.96	5.91	3.74	3.70	2.86	1.74	.55	.90	1.44	2.86		12
9		24	3.50	4.98	5.41	5.67	3.57	3.45	2.46	1.56	.75	.87	1.47	3.33		12
Mean	1929-30	24	2.45	4.40	5.63	5.53	3.54	3.52	2.66	1.64	.72	.92	1.40	2.90	35.31	12
13 2/		24	2.80	3.73	4.72	4.40	4.68	3.10	2.63	.84	1.87	.40	2.81	4.02		12
14	1931-32	24	2.61	3.36	4.51	3.85	3.28	2.68	2.55	1.11	1.06	--	1.66	4.82		11
15		24	3.16	5.04	6.22	5.15	4.21	2.96	2.29	1.01	1.23	.76	2.31	3.89		12
Mean	1931-32	24	2.86	4.04	5.15	4.47	4.06	2.91	2.49	.99	1.39	.58	2.26	4.24	35.44	12
4		24	2.76	3.82	4.81	4.05	3.55	2.79	2.22	1.60	2.79	--	2.95	3.48		11
5	1931-32	24	3.78	4.75	5.77	4.70	3.97	2.99	2.37	1.49	2.42	--	2.53	3.57		11
6		24	1.81	3.00	4.11	3.55	3.04	2.34	2.27	1.21	1.69	1.95	3.65	3.02		12
Mean	1931-32	24	2.78	3.86	4.90	4.10	3.52	2.71	2.29	1.43	2.30	1.95	3.04	3.36	36.24	12
1		36	--	3.04	2.72	1.91	1.87	1.56	1.83	1.44	1.83	1.65	2.64	4.17		11
2	1931-32	36	--	.96	2.15	2.08	1.74	1.48	1.83	--	2.33	2.13	3.29	3.04		10
3		36	--	1.24	2.67	2.10	1.77	1.45	1.84	2.44	--	1.75	3.65	2.77		10
Mean	1931-32	36	--	1.75	2.51	2.03	1.79	1.50	1.83	1.94	2.08	1.84	3.19	3.33	23.79	11
10		48	.28	.48	2.71	3.45	1.91	1.38	1.33	.91	.55	.61	.73	1.46		12
11	1929-30	48	.00	.59	1.86	2.33	1.41	1.16	.87	.52	.19	.35	.45	.84		12
12		48	.70	1.30	2.71	3.10	1.79	2.46	.12	.47	.19	.04	.15	.72		12
Mean	1929-30	48	.33	.79	2.43	2.96	1.70	1.67	.77	.63	.31	.33	.44	1.01	13.37	12

1/ All tanks exposed to rainfall Dec. 1931 to Apr. 1932, but protected at all other times.
2/ In these tanks soil was disturbed; in all other tanks soil was undisturbed.

TABLE 4

CONSUMPTIVE USE OF WATER BY WIRE RUSH IN TANK AT SANTA ANA, CALIF., 1930-32

Month	Year 1930	1931	1932
	Inches	Inches	Inches
January	--	2.65	--
February	--	2.96	1.58
March	--	6.78	4.11
April	--	7.76	8.55
May	--	8.62	--
June	--	10.30	--
July	--	13.75	--
August	5.74	12.70	--
September	5.43	10.73	--
October	5.68	8.25	--
November	5.03	4.85	--
December	4.23	--	--

unreliable and are omitted from present consideration.

The transplanted bush consisted of a single clump of 20 stems, each from 1/2 to 1 1/4 inches in diameter, growing from the same root. Their average height was 7 feet. The tank in which the bush was transplanted was 6 feet in diameter by 3 feet deep. Water table was constant at a depth of 2 feet. The drip line was approximately the same as the tank perimeter and consumptive use was computed on this basis. The general appearance of the bush is shown in Plate II-A.

Willow is a user of relatively pure water and normally does not grow where alkali salts are in high concentration. Nevertheless, some salts were present in the willow tank soil. Regardless of this, the willow bush produced a thrifty growth which consumed 52.70 acre-inches of water in 11 months, as represented in Table 5.

The relation of consumptive use to evaporation from water surfaces in the Santa Ana Valley (Table 44) indicates that water consumed by willows grown in isolated tanks exceeds evaporation from a Weather Bureau pan in but a single month of the year and averages 92 per cent of the total evaporation from June to October,

TABLE 5

CONSUMPTIVE USE OF WATER BY WILLOWS IN TANK AT SANTA ANA, CALIF., 1930-31

	Year	
Month	1930	1931
	Inches	Inches
January	--	--
February	--	2.00
March	--	3.92
April	--	5.72
May	3.28	4.76
June	4.99	4.48
July	7.34	--
August	7.80	--
September	6.63	--
October	5.36	--
November	3.54	--
December	2.12	--

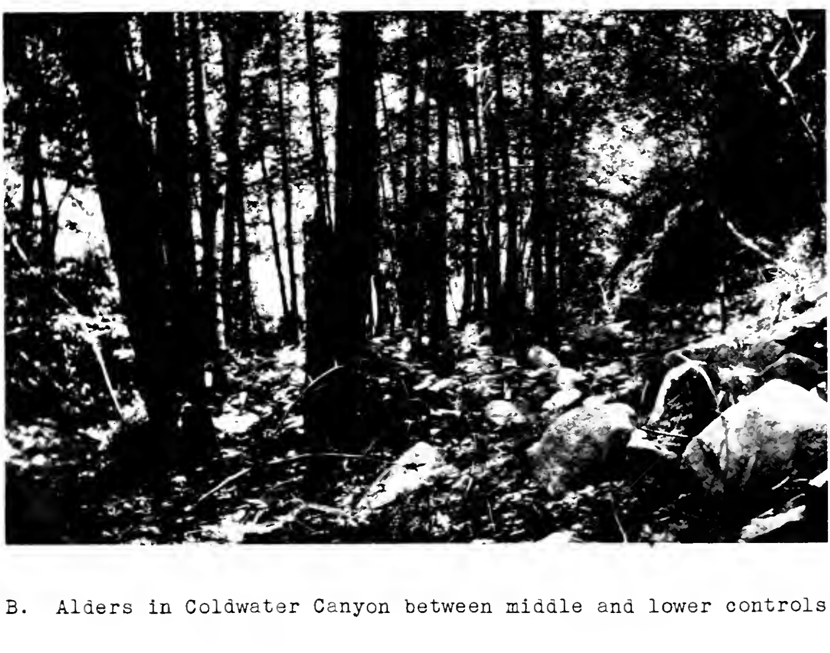
inclusive. Since these measurements were made in the open, away from other brush or similar growth, this average probably is greater than would be obtained under normal growth conditions. For the 11 months, indicated loss of water from the Weather Bureau pan was 63.11 inches, which is the equivalent of 44.2 inches of evaporation from a broad water surface. It appears, therefore, that tank-grown willows under these conditions consume a greater quantity of water than is lost from an equal area of water surface by evaporation.

Bermuda grass.--Bermuda grass (Cynodon dactylon) is a perennial with long creeping jointed stolons, often several feet in length. It spreads largely by both stolons and rootstocks, although it also seeds abundantly. It is found in many localities in exposed places but not in shade. Bermuda grass is not necessarily an indicator of ground water as is saltgrass, but like other plants it makes better growth with increased moisture. It is frequently used for pasture and makes good feed for stock.

For investigation of consumptive use of water by Bermuda grass an experimental station was established 1 mile east of San Bernardino, in the upper Santa Ana River valley, about 50 miles

PLATE II

A. Willows 6 to 7 feet high growing in 6-foot diameter tank at Santa Ana, Calif.



B. Alders in Coldwater Canyon between middle and lower controls.

above the Santa Ana station. The plot was in a level field at some distance from buildings and had good exposure. Climatic conditions represent those of the interior portion of southern California. Summers are long and hot. Winter temperatures are lower than in the valley at Santa Ana, and rainfall is greater. Records of temperature, wind, and rainfall are shown in Table 6.

Soil in the experimental tanks, classified as Chino silt loam, was taken from the station grounds. Ground water was within a few feet of the surface, yet there was no indication of alkali in the tanks after 2 years of operation. The station received artesian water from the city supply. Tanks in which Bermuda grass was grown were set in a large field of the same growth to provide normal surroundings.

As a part of the Santa Ana investigation, four tanks at San Bernardino were filled with undisturbed soil in which was growing a good Bermuda grass cover with fully developed root systems. In two tanks, the water table was maintained at a depth of 2 feet and in the other two at 3 feet, the water table being regulated by Mariotte apparatus. Grass growth was dense and several inches high.

The average annual depth of water used by the Bermuda grass having water table 2 feet from the tank surface was 34.37 inches, while those having table at 3 feet used 28.19 inches, which does not differ greatly from the water used by saltgrass. Monthly data on consumptive use of water by Bermuda grass are given in Table 7.

Tules and cattails.--The round-stem tule or common bulrush is a perennial plant with a round dark green stem growing to heights of 6 to 10 feet. It grows densely in shallow water along stream channels, in swamps, and drainage ditches. The triangular bulrush (*Scirpus olneyi*) is also an aquatic plant. Its stems are three-cornered and grow often to heights of 6 feet or more. Cattail, sometimes classed with tules and of similar height, is a perennial marsh plant with flat leaves and cylindrical head which is filled with thousands of small cottony seeds.

TABLE 6

METEOROLOGICAL DATA AT SAN BERNARDINO STATION,
SAN BERNARDINO, CALIF., 1929-32

Month and year	Temperature: Mean maximum	Temperature: Mean minimum	Temperature: Mean	Precipitation	Evaporation from a Weather Bureau pan	Wind movement: Total	Wind movement: Average
1929	°F.	°F.	°F.	Inches	Inches	Miles	Miles per hour
May	82	47	64	--	7.78	--	--
June	88	50	69	0.12	8.89	--	--
July	95	57	76	--	9.78	--	--
August	98	60	79	--	8.81	--	--
September	88	55	72	.53	5.69	1012	1.4
October	85	46	66	--	5.58	1183	1.6
November	80	34	57	--	4.98	1589	2.2
December	75	33	54	--	3.82	1255	1.7
1930							
January	61	36	48	4.71	2.32	1434	1.9
February	74	38	56	1.06	3.46	1357	2.0
March	70	41	56	3.99	5.02	1864	2.5
April	77	45	61	1.33	5.38	1143	1.6
May	74	43	58	1.76	5.50	947	1.3
June	86	52	69	--	6.59	900	1.2
July	96	54	75	--	8.08	679	.9
August	95	57	76	--	7.54	879	1.2
September	84	50	67	--	5.47	895	1.2
October	82	44	63	1.24	5.21	1086	1.5
November	77	39	58	2.08	3.77	1257	1.7
December	72	27	50	--	2.63	--	--
Year	79	44	61	16.17	60.97		
1931							
January	68	35	52	2.15	3.10	--	--
February	66	40	53	3.73	3.06	--	--
March	76	37	56	.60	5.77	--	--
April	79	44	62	2.73	4.89	--	--
May	83	52	68	.89	6.79	--	--
June	86	53	70	.06	7.38	748	1.0
July	98	62	80	--	8.92	798	1.1
August	95	61	78	1.57	8.06	890	1.2
September	89	51	70	.24	5.81	816	1.1
October	81	47	64	1.14	4.81	797	1.1
November	69	37	53	3.17	3.48	1177	1.6
December	--	--	--	3.59	2.10	1013	1.4
Year	81	47	64	19.87	64.17		
1932							
January	--	--	--	2.61	3.13	902	1.2
February	--	--	--	5.99	3.13	1168	1.7
March	--	--	--	.20	5.24	1391	1.9
April	--	--	--	.72	6.28	1391	1.9

TABLE 7

CONSUMPTIVE USE OF WATER BY BERMUDA GRASS IN TANKS AT SAN BERNARDINO, CALIF., 1929-31 1/

Tank No.	Year	Depth to water table	Water used													Number of months
			May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total	
		Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	
3	1929-30	24	5.34	6.35	7.14	6.80	3.78	3.06	1.64	1.01	0.48	0.74	1.12	3.06	--	12
4	1929-30	24	4.84	4.85	5.87	5.66	3.34	2.72	1.41	.85	.43	.68	.98	2.37	--	12
3	1930-31	24	2.92	5.55	6.71	5.61	3.52	1.34	1.19	.62	--	.50	2.04	2.70	--	11
4	1930-31	24	2.50	5.24	6.14	5.07	3.36	1.26	.89	.55	--	.21	1.67	2.46	--	11
Mean	1929-31	24	3.90	5.50	6.46	5.78	3.50	2.10	1.28	.76	.46	.53	1.45	2.65	34.37	12
1	1929-30	36	4.28	5.22	5.49	5.34	2.90	2.77	1.26	.72	.65	.65	1.14	2.14	--	12
2	1929-30	36	--	--	--	--	--	--	1.50	.76	.89	.68	.88	1.80	--	6
1	1930-31	36	2.03	4.55	4.87	3.90	2.53	.72	.53	.51	--	--	--	--	--	8
2	1930-31	36	2.16	4.52	6.00	--	3.62	.96	1.03	.59	--	--	.39	2.33	--	9
Mean	1929-31	36	2.82	4.76	5.45	4.62	3.02	1.48	1.08	.64	.77	.66	.80	2.09	28.19	12

1/ All tanks covered during rains.

Cattails and tules were grown in tanks at the Santa Ana station, the ground surface of the tank being submerged as in a swamp. Air probably is supplied to the roots through the coarse cellular structure of the stems and not directly through the soil. Ground surrounding the tule tanks was free of vegetation during the first season but later was covered with grass.

Cattail and tule tanks were in exposed locations, subject to the full effect of solar radiation and wind movement. Tules grown in tanks differ from those in swamps where protection is afforded by surrounding areas of similar growth, lower temperatures, and greater humidity. These factors have a controlling influence on the quantities of water consumed by the plants with the result that water transpired and evaporated by swamps is considerably less per unit of area than that used by similar growth in exposed tanks. Aquatic plants in tanks do not attain the maximum growth found in swamp areas. Tule growth in isolated tanks rarely exceeds 4 to 6 feet in height. Maximum growth occurs in the swamp interior with shorter stalks around the edge of the water, and in this respect the exterior growth is comparable to that in experimental tanks.

Because of abnormal exposure, consumptive use of water by tules at Santa Ana was excessive. Round-stem tules used more water than cattails, possibly because of greater density of growth. Their consumptive use was frequently 1 1/2 inches per day, and at one time averaged an inch a day for a period of 6 weeks. The use of water for the year ending April 30, 1931 was nearly 178 inches or 269 per cent of the evaporation from a Weather Bureau pan. Data on use of water by tules and cattails grown in exposed tanks at Santa Ana are given in Table 8. These data do not represent consumptive use under normal swamp conditions but are given here to show the extreme results which may be obtained under unnatural conditions. Without adjustment they are not applicable to swamp conditions.

Nevertheless, all tules and cattails do not grow in

TABLE 8

CONSUMPTIVE USE OF WATER BY TULES AND CATTAILS IN TANKS IN SOUTHERN CALIFORNIA, 1929-32 1/

Tank No.	Year	Type of vegetation	Water used: May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Total	Number of months
			Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	
19	1929-30	Round stem tules	--	--	--	23.46	23.75	28.38	23.35	11.30	1.86	3.61	6.02	17.59	139.32	9
19 2/	1930-31		22.56	23.09	28.60	24.79	19.75	18.35	12.96	8.02	3.73	2.36	5.18	8.39	177.78	12
23 2/	1930-31		10.23	12.43	17.21	15.95	13.06	12.04	8.60	3.32	2.59	2.20	8.55	11.51	117.69	12
19 2/	1931-32		17.37	27.06	31.56	25.75	19.37	14.24	6.09	--	1.27	2.51	6.05	11.72	162.99	11
23 2/	1931-32		15.71	19.07	19.68	14.88	12.43	7.30	5.06	--	1.35	.82	4.78	8.72	109.80	11
6 3/	1930-31		16.94	22.12	30.05	26.11	17.42	13.99	12.56	5.36	4.05	--	8.88	13.40	170.88	11
6 3/	1931-32		18.07	21.70	29.25	23.23	12.88	7.58	5.38	5.05	4.15	--	5.84	8.80	141.93	11
21	1930-31	Triangular tules	12.36	15.90	23.29	24.29	21.94	21.01	15.03	6.40	2.89	2.16	5.90	9.79	160.96	12
21	1931-32		17.20	24.78	31.70	30.82	29.38	20.47	6.02	1.97	2.43	1.57	5.83	11.83	184.00	12
22	1930-31	Cattails	11.88	13.53	16.91	14.92	11.21	10.14	7.43	5.21	3.01	2.10	6.85	7.89	111.08	12
22	1931-32		11.21	14.94	20.21	17.43	14.98	12.06	5.31	--	1.74	2.40	6.03	11.18	117.49	11

1/ Data not applicable to large areas without adjustment.
2/ Tank diameter 72 inches; all other tanks are 25 inches in diameter.
3/ These experiments at San Bernardino; all others at Santa Ana.

protected swamp areas. They are often found directly exposed to sun and wind in narrow ribbons along stream channels and drainage ditches where exposure is nearly similar to that in isolated tanks. Under such conditions it is reasonable to expect that consumptive use of water is somewhat less than from exposed tanks, but considerably more than from larger swamps.

Midway between Santa Ana and San Bernardino, consumptive use of water by tules was ascertained in connection with a study by the United States Geological Survey of the flow of the Santa Ana River. As the station was isolated and daily visits were not practicable, recording devices were attached to both tule tank and Weather Bureau evaporation pan. From the records, hourly rates of consumptive use and evaporation were obtained. Samples of these are plotted in Figure 6, showing also air and water temperatures.

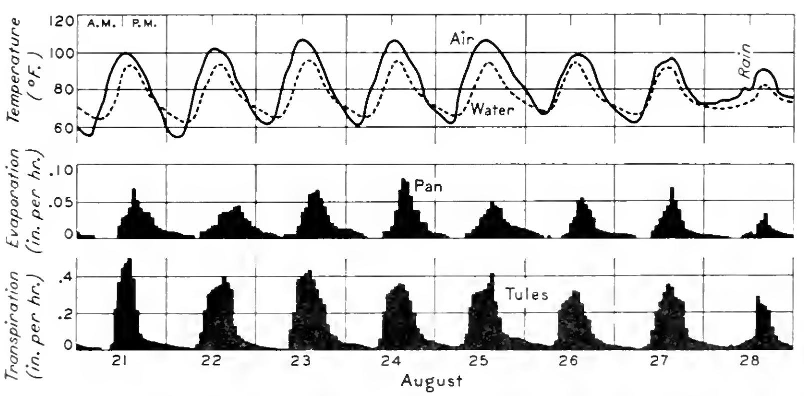


FIGURE 6.-- Hourly rate of use of water by tules, evaporation from standard Weather Bureau pan, and air and water temperatures, at Prado station.

There were periods during the early morning hours when the loss of water was too small to be recorded and evaporation or transpiration during these hours is shown as zero. Characteristic of both evaporation and transpiration is the daily increase or decrease with rising or falling temperature. The minimum rate occurs near sunrise and the maximum in the afternoon. Consumptive use, in the exposed tank, is greater than evaporation and responds more readily to sunlight and changes in temperature. The rate of evaporation increases slowly until the water in the pan has been warmed by the sun, while consumptive use increases more rapidly, comes to a peak sooner, and declines more quickly. In other words the plant is more sensitive to the factors causing water loss than is the water in the evaporation pan.

On the morning of August 28 temperature was less than normal, and a light rain occurred shortly after noon. The effect of the rain in deferring the morning increase in consumptive use and in evaporation until about 2 p.m. is noticeable. The precipitation caused a small decrease in the rate of evaporation until its effect was overcome by rising temperature. In general, the highest air temperature occurred at about 1 p.m. to 2 p.m., while the highest water temperature occurred about 2 hours later. The same interval also is noticeable in minimum temperatures. Observations elsewhere have shown the highest consumptive use of water by tules occurs approximately at the time of highest air temperatures, although such is not the case in this instance.

Coastal winds at the Prado station, in combination with high temperatures, are responsible for a continued increase in both evaporation and consumptive use until midafternoon and a higher rate of loss than at Santa Ana. The observed annual loss from the exposed tule tank reached a total of 251.3 inches or 325 per cent of the evaporation for the same period. The maximum daily loss was 3.6 inches.

Excessive rates of consumptive use of water by tules in an isolated tank were found also at the San Bernardino station. This tank was set in a Bermuda grass field. While the tule growth was stunted by exposure, the water consumed amounted to 170.88 inches in 11 months. In southern California records are taken for each month of the year; although tule and cattail stems die in the winter months, evaporation from the soil and water in the tank continues in small amounts. Monthly records of consumptive use are given in Table 8. It is again emphasized that none of the tule tank records is applicable to field conditions without adjustment.

The excessive use of water by aquatic plants growing otherwise than in their native habitat led to investigations in the Mojave Valley to determine the difference in consumptive use by tules growing naturally in swamp areas and other tules transplanted into exposed tanks removed from the swamp influence, and to establish a relation between consumptive use by natural swamp growth and evaporation from water. Both objectives are important if tank data are to have value, particularly if estimates of consumptive use are desired in other nearby localities where only evaporation data exist. With the relation once established, it is possible to apply it elsewhere within the same climatic area. Discussion of the Mojave Valley investigation appears on page 59.

Brush. 1/--In arid and semiarid regions practically all moisture from precipitation is held in the top few feet of soil where it is available for use by plants. This is the condition in the foothill area of the Santa Ana Valley. Vegetation on outwash slopes may be divided roughly into two groups: perennials having a woody structure, such as brush and shrubs; and annuals, as weeds and grasses. In this region precipitation occurs during the winter months, and the summers are long and dry. Contribution to underground water is limited to periods of heavy rainfall when the soil is moistened to field capacity below the root zone (field capacity being the amount of water retained in the soil after excess mobile water has drained away and the rate of downward movement has materially decreased following an application

1/ Field investigations with dry-land brush and grass and weeds in the Santa Ana River Valley and with tules in the Mojave River Valley were conducted by Colin A. Taylor, Associate Irrigation Engineer, Division of Irrigation, in cooperation with the Division of Water Resources, Department of Public Works, State of California.

of water from rain or irrigation). This condition seldom occurs, so that most of the moisture received is absorbed by plant life. Without replenishment during the summer, soil moisture is depleted by plant use until there is a deficiency at the beginning of each rainy season.

In connection with rainfall penetration studies initiated in southern California in 1927, various shafts, tunnels, and special plots were prepared for soil-moisture investigations from which it was possible to determine the water consumed by native brush and by various weeds and grasses. Soil samples were taken to depths below the limits of root activity, and the moisture content was determined by standard practices. The limit of rainfall penetration, depth of root activity, amount of moisture contribution to underground-water supplies and evaporation-transpiration losses chargeable to consumptive use were determined for various soil types.

A 3-year investigation of natural brush plots on outwash slopes indicated that about 19 inches of rain fell before any material moisture passed beyond the limits of the root zone. The brush varied with location but included chamiso, sage, squaw berry, scrub oak, cactus, and yucca -- all capable of existing on a small water supply. During the 3-year period rainfall at the various plots ranged from 12.66 inches to 20.90 inches, practically all of which was used by the brush cover. During this period soil moisture within the root zones was often below field capacity. Under these conditions rainfall and consumptive use are equal, assuming no run-off. In years of greater rainfall, however, or of rains falling upon soil filled to field capacity, some water passes beyond the roots to the underground basin. Under the latter condition consumptive use might increase because of increased transpiration opportunity. Results of brush-cover investigations, shown in Table 9, indicate that all precipitation in this area is consumed by the dry-land brush and that with this amount of rainfall there is no penetration to the underground

TABLE 9

CONSUMPTIVE USE OF WATER BY NATIVE BRUSH IN SOUTHERN CALIFORNIA, 1927-30

Year	Location	Soil type	Precipitation	Initial fall deficiency in moisture content of soil	Precipitation penetrating below root zone	Water used by native brush
			Inches	Inches	Inches	Inches
1927-28	San Bernardino 1/	Gravelly sand	2/ 32.00	12.5	5.0	27.00
1928-29			2/ 24.82	12.5	6.0	18.82
1929-30			20.90	12.5	1.8	19.10
1927-28	Muscoy	Gravelly sand	17.67	9.0	.0	17.67
1928-29			16.50	9.0	.0	16.50
1927-28			18.54	8.1	.0	18.54
1928-29			18.19	8.1	.6	17.59
1927-28	Claremont Tunnel	Rocky sandy loam	14.93	-	.0	14.93
1928-29			12.66	-	.0	12.66
1929-30			16.35	-	.0	16.35
1929-30	Palmer Canyon	Clay loam	19.58	10.1	.0	19.58
1927-28	San Bernardino	Gravelly sand	17.67	-	.0	17.67
1928-29			16.50	-	.0	16.50

1/ Shaft south of Devil Canyon.
2/ Natural precipitation supplemented by sprinkling.

TABLE 10

CONSUMPTIVE USE OF WATER BY NATIVE GRASS AND WEEDS IN SOUTHERN CALIFORNIA, 1927-30

Year	Location	Soil type	Precipitation	Initial fall deficiency in moisture content of soil	Precipitation penetrating below root zone	Water used by native grass and weeds
			Inches	Inches	Inches	Inches
1928-29 1/	San Bernardino 2/	Gravelly loam	10.75	6.9	3/ 0.75	10.00
1927-28	Cucamonga	Stony sand	15.49	-	.00	15.49
1928-29	Cucamonga	Stony sand	13.54	-	.00	13.54
1929-30	Cucamonga	Stony sand	17.25	-	3/ 2.25	15.00
1927-28	Anaheim	Fine sandy loam	12.58	4.6	.00	12.58
1927-28	Ontario	Sand	12.74	13.2	.00	12.74
1927-28	Ontario	Sand	14.06	6.0	.00	14.06
1927-28	Cucamonga	Loam	13.89	7.1	.00	13.89
1927-28	Wineville	Loam	13.35	8.5	.00	13.35

1/ Records ending February 21, 1929.
2/ South of Devil Canyon.
3/ Estimated values.

water table.

Grass and weeds. [1]--On grass and weed plots some penetration beyond the area of root activity may be expected on the coarser soil types when precipitation exceeds 10 to 12 inches. Here again the distribution of seasonal rainfall is an important factor in deep penetration. A contributing factor also is the density of growth. No run-off occurred from either brush or grass plots. In a majority of plots consumptive use by grass and weeds equalled the precipitation. Use of water by grass and weeds under similar conditions is slightly less than by brush and ranges from 12.58 to 15.49 acre-inches per acre. The factor of rainfall likewise limits these values. A summary of the grass and weed studies is shown in Table 10.

Mojave Valley, California [1]

Tules.--Studies on the Mojave River at Victorville, Calif. were undertaken in 1930 with triangular-stem tules transplanted into 2 tanks set deep in a tule swamp and in a third tank nearby which was exposed to surrounding desert conditions. Evaporation from a Weather Bureau pan and meteorological data were obtained. Tule tank No. 1, 2 feet in diameter by 3 feet deep, was set in the ground in an open space removed from the swamp influence to which other tanks were subjected. Tanks Nos. 2 and 3, surrounded by dense swamp growth, were 2 and 6 feet in diameter respectively by 3 feet deep. Figure 7 shows a sketch plan of the Victorville station and the general arrangement of supply tanks and soil tanks.

Under such conditions data obtained from the swamp tanks represent actual swamp consumptive use, and it is possible to establish a relation with exposed and isolated tule growth and also with evaporation from a Weather Bureau pan. The investigation continued through 1931 and 1932.

1/ See footnote 1, p. 55.

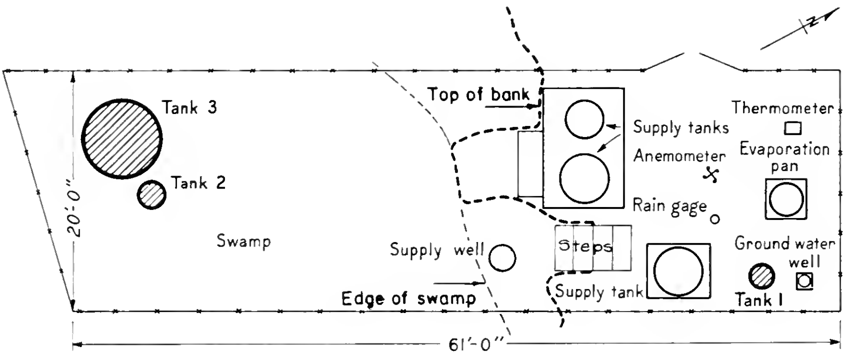


FIGURE 7.-- Plan of Victorville station.

The highest consumptive use occurred during July, averaging 14.13 inches in depth for the 6-foot tank protected by surrounding swamp vegetation as compared with 63.38 inches by the exposed 2-foot tank. No material difference in the use of water was found between tanks of different size in the swamp. The larger tank is preferred as providing greater opportunity for root expansion and maintenance of soil fertility. A condensed summary of evaporation, consumptive use of water, and meteorological data for the 2-year period is presented in Table 11.

For this period the average annual depth of water used by tules in the 6-foot tank in the swamp was 78.45 inches as against 272.24 inches by the exposed tank, clearly demonstrating the effect of unnatural exposure upon consumptive use. The second objective of the investigation was to determine the relation of consumptive use to evaporation from a Weather Bureau pan. During the 2 years of study the average annual consumptive use was 78.45 inches, or 95 per cent of the evaporation. This relation is not constant but varies throughout the year from a maximum of 122 per cent in September to a minimum of 57 per cent in March.

The conditions of evaporation from a Weather Bureau pan and from a lake or reservoir are so dissimilar that a reduction

TABLE 11

CONSUMPTIVE USE OF WATER BY TULES IN TANKS, EVAPORATION, AND METEOROLOGICAL DATA AT VICTORVILLE, CALIF., 1931 and 1932

Month	Water used			Evaporation from Weather Bureau pan (outside swamp)	Use of water by tules in tank No. 3 in proportion to evaporation	Meteorological data				
	Tank No. 1	Tank No. 2	Tank No. 3			Temperature			Wind movement	
	Diameter 2 feet (outside swamp)	Diameter 2 feet (in swamp)	Diameter 6 feet (in swamp)			Mean maximum	Mean minimum	Mean	Total	Average
	Inches	Inches	Inches	Inches	Per cent	°F.	°F.	°F.	Miles	Miles per hour
January	2.81	1.74	1.74	2.40	72	52	21	36	1458	2.0
February	2.54	3.08	2.02	3.32	61	55	24	40	1299	1.9
March	4.61	5.26	3.82	6.67	57	70	30	50	1680	2.2
April	7.25	8.16	5.08	7.79	65	74	35	54	1818	2.5
May	17.62	11.11	8.78	9.92	88	81	42	62	1746	2.3
June	35.47	14.21	10.80	10.38	104	86	46	66	1396	1.9
July	63.38	14.37	14.13	12.12	117	97	52	74	1245	1.7
August	59.54	9.87	12.32	10.68	115	94	52	73	1114	1.5
September	46.38	7.17	10.04	8.22	122	88	44	66	1044	1.4
October	25.28	4.31	5.86	5.44	108	76	37	56	1020	1.4
November	4.61	3.05	2.42	3.52	69	66	26	46	897	1.2
December	2.75	2.12	1.44	2.00	72	52	22	37	1120	1.5
Year	272.24	84.45	78.45	82.46	1/ 95	74	36	55	15837	1.8

1/ Per cent based upon totals per year.

coefficient, determined by experiment to be 0.70, must be applied to pan records to obtain equivalents for large bodies of water. Application of this value to Weather Bureau pan data at Victorville indicates an equivalent lake evaporation of 57.72 inches. Using this value it is found that the consumptive use by tules in the swamp was 135.9 per cent of the computed lake evaporation, which classes aquatic growth as a heavy user of water.

ADJUSTMENT FACTORS FOR LARGE AREAS

Tank records of consumptive use of water by aquatic growth are not suitable for extension to large areas unless modified by proper coefficients which too often have not yet been determined. Consequently, in many cases, tank records may be of little actual value for the determination of consumptive use. Save for the relation of swamp consumptive use to evaporation, determined as 95 per cent at the Victorville station in Mohave Valley, reduction coefficients in southern California are lacking. The Santa Ana Valley tank records should be reduced through application of the Victorville factor.

Table 12 has been prepared to show the consumptive use of water by tules and cattails in swamp areas as percentages of observed consumptive use in exposed tanks, the coefficient of 0.95 being used to reduce evaporation values to estimated swamp values. Swamp consumptive use as a percentage of observed tank use varies from 29 to 55 per cent with an average of 40 per cent. The figures indicate, on the whole and as far as a determination is possible, that consumptive use of water by natural growth in swamp areas in southern California averages but 40 per cent of the observed consumptive use as indicated by tank records.

No adjustment factor is necessary for grasses grown in tanks surrounded by fields of similar growth, as conditions are so nearly those of the field that factors for these crops have been taken as 100 per cent. It is emphasized that tanks should be set low in the ground with their rims protected from the rays

TABLE 12

ESTIMATED CONSUMPTIVE USE OF WATER BY TULES IN SWAMPS IN SOUTHERN CALIFORNIA, BASED ON TANK EXPERIMENTS

Location	Type of vegetation	Evaporation from a Weather Bureau pan	Water used by tules		Swamp use in proportion to observed use
			Observed, from tanks	Estimated, for swamp conditions 1/	
		Inches	Inches	Inches	Per cent
Victorville	Triangular stem tule	82.5	272.2	2/ 78.5	29
Santa Ana	Round stem tule	66.6	188.3	63.3	34
Santa Ana	Triangular stem tule	66.6	172.5	63.3	37
Santa Ana	Cattail	66.6	116.9	63.3	54
Santa Ana	Round stem tule	66.6	115.4	63.3	55
Prado	Triangular stem tule	77.4	251.3	73.5	29
San Bernardino	Round stem tule	66.1	3/ 162.1	62.8	39
Mean percentage					40

1/ Compiled as 95 per cent of evaporation based on Victorville investigations.
2/ Observed consumptive use by tules in tanks located in swamp under natural environment.
3/ February consumptive use estimated.

of the sun by surrounding grass. Crop tanks in bare fields may have a somewhat higher rate of water use, but data bearing out such a conclusion are lacking.

No definite figure is available for use as an adjustment factor for willow or other brush grown in tanks. In dense growths of brush the effect of sunlight and wind is modified by surrounding vegetation and consumptive use under such conditions will be less than by isolated growth in field or tank. Considering differences in willow distribution it is evident that an adjustment factor is not a constant, applicable to all conditions, but a variable depending upon density and size of brush area. Owing to present lack of evidence, any factor selected must be only an estimate. For willow growth in the Santa Ana Valley, where such growth is partly in solid blocks of brush and partly scattered, it is estimated that consumptive use varies from 75 to 100 per cent of consumptive use by willows grown in exposed tanks. A tentative factor of 85 per cent is adopted.

Use of water by wire rush grown in a tank at the Santa Ana station exceeds that of any other growth except tules and cattails. While the tank was not set in a field of similar growth, it was surrounded by grass and weeds. It is possible, since the wire rush did not grow in its natural moist-land habitat, that change of environment was responsible for the high use of water, but it seems more probable that an ample water supply close to the surface and an unusually heavy growth were the direct causes.

A summary of tank investigations showing estimated adjustment factors and consumptive use of water in moist areas is presented in Table 13.

TABLE 13

ESTIMATED ANNUAL CONSUMPTIVE USE OF WATER BY NATIVE VEGETATION UNDER FIELD CONDITIONS IN SOUTHERN CALIFORNIA

Location	Type of vegetation	Length of effective record	Average depth to water table	Observed annual use by vegetation in tanks	Adjustment factor	Estimated use by vegetation in fields
		Months	Inches	Inches	Per cent	Inches
Santa Ana	Saltgrass	17	12	42.1	100	42.1
		31	24	36.0	100	36.0
		11	36	2/ 24.8	100	2/ 24.8
		17	48	13.2	100	13.2
San Bernardino	Bermuda grass	32	24	36.2	100	36.2
		31	36	28.8	100	28.8
Santa Ana and Mojave Valleys	Tules and cattails 1/	22-33	+ 2	182.7	40	73.1
Santa Ana	Willow	11	24	52.7	85	44.8
Santa Ana	Wire rush	19	24	84.5	--	--

1/ These data are averages for all tule and cattail tanks in Santa Ana and Mojave Valleys and do not agree with individual tank measurements. The adjustment factor of 40 per cent is obtained from Table 12.

2/ Includes a small amount estimated for May.

Temescal Creek, California [1/]

The effect of moist-land vegetation on depletion of stream flow is well known to hydrologists, despite a scarcity of published data. Engineers have long observed diurnal changes in streamflow records which are attributable principally to consumptive use of water by vegetation on adjoining lands. It can be shown that these fluctuations may be correlated not only with transpiration and evaporation but also with air and water temperatures, and that minimum flow follows maximum transpiration.

Canyon-bottom vegetation.--A brief opportunity for this type of investigation was presented in a section of Temescal Creek, near Corona, Calif., in April and May 1929. A reach of creek bottom, 2,100 feet in length, was selected. The total area was 12.8 acres of coarse gravelly soil supporting a dense growth of brush and trees and other moist-land vegetation. Of the total area, approximately two-thirds was classified as wet land (that is, land with water at or above the surface), while the remainder had ground water from 2 to 6 feet below. The investigation was limited to a few weeks in the spring because prior to April water was pumped from the area and late in May the stream became dry. At this time of year there was no appreciable precipitation and no side inflow occurred from the adjoining hillsides.

At the upper end of the 2,100-foot section the remains of a small masonry dam brought the underflow to the surface where measurement was made through a Parshall flume. At the lower end the abutments of a small highway bridge forced the creek into a narrow section where it was measured by a second Parshall flume. Water-stage recorders were maintained at both controls. At the lower end, the coarse soil permitted some underflow which was estimated as follows: By means of recorder charts at the upper

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1/ The field investigation was made by Colin A. Taylor, Associate Irrigation Engineer, Division of Irrigation, in cooperation with the Division of Water Resources, Department of Public Works, State of California.

and lower controls differences in flow between these points were computed for 2-hour intervals during a 10-day period when cloudy weather, with traces of rain, caused periods of minimum evaporation and transpiration. On April 19 and again on April 20, evaporation from a Weather Bureau pan at Ontario, approximately 20 miles distant, was but 0.04 inch or the equivalent of 0.028 inch of lake evaporation. With this low loss from evaporation the consumptive use of water by vegetation in the early morning hours of the same period must have been exceedingly small. With evaporation and transpiration so low as to be negligible the difference in amount of inflow and outflow from the area must necessarily be attributed to underflow past the lower control, which was thus estimated to be 0.14 cubic foot per second. All remaining differences above 0.14 second-foot can be charged to consumptive use of water by the vegetation.

A summary of results, given in Table 14, indicates a total loss of 12.9 acre-inches per acre for the 30-day period April 28 to May 27, 1929. This was three times the loss from a lake surface as indicated by Weather Bureau pan records at Ontario. Figure 8 shows the daily fluctuations in stream flow and the loss of flow due to consumptive use of water by vegetation between the upper and lower controls. The effect of the advancing season in increasing the consumptive use is shown by the divergence of the lines representing stream flow at each point of measurement. Comparison of plotted temperature and rate of consumptive use by tank vegetation is likewise shown.

TABLE 14

CONSUMPTIVE USE OF WATER BY MOIST-LAND VEGETATION AS INDICATED BY STREAM LOSSES IN TEMESCAL CREEK, CALIF., 1929 1/

Date	Loss of flow in Temescal Creek		Rate of loss: Day	Rate of loss: Week
1929	Second-feet	Acre-inches	Acre inches per acre	Acre inches per acre
April 16	0.010	0.24	0.02	--
April 17	.035	.83	.06	--
April 18	.026	.62	.05	--
April 19	.011	.26	.02	--
April 20	.024	.57	.04	--
April 21	.042	1.00	.08	--
April 22	.043	1.02	.08	0.35
April 23	.052	1.24	.10	--
April 24	.070	1.67	.13	--
April 25	.078	1.86	.14	--
April 26	.080	1.90	.15	--
April 27	.079	1.88	.15	--
April 28	.094	2.24	.18	--
April 29	.105	2.50	.20	1.05
April 30	.118	2.81	.22	--
May 1	.132	3.14	.24	--
May 2	.162	3.86	.30	--
May 3	.156	3.71	.29	--
May 4	.163	3.88	.30	--
May 5	.154	3.66	.29	--
May 6	.152	3.62	.28	1.92
May 7	.150	3.57	.28	--
May 8	.176	4.19	.33	--
May 9	.178	4.24	.33	--
May 10	.188	4.48	.35	--
May 11	.220	5.24	.41	--
May 12	.234	5.57	.44	--
May 13	.259	6.16	.48	2.62
May 14	.290	6.90	.54	--
May 15	.298	7.09	.55	--
May 16	.298	7.09	.55	--
May 17	.307	7.31	.57	--
May 18	.278	6.62	.52	--
May 19	.268	6.38	.50	--
May 20	.267	6.36	.50	3.73
May 21	.297	7.07	.55	--
May 22	.298	7.09	.55	--
May 23	.318	7.57	.59	--
May 24	.330	7.86	.61	--
May 25	.353	8.40	.66	--
May 26	.347	8.26	.64	--
May 27	.343	8.16	.64	4.24

1/ Area involved equals 12.8 acres.

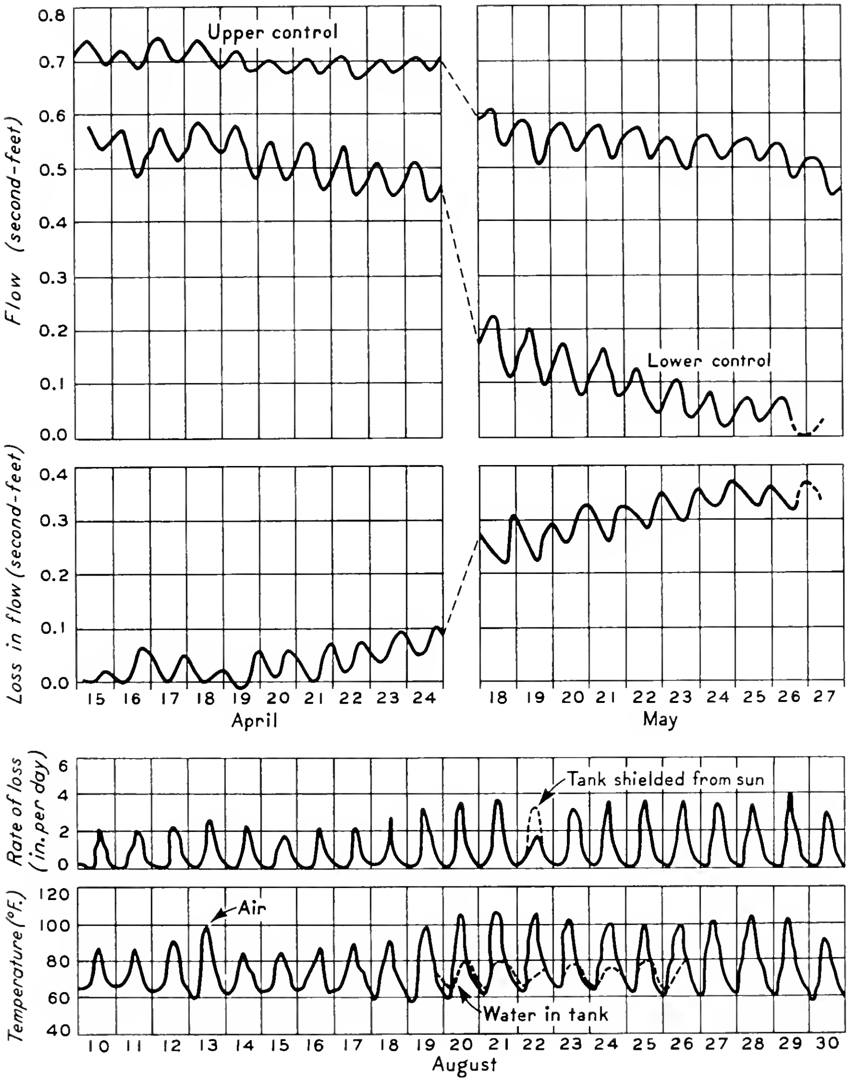


FIGURE 8.-- Stream flow, consumptive use by moist-land vegetation, and comparison of rate of consumptive use by tank vegetation with air temperatures at Temescal Creek.

SUPPORTING TANK DATA

The general data secured by measurement of consumptive use of water by stream-bottom vegetation led to further study of similar vegetation grown in tanks. Two tanks, each about 2 feet in diameter by 3 feet deep, were set in the ground near the upper control where surrounding vegetation was nearly representative of that in the entire area. Tank A was planted to tules and reeds, while small willow shoots were set in tank B. Measurements of use of water by the tank growth were carried on from October 1929 to June 1930 at this location. In June, tank B was moved 20 miles to Ontario and fitted with a sensitive automatic device for supplying water to the tank as it was consumed by the vegetation, and with a recorder for obtaining continuous hourly records of these losses. The willow shoots in tank B were not representative of normal willow growth because of their small size. In fact, they failed to survive the winter months and were gradully supplanted by swamp grass and weeds. Water was maintained at about 3 inches above the ground surface. The monthly use by vegetation in the tanks is shown in Table 15.

TABLE 15

CONSUMPTIVE USE OF WATER BY SWAMP VEGETATION IN TANKS AT TEMESCAL CREEK AND AT ONTARIO, CALIF., 1929-30

Month and year	Location	Water used: Tank A, Tules	Water used: Tank B, Willow shoots, swamp grass, and weeds
1929		Inches	Inches
October	Temescal Creek	16.79	6.64
November	Temescal Creek	9.15	5.52
December	Temescal Creek	4.83	3.81
1930			
January	Temescal Creek	3.91	4.23
February	Temescal Creek	2.74	2.95
March	Temescal Creek	4.82	4.61
April	Temescal Creek	11.53	9.19
May	Temescal Creek	14.33	14.37
June	Ontario	--	1/ 18.45
July	Ontario	--	1/ 29.60
August	Ontario	--	1/ 30.67

1/ Not applicable to large areas without adjustment.

It will be observed that tank consumptive use of 14.3 inches for May does not differ greatly from the average swamp use of 12.9 acre-inches. The larger use should be expected on account of the artificial conditions in the tanks. Moving tank B to Ontario in June placed this tank under conditions radically different from those inherent in swamp areas, and the consumptive-use records for June, July, and August are neither applicable to field conditions nor comparable with previous records at Temescal Creek. Their value lies in the chart records obtained and the opportunity presented for comparing the rate of consumptive use-of-water curves with the daily temperature curves shown in Figure 8. The maxima and minima of these curves occur respectively about the same time of day.

The effect of consumptive use on ground-water levels is apparent on the stream-flow chart. Under normal conditions the draft on the water table following the peak of transpiration is shown by the falling side of the curve representing daily stream flow. At this time consumptive use exceeds the recharge of the basin and the water table is dropping. At the bottom of the curve, consumptive use and recharge are balanced and the water table begins to rise. During periods of maximum consumptive use, the recharge may not equal the daily loss, and under these conditions the dropping water table is reflected in lower stream flow.

As sunlight and temperature so greatly affect transpiration and consumptive use by plants, the following discussion by Taylor (2) on the effects of insolation is applicable:

PROBABLE LIMITS TO THE LOSSES ALONG STREAM CHANNELS

"The indicated loss of 12.9 inches in 30 days at Temescal Creek, together with still higher rates of loss from small isolated tanks of swamp growth, has led to a consideration as to what the probable limits for losses in moist areas along stream channels might be. The radiant energy received from the sun, or insolation as it is termed, suggests certain upper limits to the amount of water that may be vaporized over large swamp areas. Average daily records of insolation are published in the Monthly Weather Review for stations at La Jolla, Pasadena and Fresno. The equivalent water of vaporization for the insolation received at Pasadena and Fresno for the calendar year 1929 is as follows:

Station	Total annual insolation 1/	Equivalent water of vaporization at 68 degrees Fahrenheit
	Gram calories per square centimeter	Depth in feet
Pasadena	165,416	9.27
Fresno	169,691	9.51
Average	--	9.39

"This suggests that, if all of the radiant energy received from the sun were used in vaporizing water, it would be possible to lose 9.39 acre-feet per acre annually, as an average for the two stations, as the result of insolation.

"Using the Fresno records for the period April 28 to May 27, 1929, we have the insolation as 20,467 gram calories per square centimeter and the equivalent water of vaporization at 68 degrees Fahrenheit as 13.8 inches. This is for the same period that the indicated loss from the swamp on Temescal Creek was 12.9 inches. It is likely, then, that the rate of loss was approaching its probable maximum when the tests on Temescal Creek ceased, due to a failing water supply late in May. There is some additional supply of heat to the swamp area from the surrounding rocky canyon walls and from the strong draft of air flowing through the canyon. On the other hand, not all of the insolation received directly on the swamp area is used in vaporization. Some of the radiant energy is stored in combination within the plant tissues, some is reflected from the plant surfaces and part goes into heat storage and in part is again radiated back to the sky.

1/ Direct plus diffuse received on a horizontal surface.

"The discussion of the receipt of energy, other than the vertical component from the sun, leads to a consideration of what the effect might be on very small patches of swamp growth. The extreme case may well be considered as an isolated tank of swamp growth two feet in diameter set in otherwise barren ground. The radiant energy intercepted by the plant growth in the tank must necessarily be a greater amount than the same area of growth in a swamp would receive because the isolated tank growth has a side exposure that in a swamp would be protected by surrounding plants. The analogy that might be drawn is that of a lens focusing the sun's rays on the restricted area of the tank.

"Take the case of the two-foot tank used at Ontario in studying the correlation between air temperature and transpiration. The loss for the month of August, 1930, from the Ontario willow and reed tank was 30.67 inches depth. This is about two and one-half times the depth of water that could be vaporized by the insolation falling on the horizontal area of the tank. A partial explanation is that the tall growth in the isolated tank intercepts a much larger amount of insolation than the same area of growth would receive in a swamp. But in the case of the small tank, the heat energy brought to the growth in the tank by air movement also is relatively large. An experiment investigating this point was performed at Ontario on August 22, 1930. On this date, the willow and reed tank was shielded from the direct rays of the sun by a corrugated iron roof, eight by ten feet, placed just high enough to clear the plants and allow free lateral wind movement. The record of water loss is shown in Figure 8 (this bulletin). The full line on August 22 is the actual loss with the tank shielded. The dotted line is the average of August 21 and 23. The values are:

Loss August 21	1.296 inches
Loss August 23	1.274 inches
Average loss for August 21 and 23	1.285 inches
Loss August 22	0.778 inch (with tank shielded)

"The heat supply for vaporizing this 0.778 inch of water on August 22 must have come almost entirely from the moving air currents passing through the growth in the tank.

"However, when a large swamp area is considered, there must be a rapid drop in temperature of the air as it passes through the swamp growth if it is to give up its heat supply at the rate indicated by the above experiment. As soon as the air is cooled to the same temperature as the plants there can be no further transfer of heat from the air to the plants. When this condition is reached, the energy for vaporization must come solely from insolation.

"It may be expected, then, that small isolated patches of swamp growth will show rates of loss per unit area higher than that accounted for by insolation alone, but it also is probable that the loss from an extensive swamp area is limited to a value not widely variant from that indicated by insolation.

"The inference is that in conducting tank work to gain data for use in estimating losses from field areas, that the tank should be set in a field of growth similar to that in the tank and the outside growth must completely surround the tank so the exposure of the growth in the tank is normal."

Coldwater Canyon, California 1/

Canyon-bottom vegetation.--The mountain slopes of southern California support a growth of dry-land chaparral which must depend upon the immediate precipitation for moisture, but vegetation adjacent to small canyon streams is of a more water-loving nature. This includes such broadleaf trees and shrubs as alders, willows, sycamores, and California laurels, changing at times to coniferous types at higher altitudes. As evidence of their water-loving character these species are seldom found away from a dependable

1/ The field investigation was made by Colin A. Taylor, Associate Irrigation Engineer and Harry G. Nickle, Assistant Irrigation Engineer, Division of Irrigation, in cooperation with the Division of Water Resources, Department of Public Works, State of California.

water supply. The effect of such vegetation on depletion of flowing streams becomes increasingly important as water becomes scarcer and more valuable.

Lack of data on consumptive use of water by canyon-bottom growth led in 1931 to an investigation in selected sections of Coldwater Canyon, near San Bernardino, Calif., to determine stream losses chargeable to this type of vegetation. The initial investigation covered a section of canyon 2,090 feet in length between elevations 2,300 and 2,500 feet, the average bottom width being 49 feet. The area comprised 2.36 acres of typical canyon-bottom growth. Within this area vegetation depended for water entirely upon the flow of Coldwater Canyon. Beyond the influence of the stream the vegetation changed rapidly from alders and sycamores to dry-land chaparral. During the second year studies were extended upstream to include also an upper canyon section immediately adjacent to the lower section. This lay between elevations 2,500 and 3,100 feet; it averaged 44 feet in width and was 5,875 feet in length. Thus in the second year the investigation included nearly 8,000 feet of canyon bottom. The area of the upper section covered 5.89 acres of growth nearly similar in type to that of the lower section. A vegetative classification of both upper and lower sections, shown in Table 16, gives alder as predominating, with California laurel showing the next highest percentage of total growth. The under story consisted of scattered grapevine, blackberry, poison oak, and fern bracken. Plate II-B shows alders growing between the lower and middle controls.

Bedrock controls at the upper and lower ends of each section insured complete measurement of all water in the canyon. Parshall flumes were installed with water-stage recorders for the earlier records, but for greater convenience these were later changed to direct flow recorders. The small flow in dry seasons made necessary a modification of the Parshall flume that would measure accurately low flows in summer as well as maximum flows during spring floods. For this purpose the Division of Irrigation

TABLE 16

VEGETATIVE CLASSIFICATION IN COLDWATER CANYON NEAR SAN BERNARDINO, CALIF.

Type of vegetation	Lower section of canyon			Upper section of canyon		
	Trees and shrubs	Maximum diameter	Proportion of total	Trees and shrubs	Maximum diameter	Proportion of total
	Number	Inches	Per cent	Number	Inches	Per cent
Alder	737	24	81.9	1286	30	47.9
Sycamore	71	24	7.9	169	32	6.3
California laurel	37	8	4.1	701	14	26.1
Willow	25	12	2.8	181	14	6.7
Maple	23	14	2.5	234	22	8.7
Oak	5	38	.6	63	36	2.4
Mountain mahogany	2	2	.2	38	4	1.4
Cedar	--	--	--	9	40	.3
Spruce	--	--	--	6	40	.2
Cottonwood	--	--	--	1	10	.0
Total	900		100.0	2688		100.0

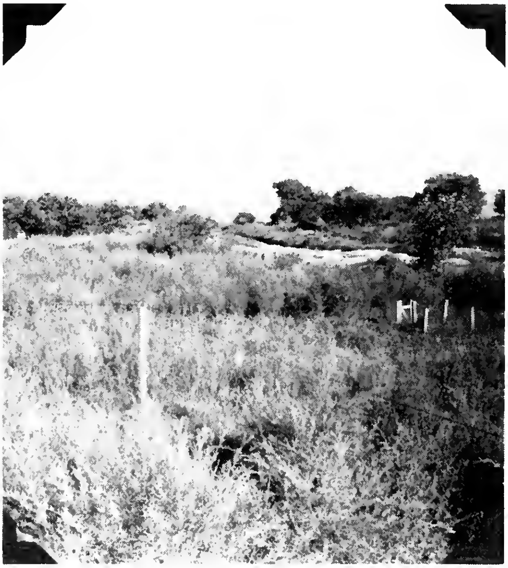
investigators designed the satisfactory combination Parshall flume previously described in detail (p. 33) and shown in Figure 3. This permitted a range of discharge from a minimum flow through a 3-inch Parshall flume up to a maximum of 23 second-feet through the 2-foot throat.

Flow recorders were used to eliminate a large part of the routine work of calculation. They consisted essentially of a spiral cam that mechanically computed the stream flow at the point of control. The cam was geared to a float pulley wheel and a pencil cord attached to the cam. For greater accuracy a 30-inch diameter float was used, as it was found that smaller floats permitted lag in the record. Movement of the float with rising or falling water was transmitted through the pencil cord to a recording chart which gave direct measurements in units of discharge. Superposing two charts, one from each control, and measuring with a planimeter the area between the two gave the daily loss of water in the stream between points of measurement. Flow recorder installation is shown in Plate III-A.

Equipment was likewise developed to measure the transpiration opportunity. Briggs and Shantz (7) showed that evaporation from a shallow black pan was in closer correlation with transpiration than that obtainable with other devices. With this in mind an evaporimeter was designed with such an evaporation pan attached to the weighing mechanism of a recording rain gage, so that continuous records of loss of water were obtained. The practical depth of the pan, sufficient for one day's maximum evaporation loss, was limited to 0.6 inch. The diameter was 2 feet. It was necessary to refill the pan with water each day on account of its shallow depth. From the charts, hourly rates of evaporation were obtained.

PLATE III

A. Flow recorder installation in Coldwater Canyon: above, 7-day chart on clock-driven drum; below, spiral cam which permits a direct record on the chart in units of discharge.



B. Site of experimental station at Isleta, N. Mex., showing type of surrounding vegetation. Consumptive use of water by sedge was determined in the small area fenced at the extreme right.

STREAM LOSSES BY EVAPORATION AND TRANSPIRATION

The consumptive use of water by canyon-bottom vegetation is taken as the difference between the flow at the upper and lower controls of each section of creek bottom. Previous to the initial work a survey of the rock outcrop in ravines entering the canyon indicated that there was no side inflow into the stream.

The characteristic curve of transpiration demand is similar to the daily discharge curve of a flowing stream, although the maximum and minimum points of the curve occur at different times of day. Transpiration is at a maximum in the early afternoon and at a minimum about sunrise. Stream flow, on the other hand, on clear days and with normal transpiration, has a maximum during midmorning and a minimum in late afternoon. Figure 9 shows a curve of stream discharge at the middle control for the period August 9 to 15, 1931. On the 9th, 10th, and 11th the days were warm and discharge curves were normal in appearance. On the 12th a light rain reduced transpiration and the effect was shown in a

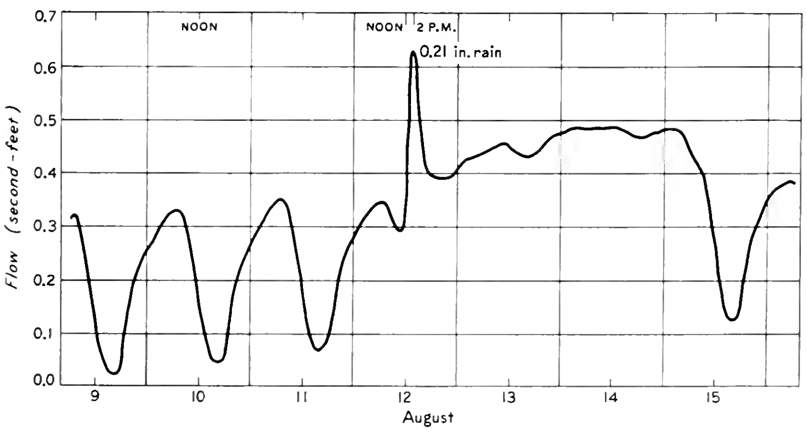


FIGURE 9.-- Flow at middle Coldwater Canyon control.

sudden rise of the stream surface. The 13th and 14th were cool and cloudy, transpiration was low and there was little fluctuation. The 15th was again warm, transpiration increased, and the stream surface dropped.

The daily loss of water from the stream in both upper and lower sections of canyon bottom is shown in Tables 17 and 18. These data are arranged to present also the average daily losses for each section of canyon and the average loss per day per 1,000 feet of stream bed. There was considerable difference in losses in the two growing seasons. In both years there was outflow at the lower control, hence never a shortage of water for the trees. The summer of 1931 had some light rain and cloudy weather, whereas in 1932 the weather was clear. On the other hand, in 1931 temperatures were higher than during 1932, which would tend to offset the effect of cloudy periods. On the whole, there seems to be no reason why consumptive use should be greater in one season than in another.

It will be observed also that consumptive use by trees in the upper stream section is less than in the lower section. This cannot be accounted for by density of growth as there are more trees per acre in the upper section. In the lower canyon, however, alders account for 81.9 per cent of all trees and shrubs whereas in the upper canyon they are 47.9 per cent of the total. In the upper section there is an increase in California laurel from 4.1 per cent to 26.1 per cent. It appears probable that the fewer alders in the upper section account for the smaller consumptive use.

The consumptive use by canyon-bottom trees and shrubs from June to October commands attention. This is the period of maximum use, not only by natural growth but by irrigated crops as well. In estimating water supplies for irrigation a knowledge of the effect of consumptive use of water by alders, willows, and other stream-fed vegetation on depletion of stream flow is important to engineers. The study shows a maximum use of 13.7 acre-inches per

TABLE 17

CONSUMPTIVE USE OF WATER BY CANYON-BOTTOM VEGETATION AS INDICATED BY STREAM LOSSES IN COLDWATER CANYON NEAR SAN BERNARDINO, CALIF., 1931-32 1/

Day of month	Loss of water from stream between middle and lower controls								
	1931			1932					
	Aug.	Sept.	Oct.	June	July	Aug.	Sept.	Oct.	Nov.
	Acre-inches	Acre-inches	Acre-inches	Acre-inches	Acre-inches	Acre-inches	Acre-inches	Acre-inches	Acre-inches
1	2/ 0.55	0.33	--	--	0.85	1.10	1.07	0.64	0.40
2	.76	2/ .23	0.22	--	.75	1.11	.97	.48	.12
3	.60	--	.31	--	.66	1.15	.95	.60	--
4	.78	--	.42	--	.64	1.21	1.12	.70	--
5	.76	--	.39	--	.68	1.20	1.01	1.00	--
6	.57	.74	.34	--	1.07	1.27	1.03	.76	--
7	.65	.62	2/ .19	--	.83	1.22	1.28	.51	--
8	.73	.49	--	--	1.02	1.19	1.44	.64	--
9	.66	.40	.01	--	.96	.92	1.19	--	--
10	.56	.37	.08	--	.92	.76	.91	.92	--
11	.49	.55	.02	--	.96	.91	.86	.96	--
12	--	.57	.15	--	.83	1.01	1.01	.82	--
13	--	.63	.31	--	.61	.92	.97	.58	--
14	--	.22	.30	--	.94	.86	1.01	.85	--
15	--	.27	.35	--	1.05	.95	.95	1.01	--
16	--	.47	.34	--	1.09	1.08	.78	.76	--
17	2/ .87	.42	2/ .17	--	1.15	1.31	.61	.44	--
18	.97	.65	--	--	.98	1.38	--	.58	--
19	.87	.25	--	--	.91	1.41	--	.69	--
20	.93	--	--	--	1.05	1.29	--	.54	--
21	.88	--	--	--	1.16	1.25	--	.45	--
22	.91	--	--	--	1.17	1.28	.83	.33	--
23	1.04	--	--	--	1.33	1.15	.94	.29	--
24	.99	--	--	--	1.32	1.18	.94	.31	--
25	.96	--	--	0.70	1.26	1.15	.81	.44	--
26	1.00	.29	--	.72	1.20	.99	.68	.54	--
27	--	.32	--	.76	1.07	.71	.58	.58	--
28	--	.25	--	.82	.91	.60	.42	.48	--
29	.38	.08	--	1.04	1.04	.58	.83	.42	--
30	.47	2/ .20	--	.95	1.04	.50	.54	.43	--
31	.56	--	--	--	1.07	.69	--	.52	--
Mean	.75	.42	.25	.83	.98	1.04	.91	.61	--
Mean per day 3/	.36	.20	.12	.40	.47	.50	.44	.29	--

1/ Length of stream, 2,090 feet between middle and lower controls.
2/ For portion of day only and not included in mean.
3/ Per 1,000 feet of canyon bottom.

TABLE 18

CONSUMPTIVE USE OF WATER BY CANYON-BOTTOM VEGETATION AS INDICATED BY STREAM LOSSES IN COLDWATER CANYON NEAR SAN BERNARDINO, CALIF., 1932 1/

Day of month	Loss of water from stream between upper and middle controls				
	July	August	September	October	November
	Acre-inches	Acre-inches	Acre-inches	Acre-inches	Acre-inches
1	--	2.04	--	0.98	0.73
2	--	2.12	2.08	.60	.16
3	--	2.23	2.28	.75	--
4	--	2.25	2.43	1.65	--
5	--	2.53	2.50	1.91	--
6	--	2.36	2.52	1.64	--
7	--	2.23	2.73	.14	--
8	--	2.13	2.81	.47	--
9	--	2.09	2.54	--	--
10	--	1.53	1.88	.89	--
11	--	1.76	--	1.53	--
12	--	1.79	--	1.38	--
13	--	1.62	--	1.14	--
14	--	1.66	--	1.36	--
15	1.90	1.70	--	1.71	--
16	1.80	2.11	1.99	1.64	--
17	1.93	2.29	1.89	.95	--
18	1.41	2.55	--	1.00	--
19	1.00	2.32	--	1.22	--
20	1.74	2.40	--	1.30	--
21	1.96	2.43	--	1.36	--
22	2.11	2.51	1.70	1.30	--
23	1.96	2.67	1.97	1.31	--
24	1.77	2.54	2.12	1.58	--
25	2.05	2.67	1.96	1.38	--
26	2.10	2.15	--	1.44	--
27	1.96	1.47	--	1.30	--
28	2.05	1.11	--	1.03	--
29	2.24	1.38	--	.88	--
30	2.18	.75	--	.77	--
31	2.29	--	--	1.02	--
Mean	1.91	2.05	2.23	1.19	--
Mean per day 2/	.32	.35	.38	.20	--

1/ Length of stream, 5,875 feet between upper and middle controls.
2/ Per 1,000 feet of canyon bottom.

acre of canyon bottom in August and a total of 47 acre-inches per acre in the period July to October, inclusive. This amount exceeds water used by tules in a swamp at Victorville and is about 2 1/2 times the amount required by either saltgrass or Bermuda grass where the water table was but 2 feet from the surface.

Studies in Sacramento-San Joaquin Delta, California 1/

The Sacramento-San Joaquin Delta area in California differs from the southern portion of the State in the comparative ease with which water is secured for crop use. In the southern portion water is scarce and ground water is found at depths beyond the reach of plant roots. In the Delta, especially in the peat lands, water is close to the surface, even invading the root zone, and open water areas are numerous. Under these conditions tule and cattail growth is encouraged and many areas, now considerably decreased in size by reclamation, support aquatic plants. Weeds likewise are prolific because of high ground water and the opportunity of obtaining an ample water supply. In addition, a long growing season and high summer temperatures increase transpiration rates. As a result of these conditions wild growth often extracts from the soil large quantities of water.

Tules and cattails.--As in other sections of the State, investigations have been carried on by the Division of Irrigation in cooperation with the California State Division of Water Resources to determine monthly and annual use of water by aquatic and weed growth. Data on quantities of water consumed by tules and cattails grown in exposed tanks at Clarksburg are given in Table 19. The excessive monthly rate and the high annual total should not be taken as actual consumptive use under normal conditions of growth. Previous discussion has shown the fallacy of attempting to determine consumptive use of water by plants grown

1/ Field work was conducted under the supervision of the late O. V. P. Stout, Irrigation Engineer, Division of Irrigation, in cooperation with Division of Water Resources, Department of Public Works, State of California.

TABLE 19

CONSUMPTIVE USE OF WATER BY CATTAILS AND TULES IN EXPOSED TANKS, AT CLARKSBURG, CALIF., 1929-30 1/

Year	Type of vegetation 2/	Water used												
		Jan.	Feb.	Mar.	Apr.	May	June	July 3/	Aug.	Sept.	Oct.	Nov.	Dec.	Year
		Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches
1929		--	--	--	--	--	--	13.56	31.08	26.04	21.24	11.76	--	--
1929		--	--	--	--	--	--	14.76	30.96	24.24	20.52	13.20	--	--
1929	Cattails	--	--	--	--	--	--	11.76	23.76	29.88	24.72	15.48	--	--
1929		--	--	--	--	--	--	11.04	29.28	30.72	24.36	11.04	--	--
1929		--	--	--	--	--	--	12.48	29.16	31.20	26.76	14.64	--	--
1929		--	--	--	--	--	--	15.60	34.20	30.00	26.76	16.80	--	--
1929		--	--	--	--	--	--	15.96	36.36	30.72	27.72	17.88	--	--
1929	Tules	--	--	--	--	--	--	14.52	33.72	28.68	23.88	14.28	--	--
1929		--	--	--	--	--	--	14.16	34.32	27.84	22.44	11.88	--	--
1929		--	--	--	--	--	--	16.08	34.44	27.12	21.12	14.04	--	--
1929		--	--	--	--	--	--	15.84	32.76	25.08	20.76	14.16	--	--
1930		5.16	2.28	6.24	15.84	24.48	25.08	29.76	31.68	22.40	18.48	8.28	4.64	194.32
1930		4.80	2.04	5.28	12.96	23.40	27.48	27.84	26.52	18.60	16.32	7.92	4.20	177.36
1930	Cattails	5.04	2.04	6.24	16.92	29.16	32.88	34.32	32.40	19.80	18.24	8.04	4.32	209.40
1930		5.04	1.92	6.24	16.08	27.00	28.44	28.08	23.16	14.04	10.92	5.28	3.72	169.92
1930		4.80	2.04	7.20	19.68	29.52	35.28	42.36	39.72	25.92	20.88	8.76	4.80	240.96
1930		5.04	2.16	12.12	25.92	37.20	45.84	60.96	51.96	31.80	25.68	10.44	4.92	314.04
1930		5.04	2.04	7.56	19.32	27.00	30.72	39.96	34.56	22.56	19.44	8.64	3.96	220.80
1930		5.16	2.28	8.76	18.36	23.16	26.88	38.64	32.52	20.88	17.88	7.80	4.08	206.40
1930	Tules	4.80	2.04	9.24	18.36	24.12	31.80	39.24	32.64	22.80	18.72	8.40	4.20	216.36
1930		5.16	2.04	6.72	17.52	22.32	24.24	30.60	29.52	18.60	18.96	8.52	4.80	189.00
1930		5.04	2.04	6.48	14.14	22.80	28.44	30.24	28.32	18.00	16.20	7.44	4.08	183.22

1/ Not applicable to large areas without adjustment.
2/ Water in tanks fluctuated from 4 inches above ground to several inches below.
3/ For period July 15 to 31, inclusive, during 1929.

under unnatural conditions, without adjustment.

Because of the high rate of consumptive use in exposed tanks, other investigations were undertaken at King Island in the Delta, with similar growth in tanks set in natural swamp areas. Under these conditions, recorded consumptive use more nearly approximates actual swamp use without the necessity of applying a modifying factor. Data from this investigation, shown in Table 20, while not as complete as in the previous table, indicate that actual swamp use of water by aquatic growth in this region is about 46 per cent of amounts indicated by exposed tank data. This indication closely agrees with the average of approximately 40 per cent resulting from the southern California investigations. From incomplete data, Lee (18) has estimated that a factor of 50 per cent applied to consumptive use by tules and cattails grown in exposed tanks will closely approximate actual swamp consumptive use of water. It seems that a value between 40 or 50 per cent may be used with safety. It will be seen that aquatic growth uses large quantities of water.

Weeds.--The measure of encroachment of weeds on the water supplies of irrigated crops has also been given consideration. The results warrant the statement that weeds are likely to use more water, in proportion to the ground actually occupied, than the general run of crops. A heavy stand of what is known locally in the Delta as smartweed (*Polygonum acre*) is likely to use two to three times as much water as is required for the proper irrigation of alfalfa. Curly dock may use as much as 100 inches in depth during a single season where there is an ample water supply within easy reach of the plant roots. Results of weed investigations in the high ground-water Delta area are shown in Table 21. According to Stout (30) nearly 300,000 acre-feet of water, or 24 per cent of the annual consumptive use in the Delta, goes to sustain plants serving little or no useful purpose. He estimates that about five parts go to crops and such weeds as grow in the field with them, and two parts to noncrop plants of all kinds which grow apart from

TABLE 20

CONSUMPTIVE USE OF WATER BY CATTAILS AND TULES IN TANKS SET IN SWAMP ON KING ISLAND, SACRAMENTO-SAN JOAQUIN DELTA, CALIF., 1930-32

Year	Type of vegetation	Water used												
		Jan.	Feb.	Mar.	Apr.	May	June	July [1/]	Aug.	Sept.	Oct.	Nov.	Dec. [2/]	Year
		Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches
1930	Cattails [3/]	--	--	--	--	--	--	4.80	14.16	7.80	5.16	2.04	0.36	--
	Cattails [4/]	--	--	--	--	--	--	3.24	16.68	10.08	7.92	3.84	.48	--
	Tules [3/]	--	--	--	--	--	--	2.88	15.12	11.64	8.88	4.32	2.04	--
	Tules [4/]	--	--	--	--	--	--	5.88	18.00	11.16	5.52	2.16	.48	--
1932	Tules [4/]	1.20	2.40	6.60	9.96	18.00	14.40	16.32	10.92	9.00	9.60	4.20	.96	103.56
	Cattails [4/]	2.04	3.24	5.88	6.00	12.24	11.40	16.20	11.16	8.64	6.84	4.20	2.16	90.00

1/ 1930 records cover July 23 to 31, inclusive.
2/ 1930 records for Dec. 1 to 16, inclusive.
3/ Water table at ground surface.
4/ Water table 12 inches above ground surface.

TABLE 21

CONSUMPTIVE USE OF WATER BY WEEDS GROWN IN TANKS AT KING ISLAND, CALIF., 1932-33

Type of vegetation	Average depth to water table	Period of record	Yield per acre (air dried)	Water used
	Inches		Tons	Inches
Cockleburs (Xanthium canadense)	18	Apr. 13, 1932 to Nov. 8, 1932	7.98	86.88
	24		4.98	55.32
	30		6.57	62.52
	36		5.72	57.84
	42		8.16	62.52
Nettles	--	Apr. 6, 1932 to Dec. 30, 1932	1.88	48.00
	--		1.97	49.68
	--		2.55	61.80
Smartweed (Polygonum acre)	18	Apr. 12, 1932 to Oct. 6, 1932	20.52	127.80
	24		23.62	118.08
	30		19.90	120.48
	36		18.59	101.88
	42		18.01	113.76
Prickly lettuce (Lactuca scariola)	18	Apr. 20, 1932 to Sept. 13-28, 1932	4.45	43.20
	24		6.07	55.32
	30		7.30	70.44
	36		8.66	72.00
	42		12.88	99.72
Kelp (Polygonum amphibium)	16	Nov. 16, 1932 to Nov. 10, 1933	5.18	105.72
	20		4.04	87.48
	22		3.23	64.08
	31		3.14	50.88
	36		4.35	73.44
Lambsquarters (Chenopodium album)	30	May 11, 1933 to Sept. 20, 1933	6.64	52.92
	30		4.52	52.44
	30		6.11	46.08
	30		7.15	51.84
	30		6.68	54.84
Nut grass (Cyperus esculentus)	18	June 3, 1933 to Nov. 8, 1933	2.29	49.20
	18		5.19	49.92
	24		3.37	43.56
	24		3.60	43.20
Curly dock (Rumex crispus)	18	Feb. 13, 1933 to Nov. 10, 1933	13.70	100.20
	24		13.75	95.04
Goldenrod (Solidago occidentalis)	30	May 31, 1933 to Nov.10, 1933	8.88	96.48
	30		5.62	69.00

the crops. It is not known that similar estimates have been made for other irrigated regions. Probably in only a few of them would the figures be as impressive as in the Sacramento-San Joaquin Delta where ground water is near the surface and subirrigation is practiced.

Northern Colorado Studies

Grasses, aquatic plants, and weeds.--The Division of Irrigation, cooperating with the Colorado Agricultural Experiment Station, carried on investigations of use of water by grasses, aquatic plants, and weeds growing in tanks at Fort Collins, Colo., during the growing season of 1929, 1930, 1931, and 1932 (23). A brief summary of the results of the investigation is given in Table 22.

TABLE 22

CONSUMPTIVE USE OF WATER BY GRASSES, AQUATIC PLANTS, AND WEEDS AT FORT COLLINS, COLO., 1929-32

Plants	Average depth to water table	Water used			
		July 1 to Oct. 21, 1929	May 20 to Oct. 14, 1930	July 1 to Oct. 21, 1931	May 3 to Sept. 27, 1932
	Inches	Inches	Inches	Inches	Inches
Bluegrass	6	31.10	41.00	--	--
	12	30.64	36.73	--	--
	18	23.99	36.57	--	--
Sedge grass	6	50.49	60.22	--	--
	12	44.16	46.19	--	--
	18	41.54	53.63	--	--
Cattails	1	--	--	52.50	77.00
Rushes	1	--	--	52.59	86.60
Sweetclover 1/	12	--	--	158.11	179.76
	18	--	--	196.73	138.84
Sunflowers	12	--	--	39.42	--
	18	--	--	51.18	--
Russian thistle	12	--	--	--	22.88
	18	--	--	--	26.06
Redroot (pigweed)	18	--	--	--	31.69

1/ Consumptive use by sweetclover is excessive due to spread or overhang beyond confines of tank area.

An examination of the data suggests that caution be used in extending certain measured losses to wider areas. All tanks were grouped at a central station, but it is extremely doubtful that consumptive use as determined represents field consumptive use of all crops. Crop overhang of vegetation spreading beyond the tank area, as in the sweetclover tanks, without doubt induces the drawing of erroneous conclusions. Likewise, the vertical intercept of insolation varies, and consumptive use is increased for those plants which normally protect themselves by dense growth.

Studies of Upper Rio Grande Basin 1/

At the request of the National Resources Committee, the Division of Irrigation in 1936 undertook investigations in the upper Rio Grande Basin in Colorado, New Mexico, and western Texas to determine, among other things, the quantity of water consumed by various species of native vegetation (5). The Division began investigations at Parma, 6 miles east of Monte Vista in San Luis Valley, Colo.; at Isleta, 13 miles below Albuquerque, in Middle Rio Grande Basin; and at Mesilla Dam, 5 miles below State College in Mesilla Valley. Investigations at Mesilla Dam are being continued in cooperation with New Mexico Agricultural Experiment Station.

San Luis Valley, Colorado

Tules and grasses.--The general arrangement of the Parma station is shown in Figure 10. Tules and native meadow grasses were transplanted into ground tanks, each being surrounded by areas of similar growth. Tules in tank No. 1 and meadow grass in tank No. 2 stood in shallow water above the soil surface. Tank No. 3 was equipped with a Mariotte supply bottle to maintain a water table 8 inches below the soil level, but this was not always possible because of rains.

1/ This investigation was conducted by Harry F. Blaney, Irrigation Engineer, Division of Irrigation.

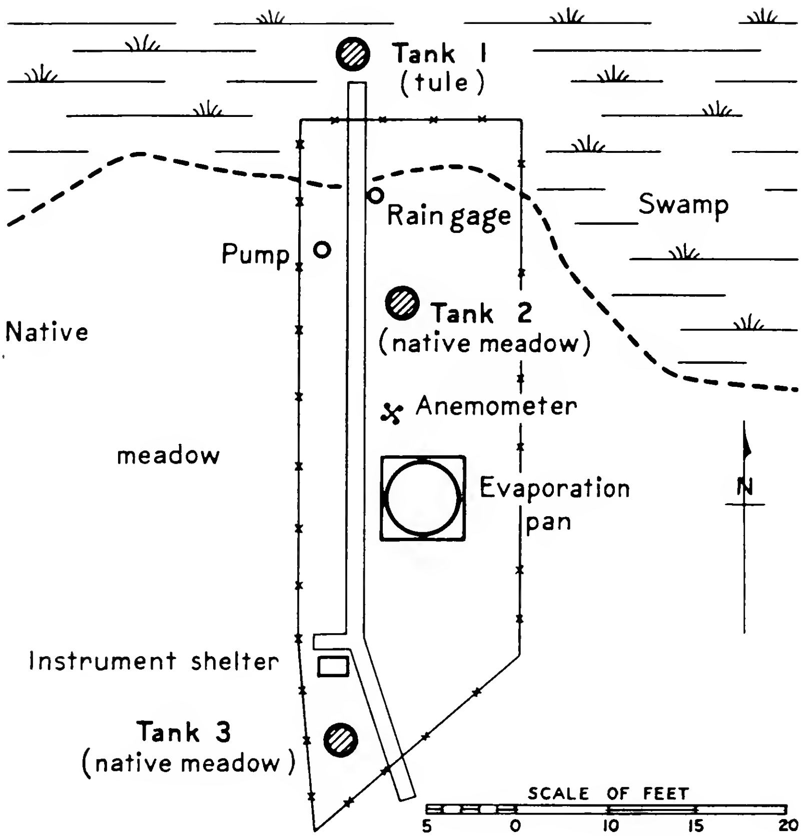


FIGURE 10.-- Plan of Parma station, San Luis Valley, Colo.

Consumptive use data for 1936 are available only for the period June to November, inclusive. Comparison of the October and November consumptive use with loss from a Weather Bureau evaporation pan indicates that all water lost by the tanks during this period was chargeable to evaporation rather than transpiration by plant growth. It is apparent that in the high altitudes of San Luis Valley the growing season for native vegetation ends late in September, and transpiration by plant growth is not a factor in ground-water discharge beyond that time.

A measure of consumptive use is available through comparison with evaporation from a free water surface. Thus, evaporation from a Weather Bureau pan for the June to November period was 30.80 inches. Application of this value indicates that consumptive use by the tules was 126 per cent of the evaporation; by native meadow tank No. 2, 118 per cent; and by meadow grass with a water table 8 inches below the surface, 99 per cent. It should be remembered that these percentages are for but 6 months of the year and do not represent annual values. At Victorville, Calif., as previously reported, consumptive use by tules growing under swamp conditions similar to those at Parma was 95 per cent of the evaporation from a Weather Bureau pan computed on an annual basis. For the period July to November, inclusive, this value would be 112 per cent instead of 95 per cent, showing that summer ratios exceed those for the entire year. Consumptive use by tules and meadow grass and pertinent meteorological data are shown in Table 23.

Middle Rio Grande Valley, New Mexico

This station was located on the east side of the Rio Grande near the pueblo of Isleta in a low moist area containing such water-loving plants as sedges, tules, cattails, saltgrass, and willows (Pl.III-B). The observations were conducted in cooperation with the Middle Rio Grande Conservancy District during 1936 and 1937. A sketch of the station is given in Figure 11. Mariotte apparatus was used to supply water to vegetation tanks and keep the water surface at constant levels, as indicated in Figure 12. To provide a natural environment, each vegetation tank was set in a surrounding growth of the same species. Tule tanks were placed in a dense swamp, grasses in meadow land, and willow growth in a willow thicket. Each species represented a large area of similar growth in the Middle Rio Grande Valley. Consumptive use of water by cattails, sedge, saltgrass, and willows, with meteorological data, are shown in Table 24.

TABLE 23

CONSUMPTIVE USE OF WATER BY TULES AND NATIVE MEADOW GRASS IN TANKS, EVAPORATION, AND METEOROLOGICAL DATA AT PARMA STATION, SAN LUIS VALLEY, COLO., 1936

Month	Water used			Average depth to water table, tank No. 3	Evaporation from Weather Bureau pan	Meteorological data					
	Tank No. 1	Tank No. 2	Tank No. 3			Temperature			Wind movement		
	Tules 1/	Native meadow grass 2/	Native meadow grass			Mean maximum	Mean minimum	Mean	Total	Average	Precipitation
	Inches	Inches	Inches	Inches	Inches	°F.	°F.	°F.	Miles	Miles per hour	Inches
June	11.45	3/ 7.00	6.51	10.0	8.26	80	42	61	1286	1.8	1.07
July	11.60	9.55	8.27	8.5	6.52	89	50	70	1029	1.4	.99
August	8.31	8.04	7.79	7.5	6.61	81	49	65	618	.8	3.06
September	4.10	7.79	5.80	7.8	4.70	77	40	58	616	.8	1.28
October	2.01	2.74	1.18	3.8	3.22	65	28	46	487	.6	.59
November	1.30	1.15	.95	8.9	1.49	58	15	36	352	.5	.14
June to November, inclusive	38.77	36.27	30.50	7.8	30.80	75	37	56	4388	1.0	7.13

1/ Growing in water.
2/ Water approximately at ground surface.
3/ Quantity estimated by comparison.

TABLE 24

CONSUMPTIVE USE OF WATER BY CATTAILS, SEDGE, SALTGRASS, AND WILLOW IN TANKS, EVAPORATION AND METEOROLOGICAL DATA AT ISLETA, MIDDLE RIO GRANDE VALLEY, N. MEX., 1936-37

Month and year	Water used: Cat-tails 1/	Water used: Sedge 1/	Water used: Salt-grass	Water used: Willow	Average depth to water table: Salt-grass	Average depth to water table: Willow	Evaporation from Weather Bureau pan	Meteorological data: Temperature 2/: Mean maximum	Temperature 2/: Mean minimum	Temperature 2/: Mean	Precipitation	Wind movement: Total	Wind movement: Average	Relative humidity at Albuquerque
	Inches	Inches	Inches	Inches	Inches	Inches	Inches	°F.	°F.	°F.	Inches	Miles	Miles per hour	Per cent
1936														
June	15.58	8.98	5.46	3.77	9.6	13.4	11.07	91	56	74	0.38	--	--	36
July	16.98	11.45	6.07	4.24	8.5	9.7	10.05	92	62	77	1.58	1644	2.2	42
August	16.52	15.57	3/ 5.59	4.80	9.7	12.7	9.05	92	61	76	.68	1423	1.9	44
September	11.25	7.39	3/ 3.81	4.18	5.5	8.6	6.62	82	55	68	3.11	1280	1.8	54
October	4.82	4.54	1.75	2.92	3/ 5.1	9.5	4.60	73	42	58	.29	1739	2.3	49
November	3/ 2.52	3/ 2.13	3/ .79	3/ 1.34	3/ 6.0	3/ 12.0	2.95	59	25	42	T	3124	4.3	51
December	3/ 1.90	3/ 1.45	3/ .62	3/ .96	3/ 6.0	3/ 12.0	--	48	17	32	--	--	--	67
1937														
January	1.27	.76	3/ .49	3/ .58	7.0	3/ 14.0	--	41	9	25	--	--	--	61
February	3.06	2.87	.56	3/ .76	6.0	3/ 14.0	--	53	21	37	.33	--	--	52
March	5.67	4.78	3/ 1.08	3/ 1.19	8.0	3/ 15.0	--	55	27	41	1.10	--	--	52
April	6.23	6.49	3/ .60	3/ 2.28	10.0	3/ 16.0	--	69	34	52	.39	--	--	35
May	3/ 11.49	3/ 10.53	3/ 4.77	3/ 3.47	3/ 11.0	3/ 17.0	--	78	45	62	3.03	--	--	42
Year	97.29	76.94	31.59	30.49	7.7	12.8	--	69	38	54	10.89	--	--	49
June	14.71	12.41	3/ 7.55	3/ 4.24	3/ 10.0	3/ 18.0	8.59	87	51	69	.79	--	--	43
July	17.19	16.19	--	--	--	--	10.29	92	60	76	1.79	--	--	50
August	13.30	11.71	--	--	--	--	8.57	92	60	76	.98	--	--	48
September	8.35	7.47	--	--	--	--	5.94	84	53	68	.92	--	--	55
October	4.44	5.56	--	--	--	--	4.27	74	40	57	1.15	--	--	50
November	3.57	3.01	--	--	--	--	3.18	64	26	45	--	--	--	43

1/ Growing in water.
2/ Temperature records from Albuquerque May 19 to June 15 and Nov. 2 to Dec. 1, 1936, and from Los Lunas Station (near) Dec. 1, 1936 to Dec. 31, 1937.
3/ Partly estimated.

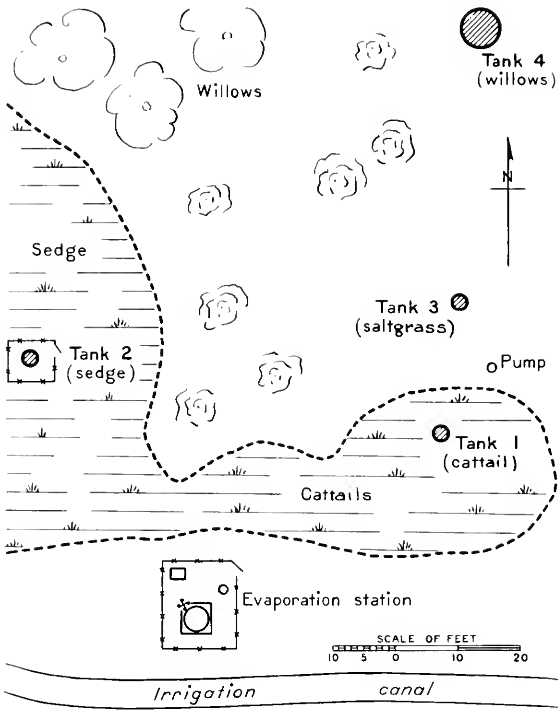


FIGURE 11.--Plan of Isleta station, N. Mex., 1936.

Cattails.--Cattails are heavy users of water and should be prevented wherever possible from wasting an inadequate supply. Throughout the arid and semiarid West water is the controlling factor in the maintenance and increase of agriculture and population. Any waste of a natural resource is to be deplored. Tules and cattails sometimes provide preserves for wildlife, but where they serve no useful purpose they should be eliminated in the interests of water conservation (Pl. IV-A).

Sedge.--Sedge is likewise a great water user, transpiring nearly as much annually as tules and cattails. The maximum monthly use of water by this species at Isleta was 16.19 acre-

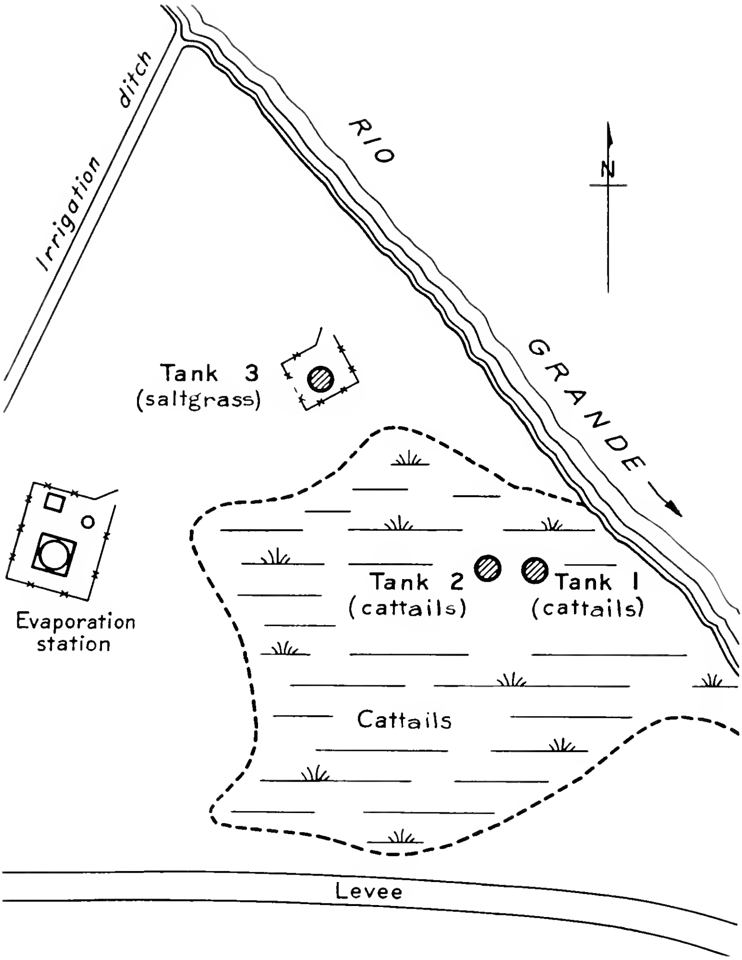


FIGURE 12.--Sketch of water supply lay-out at Isleta station.

inches per acre in July 1937, equaling 157 per cent of the evaporation loss from a Weather Bureau pan.

Saltgrass.--Consumptive use by saltgrass is small compared with that of cattails and sedge. In the experimental results it appeared as about half the evaporation loss from a Weather Bureau pan despite a high water table in the saltgrass tank. Records for southern California (4) show a higher consumptive use for the coastal region than for the more arid climate of central New Mexico, possibly due to differences in density of growth.

Willows.--Measurement was also made of the quantity of water consumed by willows growing 6 to 8 feet high, in a tank

PLATE IV

A. Cattails in tank surrounded by similar growth at Isleta, Middle Rio Grande Valley, N. Mex.

B. Dense growth of water-loving shrubs and trees along the Santa Ana River, near Prado, Calif. Studies have shown this vegetation uses approximately 50 acre-inches of water per acre annually.

6 feet in diameter set in a thicket of the same growth. The water table in the tank fluctuated slightly throughout the season but averaged about 13 inches below the surface. Consumptive use for 12 months amounted to 30.49 inches in depth for the area of the tank. Evaporation records are not available for all this period, but for the first 6 months, June to November, inclusive, consumptive use by the willows was 47.9 per cent of the evaporation from a Weather Bureau pan. A similar test in southern California, involving an isolated tank unprotected by other willow growth in which depth to water was 2 feet, resulted in a consumptive use of water equalling 92.7 per cent of the evaporation loss from a Weather Bureau pan.

Summarizing vegetative use of water at Isleta: Cattails and sedge are extravagant users of water, while saltgrass and willows use less. This conclusion is supported by similar investigations elsewhere.

Mesilla Valley, New Mexico

The evaporation-transpiration station established at Mesilla Dam to determine consumptive use of water by cattails and saltgrass was on low ground along the west bank of the Rio Grande in an area of similar growth. The site was made available by the Bureau of Reclamation. There was exposure in all directions except to the west where the mesa rose abruptly about 15 feet some 50 yards from the station. To the south were a few scattered trees, while the river bordered the northeast side. A sketch of the station site is shown in Figure 13.

Cattails.--Two cattail tanks were located in a swamp completely surrounded by natural growth. Tanks were 2 feet in diameter by 3 feet deep. Healthy broadleaf cattails were transplanted into the tanks and the water surface was maintained approximately 2 inches above the soil. Each developed a vigorous growth although the plants were somewhat larger in one tank than in the other. This difference is reflected in consumptive use, as will

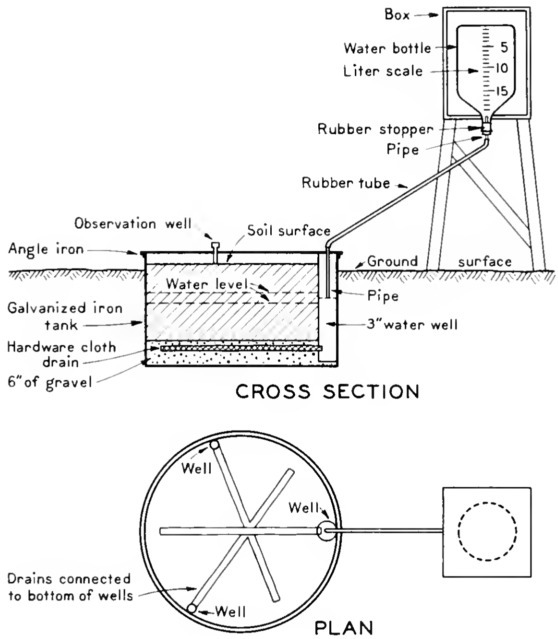


FIGURE 13.-- Plan of Mesilla Dam station.

be seen in Table 25 which presents all consumptive use and meteorological data.

The average consumptive use of water by cattails corresponded closely with data obtained at Isleta for the same period. The average for both stations amounted to about 111 inches in depth for the 12-month period.

Saltgrass.--Saltgrass was transplanted into a tank set in a saltgrass area of high ground water. A Mariotte control provided an automatic supply, keeping the water level in the tank at a fairly constant depth of 14 inches. A thick growth of grass developed to a height of 7 to 10 inches by midsummer. As at other

TABLE 25

CONSUMPTIVE USE OF WATER BY CATTAILS AND SALTGRASS IN TANKS, AND METEOROLOGICAL DATA, AT MESILLA DAM, IN MESILLA VALLEY, N. MEX., 1936-37

Month and year	Water used			Evaporation from Weather Bureau pan	Meteorological data-State College Station 1/			
					Temperatures			
	Cat-tails	Cat-tails	Salt-grass 2/		Mean maximum	Mean minimum	Mean	Relative humidity
1936	Inches	Inches	Inches	Inches	°F.	°F.	°F.	Per cent
July	19.62	14.90	9.20	10.53	93	66	80	47
August	16.10	12.26	7.90	9.04	91	63	77	54
September	9.87	8.49	6.11	6.56	82	58	70	64
October	4.40	4.02	4.12	5.37	74	43	58	59
November	2.58	1.98	1.21	3.04	61	32	46	59
December	1.69	1.47	.75	1.99	57	28	42	69
1937								
January	3.17	2.04	.43	2.70	53	21	37	54
February	4.66	3.91	1.13	4.28	60	29	44	56
March	6.04	6.99	1.12	6.92	64	33	48	52
April	7.36	9.65	1.96	8.10	77	40	58	29
May	15.29	16.57	2.11	11.59	85	50	68	39
June	26.65	21.62	3.77	9.68	93	58	76	35
July	22.32	18.34	--	9.38	94	65	80	40
August	19.21	14.09	--	7.83	93	66	80	51
September	11.02	9.92	--	6.85	86	60	73	55
October	5.82	5.14	--	6.40	77	46	62	59
November	3.62	2.92	--	3.50	68	30	49	53
December	3.00	2.31	--	1.92	58	29	44	64
Year	128.16	113.50	3/ 39.81	79.15	76	44	60	49

1/ State College Station is 5 miles northeast.
2/ Average depth of 14 inches to water in soil tank.
3/ Total for July 1936 to June 1937.

stations, a Weather Bureau evaporation pan provided data for comparison with consumptive use records.

The 12-month use of water by saltgrass, approximately 40 inches in depth, was slightly more than the amount determined at Isleta in spite of greater depth to water table, and approximated results obtained in southern California under similar tank conditions. Thus, in widely separated localities, consumptive use by saltgrass, growing under conditions of ground water within approximately 12 inches of the surface, appears not to exceed 40 acre-inches per acre. There are probably few extensive localities where such conditions exist. For this species, at least, consumptive use decreases with increasing depth to ground water, so that the annual draft on water supplies caused by saltgrass is probably less than would be required by many cultivated crops in the same area.

CHAPTER 5

OTHER INVESTIGATIONS

Other investigations, fully as important as those by the Division of Irrigation, have been conducted by other agencies. Standard methods have been used, and the results form an important addition to the general knowledge of consumptive use by native growth. These data have been collected and are presented in the following discussions.

SOUTH-CENTRAL OREGON

The early irrigation development of south-central Oregon was largely by wild flooding with little regard to the economical use of water. Much of the irrigated area was used for hay and pasture. The practice of flooding when water was plentiful was not only wasteful of the water supply but was also likely to injure the soil and reduce yields. Reports indicate that at one time 300,000 acres of marsh lands in Chewaucan and Harney Valleys and in Klamath Basin were irrigated in this manner.

In 1915 investigations were undertaken under a cooperative agreement by the Oregon Experiment Station and the Division of Irrigation (24) to determine the use of water by such native marshland plants as were suitable for hay and pasture. Experiments were carried out on fields and plots and in tanks. The general plan was to apply water in three amounts: the usual irrigation by the farm operator, a larger amount as determined by the investigator, and a smaller amount. Investigations continued through the seasons 1915, 1916, and 1917. Marsh grass, native meadow, sugar grass, and wire rush were grown in tanks and plots. The amounts of water used are shown in Tables 26 to 29.

TABLE 26

CONSUMPTIVE USE OF WATER BY MARSH GRASS IN THE CHEWAUCAN VALLEY, OREG. (24)

Year	Soil	Altitude	Area irrigated[1]	Water used: Rain and soil moisture	Water used: Irrigation	Water used: Total	Yield per acre
		Feet		Inches	Inches	Inches	Tons
1915	Silt loam	4300	Plot	5.67 3.31 3.16	27.48 .00 11.28	33.15 3.31 14.44	0.89 .57 1.03
1915	Silt loam	4300	Plot	6.50 4.32 5.04	18.12 .00 6.60	24.62 4.32 11.64	.70 .70 .73
1915	Peat	4300	Tank	13.49 18.11 9.89	26.47 4.00 13.81	39.96 22.11 23.70	-- -- --
1917	Peaty	4300	Tank	1.50 1.49 1.27	33.48 13.77 18.63	34.98 15.26 19.90	-- -- --
1917	Peaty	4300	Plot	4.65 3.48 3.18	27.90 3.00 14.78	32.55 6.48 17.96	1.03 .94 .92

1/ Area of tanks - 1.39 square feet; of plots - 0.10 acre.

TABLE 27

CONSUMPTIVE USE OF WATER BY NATURAL MEADOW IN CHEWAUCAN AND HARNEY VALLEYS, OREG. (24)

Year	Soil	Altitude	Area irrigated[1/]	Water used: Rain and soil moisture	Water used: Irrigation	Water used: Total	Yield per acre
		Feet	Acres	Inches	Inches	Inches	Tons
				12.50	21.50	34.00	2.18
1916	Silt loam	4120	100	10.03	0	10.03	2.18
				14.98	10.75	25.73	2.18
				6.85	24.50	31.35	1.96
1916	Silt loam	4120	100	6.03	0	6.03	2.61
				9.94	12.25	22.19	1.96
				11.14	28.00	39.14	2.83
1916	Silt loam	4120	100	12.51	0	12.51	1.96
				10.96	14.00	24.96	2.83
				6.96	26.50	33.46	1.47
1916[2/]	Peaty	4400	Plot	8.64	8.50	17.14	1.24
				7.91	19.20	27.11	1.94
				6.12	26.20	32.32	.60
1916[2/]	Silt loam	4400	Plot	4.50	5.75	10.25	.57
				5.86	14.50	20.36	.43
				6.33	11.00	17.33	--
1916	Silt loam	4120	Tank	6.32	3.50	9.82	--
				7.00	6.00	13.00	--
				5.94	11.00	16.94	--
1916	Silt loam	4120	Tank	5.55	4.50	10.05	--
				6.88	6.00	12.88	--

1/ Area of tanks - 1.39 square feet; of plots - 0.10 acre.
2/ These tests made in Chewaucan Valley - all others in Harney Valley.

TABLE 28

CONSUMPTIVE USE OF WATER BY SUGAR GRASS IN THE CHEWAUCAN VALLEY AND THE KLAMATH BASIN, OREG. (24)

Year	Soil	Altitude	Area irrigated[1]	Water used: Rain and soil moisture	Water used: Irrigation	Water used: Total	Yield per acre
		Feet		Inches	Inches	Inches	Tons
1916[2]	Peaty	4400	Tank	8.92	32.00	40.92	2.40
				11.30	12.00	23.30	1.31
				9.50	16.00	25.50	1.96
1918	Peaty	4100	Tank	9.09	25.00	34.09	--
				15.72	7.00	22.72	--
				4.80	13.00	17.80	--
1918	Peaty	4100	Tank	9.03	25.00	34.03	--
				16.29	7.00	23.29	--
				9.94	13.00	22.94	--

1/ Area of tanks - 1.39 square feet.
2/ These tests made in Chewaucan Valley - all others in Klamath Basin.

TABLE 29

CONSUMPTIVE USE OF WATER BY WIRE RUSH GROWN IN THE KLAMATH BASIN, OREG. (24)

Year	Soil	Altitude	Area irrigated[1]	Water used: Rain and soil moisture	Water used: Irrigation	Water used: Total	Yield per acre
		Feet		Inches	Inches	Inches	Tons
1917	Peaty	4100	Tank	39.98	20.00	59.98	3.47
				6.79	7.00	13.79	.75
				8.46	11.00	19.46	1.39
1919	Peaty	4100	Tank	-1.60	24.00	22.40	--
				1.58	8.00	9.58	--
				.47	16.00	16.47	--
1919	Peaty	4100	Tank	- .48	24.00	23.52	--
				3.65	8.00	11.65	--
				- .48	16.00	15.52	--

1/ Area of tanks - 1.39 square feet.

The soil moisture conditions in tanks used in the investigation were different from others discussed in this report. Ordinarily tank studies are conducted in the presence of a water table under the control of the investigator. All other studies discussed here have been of this type. In tanks used for growth of marsh grasses in south-central Oregon, however, the investigation was characterized by an absence of water table and the use of water is taken as the sum of rainfall and soil moisture consumed plus irrigation water applied.

On the basis of differences between inflow and outflow, consumptive use of water by wild meadows was estimated as follows: Chewaucan Valley 1.52 acre-feet per acre; Harney Valley 1.34 acre-feet per acre; and Klamath Basin, a 5-year average, 1.30 acre-feet per acre. This method does not give the total consumptive use as neither deep percolation losses, underflow out of the basin nor precipitation are included.

Marsh grass.--From data available, there does not appear to be a close relation between quantity of water received by marsh grass and yield in tons per acre. However, the record is not complete. On plots of silt loam the yield varied from 0.57 to 1.03 tons per acre, while the water received for these yields varied from a minimum of 3.31 inches to a maximum of 14.44 inches for the season. On peaty soil a maximum of 32.55 inches of water produced 1.03 tons, while a minimum of 6.48 inches was sufficient for 0.94 ton. Because of the inconsistency of the use-yield relation, it does not seem improbable that the marsh grass grown in plots received quantities of ground water not included in the record. Records of marsh grass grown in tanks, with weight of crop measured in grams, show a more uniform use-yield ratio.

Native meadow.--Native meadow in farms, plots or tanks received a maximum water supply of 39.14 inches of depth and a minimum of 6.03 inches. Yields for these amounts are inconsistent. From the record it appears that water received by the crop is not a water requirement and has no relation to the amount necessary to plant existence. In instances where no water was applied by irrigation and the grass received only a low rainfall the yield was equal to or greater than that produced when 21.5 inches of irrigation was applied.

Sugar grass.--Water received by sugar grass (*Carex aquatilis*) grown in tanks varied from 17.80 inches to 40.92 inches. Records of yield are incomplete, but those available show the greatest yield for the most water received.

Wire rush.--Use of water by wire rush in tanks varied from 9.58 inches of depth to 59.98 inches for peaty soil. Yield in tons per acre is available only for three tanks which show the largest yield for the most water received.

MUD LAKE, IDAHO (29)

Tules.--Additional data on consumptive use of water by tules in a tank set in a swamp area are afforded by an investigation of water resources of Mud Lake, Idaho, from 1921 to 1923, inclusive. Results of the investigation indicate that 162,000 acre-feet of water appeared in Mud Lake and five smaller lakes or reservoirs in the same vicinity during the year ending March 31, 1922. At that time three-fourths of the lake area and adjoining marshes were occupied by tule growth.

Stearns and Bryan (29) state that "about 49,000 acre-feet was used for the irrigation of about 13,300 acres, and about 108,000 acre-feet was discharged by evaporation and transpiration from tules and other native plants of small economic value. The data show that the natural losses were very large in proportion to the quantity used for irrigation. They at once raise the question whether the supply for irrigation can be increased by reducing the natural losses."

As a means of measuring losses from swamp areas a tule pan 4 feet in diameter by 4 feet deep was set in the swamp. Tules of about the same density as the surrounding growth were transplanted into the pan. The soil was generally submerged to represent swamp conditions. Records of consumptive use and meteorological data for the summer months of 1921 to 1923, inclusive, are shown in Table 30.

TABLE 30

CONSUMPTIVE USE OF WATER BY TULES IN TANKS, AND METEOROLOGICAL DATA AT MUD LAKE, IDAHO, 1921-23 (29)

Month and year	Water used by tules	Meteorological data					
		Temperature				Wind movement	
		Mean maximum	Mean minimum	Mean	Precipitation	Total	Average
1921	Inches	°F.	°F.	°F.	Inches	Miles	Miles per hour
June	1/ 8.85	79	50	64	0.36	4040	5.6
July	18.98	87	50	68	.62	3640	4.9
August	17.98	85	48	66	.23	3020	4.1
September	2/ 5.54	70	33	52	.42	4020	5.6
June to Sept., inclusive	51.35	80	45	62	1.63	14720	5.0
1922							
June	13.47	82	45	64	.62	3485	4.8
July	21.42	86	49	68	.63	3160	4.2
August	17.33	84	41	62	2.02	2865	3.8
September	10.26	80	43	62	--	2660	3.7
June to Sept., inclusive	62.48	83	44	64	3.27	12170	4.1
1923							
June	3/ 5.79	71	43	57	1.80	4060	5.6
July	11.70	88	53	70	1.40	4/ 3590	4/ 4.8
August	13.38	83	47	65	1.05	4/ 4140	4/ 5.6
September	11.06	77	40	58	.50	4275	5.9
June to Sept., inclusive	41.93	80	46	62	4.75	16065	5.5

1/ June 13 to 30.
2/ September 1 to 23.
3/ June 12 to 30.
4/ Uncertain.

The second year of record shows the highest seasonal use of water. This seems reasonable, as during the first year the plants were becoming reestablished after the shock of being transplanted; in the third year there was danger of loss of fertility or of the roots becoming pot-bound. Seasonal consumptive use of 62.48 inches from June to September, inclusive, at Mud Lake agrees closely with consumptive use by tules at Isleta, N. Mex., but exceeds amounts at other tule stations where measurements were obtained in swamp areas as distinguished from exposed tanks.

ESCALANTE VALLEY, UTAH

The general method of estimating consumptive use by native vegetation through attention to ground-water fluctuations has been previously described. White (38), using the same method in the Escalante Valley, Utah, as described by Smith in Arizona (see page 18), shows that ground-water fluctuations respond to the vegetal demand for moisture with declining water tables during hours of sunlight and rising water tables during the night.

Observations were made in 1926 and 1927 to determine consumptive use by various species of native vegetation and to estimate the water resources of the valley. This is a desert region yet one in which a considerable area of native growth subsists upon ground water close to the surface. Vegetation consisted principally of saltgrass, greasewood, sagebrush, rabbitbrush, shadscale, pickleweed, and willow.

To determine the effect of consumptive use by these plants, wells sunk in areas of each predominant species were equipped with water-stage recorders. With this equipment, diurnal fluctuations of the water table for each area were determined. The extent of the fluctuations varied, not only with soil type but also, and what is of greater importance, with the age, vigor, density, and type of plant growth. The maximum daily draw-down observed ranged from 1 1/2 inches for an area of greasewood to 4 1/4 inches in a field of marsh grasses. Samples of recorder charts for several vegetative species are shown in Figure 14.

Ground-water fluctuations as described can only be translated into depths of consumptive use through determination of the specific yield of the soil on which the vegetation grows. Obviously for large areas this is difficult because of ever-changing soil conditions throughout the area. To obtain values of specific

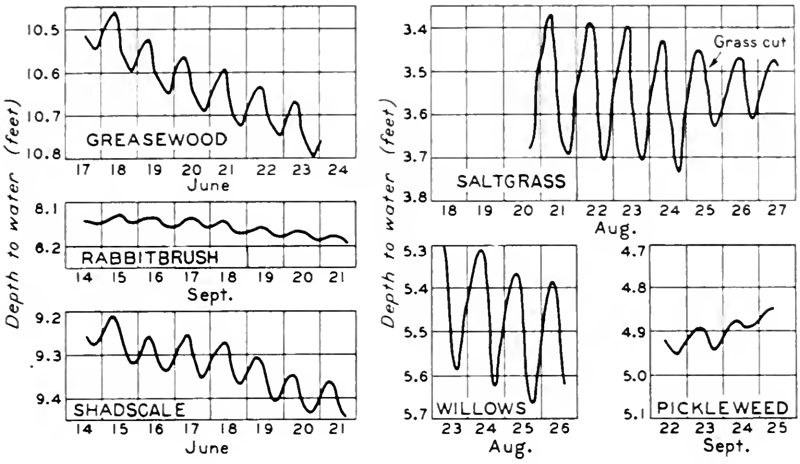


FIGURE 14.--Examples of recorder charts showing ground-water fluctuations due to daily transpiration losses by various species of native vegetation (after White).

yield usable in the consumptive use formula $\underline{c} = \underline{y}(24\ \underline{r} \pm \underline{s})$, tanks were filled with undisturbed soil in the vicinity of wells where recorders were maintained. Water was added to or subtracted from the soil and the specific yield computed according to the changed level in the tank. Estimates of consumptive use were made for a number of vegetative species by this method of obtaining specific yield values.

Saltgrass.--To support some of the findings reached by means of water-table fluctuations, saltgrass and greasewood were grown in tanks supplied with measured amounts of water. Two saltgrass tanks were employed, one using transplanted sod, the other undisturbed sod and soil obtained by driving the tank into the ground. Greasewood was transplanted in the tank, but only four out of seven plants lived and for some time these grew slowly. By the end of the summer of 1926 these plants were thrifty, and were vigorous during the following season.

Each tank was equipped with automatic water-supply Mariotte apparatus. In some respects these were unsatisfactory, as they were not protected against temperature changes. In periods of rising temperatures, expanding air forced water out of the bottle beyond the capacity of plant absorption, and the water table in the soil tank rose above the desired level. As air in the bottle became cooler, flow of water was retarded and transpiration occurred faster than water could be supplied. Water levels dropped in the soil tank. Over a considerable period of time these changes were unimportant, but they destroyed the opportunity to obtain accurate hourly records of transpiration losses.

Greasewood.--Attempts were made to separate transpiration from greasewood plants and evaporation from soil. Separate soil evaporation tanks were used for this purpose. Saltgrass growing in tanks shades the ground surface so that little soil evaporation occurs, and the principal loss is caused by transpiration. In a tank of greasewood there would be some bare soil, and evaporation would be a factor in the total loss of water. White (38) has estimated this as approximately 25 per cent of the total. Consumptive use of water by saltgrass and greasewood grown in tanks in the Escalante Valley is presented in Table 31.

SAN LUIS VALLEY, COLORADO

Saltgrass.--Tipton and Hart, for the State Engineer of Colorado, conducted studies for several years on the use of water by saltgrass in tanks and of evaporation in the San Luis Valley, Colo. (32).

The evaporation and transpiration laboratory was established at Garnett in 1927 and continued in 1928. The station was rehabilitated and placed in operation again in April 1930 and continued in 1931. No change was made in the apparatus or in the depth at which the water table was maintained in the various tanks. An additional saltgrass tank was installed to maintain the water table at a depth of about 40 inches, but this tank did not begin to function properly

TABLE 31

CONSUMPTIVE USE OF WATER BY SALTGRASS AND GREASEWOOD IN TANKS IN ESCALANTE VALLEY, UTAH, 1926-27 (38)

Month and year	Saltgrass				Greasewood				Precipitation
	Water used [1]	Average depth to water table	Water used [2]	Average depth to water table	Soil evaporation	Transpiration	Total water used	Average depth to water table	
1926	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches
May	1.06	28	--	--	--	--	--	--	0.78
June	1.75	21	--	--	0.58	0.52	1.10	40	.06
July	1.92	36	--	--	.54	1.42	1.96	40	.54
August	6.26	28	4.55	12	.97	2.58	3.55	31	.42
September	3.14	30	3.45	13	1.06	3.19	4.25	24	.28
October	.60	41	1.12	23	.42	.56	.98	40	.20
Seasonal	14.73	31	--	--	3.57	8.27	11.84	35	2.28
1927									
May	2.56	21	2.78	23	.82	.82	1.64	30	1.02
June	3.68	31	5.70	24	1.20	3.64	4.84	27	.10
July	4.70	28	5.80	25	1.06	5.54	6.60	28	.91
August	3.11	25	4.00	21	1.07	4.83	5.90	28	.47
September	2.61	23	3.13	23	.93	3.48	4.41	26	.50
October	1.22	28	1.18	24	1.33	.48	1.81	15	1.47
Seasonal	17.88	26	22.59	23	6.41	18.79	25.20	26	4.47

1/ Transplanted sod.
2/ Undisturbed sod and soil.

until late in the season. Readings of all apparatus were made two to three times a week. Daily temperature, wind movement, precipitation, evaporation, and evapo-transpiration records were kept.

Tanks Nos. 1, 2, and 3 were 3 feet in diameter and 3 feet deep, sunk in the ground nearly flush with the rim and filled with sandy loam soil. The soil was placed in these tanks in the spring of 1927; therefore, both soil and vegetation were well stabilized. Tanks Nos. 1, 2, and 3 had a growth of saltgrass with water levels maintained at approximate depths of 4, 12, and 24 inches, respectively. The water table was maintained below the surface by means of Mariotte apparatus. Tank No. 4-A was similarly installed in 1930 except that it was 4 feet deep with the water level kept at about 38 inches below the surface.

The results of these experiments are summarized in Table 32. The investigation was divided into two periods, separated by the year 1929, during which no records were obtained. Although the Mariotte apparatus was designed to hold the water table in the soil tanks at constant levels, fluctuations of 2 to 3 inches occurred. Total consumptive use during the growing season is influenced by the depth to water, plants located where water is near the surface showing the greater consumptive use because of more luxuriant growth and increased soil evaporation. Fluctuation of 2 or 3 inches is, however, too small noticeably to influence the quantity of water used.

Averaging the total use of water during the 4-year period, from June to October, inclusive, shows that saltgrass in tank No.1 used 20.19 inches with an average depth of 4.2 inches to the water table. Tank No. 2 consumed 19.47 inches with an average depth of 12.8 inches to water -- practically the same as the tank with a higher water level. Tank No. 3 used 16.05 inches with the water table 24.2 inches below the surface. Tank No. 4-A used 16.92 inches of water with an average depth to water table of 38 inches in 1931, the only year in which observations were taken. The

TABLE 32

CONSUMPTIVE USE OF WATER BY SALTGRASS IN TANKS AT GARNETT, SAN LUIS VALLEY, COLO., 1927, 1928, 1930, and 1931 (32)

	Water used																
	Tank No. 1				Tank No. 2				Tank No. 3				Tank No.4-A				
	Average depth to water table, in inches													Evaporation from Weather Bureau pan			
	6	4	4	3	15	14	10	12	25	24	23	25	38				
Month	1927	1928	1930	1931	1927	1928	1930	1931	1927	1928	1930	1931	1931	1927	1928	1930	1931
	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches
April	--	2.76	--	3.00	--	2.52	--	1.68	--	1.92	--	0.84	1.56	--	1.92	--	4.20
May	--	3.72	4.68	3.60	--	3.48	2.64	3.00	--	2.76	2.64	1.92	1.68	--	5.16	6.24	5.64
June	4.56	5.52	6.84	5.28	4.56	5.52	4.32	6.24	3.12	3.84	4.20	4.20	3.96	5.88	7.20	6.36	6.96
July	3.84	6.36	5.40	5.76	3.96	5.28	5.16	6.72	2.76	5.04	4.32	5.64	4.56	5.40	6.24	5.28	6.36
August	3.96	4.32	5.16	4.80	4.08	3.48	4.08	5.88	3.48	2.88	3.36	4.56	3.96	4.08	5.28	4.56	5.28
September	3.00	2.76	3.00	3.00	3.24	2.28	3.48	3.48	2.64	2.28	3.00	3.24	3.00	3.36	4.08	3.96	3.96
October	1.68	1.68	2.04	1.80	2.04	1.20	1.32	1.56	1.32	1.56	1.32	1.44	1.44	2.64	3.24	2.88	3.12
June to October, inclusive	17.04	20.64	22.44	20.64	17.88	17.76	18.36	23.88	13.32	15.60	16.20	19.08	16.92	21.36	26.04	23.04	25.68

slight differences in consumptive use in relation to depth to water table are unusual. The difference between the first two tanks indicates a nearly uniform use of water for all depths to 15 inches. Between 24 and 38 inches, consumptive use is nearly constant. In plotting these values a straight-line relation appears to exist for all depths except 24 inches.

NORTHEASTERN COLORADO

Weeds.--As has appeared from previous discussions in this report, investigations of use of water by crop or noncrop plants, conducted by engineers and others interested in irrigation or water supply, usually measure the quantities of water consumed in inches of depth for the growing season. This measure is comparable to rainfall and may be converted into units of flowing water. Other investigators more interested in transpiration losses as a function of the plant determine the ratio of the weight of water absorbed to the weight of dry matter harvested. In each case there is a similarity in technique but the results are in units that are not comparable.

Probably the most extensive investigation of the latter kind to include native vegetation was conducted at Akron, Colo., by the Bureau of Plant Industry, United States Department of Agriculture, from 1911 to 1917 (27). A study less extensive as regards native vegetation was also carried on by the same Bureau at Mandan, N. Dak., from 1919 to 1922 (11).

The term "water requirement," as defined by the investigators, "indicates the ratio of weight of water absorbed by the plant during its growth period to the weight of dry matter harvested." Other investigators have defined the term as "the total quantity of water required by crops for normal growth under field conditions." (13) (See also p. 1.) The water required is disposed of by transpiration from the plant, evaporation from the soil, deep percolation, and other unavoidable losses. The Bureau of Plant Industry sealed the soil and roots in closed containers so that the only loss was by transpiration. Thus the meaning of the term "water requirement" differs according to investigational practices followed.

The results of the investigations at Akron indicate that pigweed, tumbleweed, Russian thistle, purslane, buffalo grass, and grama grass use small amounts of water in relation to weight of dry matter harvested, and that cocklebur, buffalo bur, and sunflower use medium amounts. Some of these results do not agree entirely with those of investigations in the Sacramento-San Joaquin Delta, Calif., where the water table was close to the ground surface and weeds consumed greater quantities. Table 33 shows the use of water by weeds presented as weight of water absorbed to weight of dry matter harvested.

MIDDLE RIO GRANDE VALLEY, NEW MEXICO

Investigations were started in 1926 by the United States Bureau of Reclamation in cooperation with the Middle Rio Grande Conservancy District and the Weather Bureau (10, 14) to determine monthly and annual use of water by saltgrass and by tules at a station established at Los Griegos, near Albuquerque, N. Mex. The purpose of the investigation was to study natural losses from undrained bottom lands along the Middle Rio Grande Valley. Evaporation from moist sands with water at various depths was included in the investigation.

Saltgrass.--Saltgrass was grown in galvanized iron stock tanks approximately 4 feet in diameter with depths from 2 to 4 feet. Soil obtained from excavations in which the tanks were set was placed in thin, tamped layers in approximately the same order as excavated. Samples were classified as Gila clay loam. Tules also were grown in a tank set in a small swamp one-half mile from the original station. Water in the tule tank was approximately 2 inches above the surface.

Mariotte supply tanks, similar to those described on page 19, were used. The soil tanks, however, were the single-wall type, and

TABLE 33

WEIGHT OF WATER ABSORBED BY WEEDS DURING THE GROWTH PERIOD RELATED TO WEIGHT OF DRY MATTER HARVESTED, AKRON, COLO., 1911-17. AFTER SHANTZ AND PIEMEISEL (27)

Year	Plants	Water consumed per pound of dry matter harvested
		Pounds
1911	Pigweed (*Amaranthus retroflexus*)	356
1913		320
1914		306
1915		229
1916		340
1917		307
1911	Tumbleweed (*Amaranthus graecizans*)	275
1914		272
1911	Russian thistle (*Salsola pestifer*)	336
1913	Lambsquarters (*Chenopodium album*)	801
1916		666
1913	Purslane (*Portulaca oleracea*)	292
1913	Cocklebur (*Xanthium commune*)	432
1914	Nightshade (*Solanum triflorum*)	506
1914	Buffalo Bur (*Solanum rostratum*)	557
1912	Gumweed (*Grindelia squarrosa*)	468
1913	Sunflower, annual (*Helianthus annuus*)	705
1916		579
1913	Sunflower, narrow leaved	570
1913	(*Helianthus petiolaris*)	774
1911	Mountain sage (*Artemisia frigida*)	765
1912		474
1914	Verbena (*Verbena bracteosa*)	730
1913	Fetid marigold (*Boebera papposa*)	881
1913	Buffalo grass (*Bulbilis dactyloides*)	308
1914	Grama grass (*Bouteloua gracilis*)	389
1915		312
1916		336
1917		290
1914	Clammyweed (*Polanisia trachysperma*)	502
1916	Iva (*Iva xanthifolia*)	652
1913	Western ragweed (*Ambrosia elatior*)	948
1913	Western wheat grass (*Agropyron smithii*)	1076
1914	Franseria (*Franseria tenuifolia*)	1176

pipe connections from the supply tank entered directly into the bottom of the soil tank instead of into an annular space. Coarse gravel was spread over the bottom of the soil tank to enable water to spread evenly throughout the tank area.

Operation of Mariotte tanks does not appear as satisfactory when connected to single-wall tanks as when used with the double type. Some difficulty was experienced at Los Griegos in maintaining a constant water level in tanks which apparently has not occurred elsewhere. It appears that the reservoir of water in the annular space is an advantage not found when water from the supply tank is piped directly to the soil tank. There is a possibility that at times water is transpired faster than it can be supplied through the soil, with a resulting drop in water table. In a single tank water has to pass upward through the soil column, whereas in the double tank the inner tank wall may be perforated up to the water table and water be supplied partly from the side as well as from the bottom, thus supplying water more rapidly to the plant roots.

This investigation has confirmed results obtained elsewhere. Consumptive use decreased as depth to water table increased. A minimum consumptive use of 10.08 inches occurred where depth to water table was 37 inches, and a maximum use of 48.36 inches where there was a depth of 5 inches. Between these extremes consumptive use was fairly uniform. These data are presented in Table 34.

Tules.--Consumptive use by tules in a tank surrounded by swamp growth amounted to 64.68 inches for a 12-month period, or 83.3 per cent of evaporation from a Weather Bureau pan, a low ratio compared with results of other investigations.

TABLE 34

CONSUMPTIVE USE OF WATER BY SALTGRASS AND TULES IN TANKS, EVAPORATION, AND METEOROLOGICAL DATA AT LOS GRIEGOS, NEAR ALBUQUERQUE, N. MEX., 1926-28 (10)

Month and year	Saltgrass								Tules	Evaporation from Weather Bureau pan	Meteorological data		
	Water used	Average depth to water table	Water used	Average depth to water table	Water used	Average depth to water table	Water used	Average depth to water table	Water used		Mean temperature	Average wind movement	Relative humidity
1926	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	°F.	Miles per hour	Per cent
October	3.48	6	2.16	16	1.20	25	--	--	--	5.00	57	2.4	64
November	.96	5	.96	14	.12	28	--	--	--	1/ 4.03	44	3.5	50
December	.84	2	1.08	12	1.08	25	--	--	--	1.27	35	2.4	75
1927													
January	.36	3	.12	14	.12	22	--	--	--	1.45	39	2.0	64
February	.84	5	.84	15	.48	22	--	--	--	3.23	44	3.6	56
March	1.68	5	1.32	13	.60	20	--	--	--	6.23	46	4.7	50
April	3.12	6	1.44	15	.12	20	--	--	--	8.37	54	4.0	45
May	7.08	4	3.12	15	.60	28	--	--	--	13.24	62	4.6	30
June	7.08	5	4.56	15	2.76	27	--	--	--	10.20	68	3.1	45
July	9.00	5	6.12	15	3.48	27	--	--	--	11.25	75	2.7	55
August	8.04	5	7.32	13	4.20	27	--	--	--	9.12	71	2.5	60
September	5.88	5	4.20	13	3.36	28	--	--	--	6.70	66	2.8	62
Total for water year	48.36		33.24		18.12		--		--	80.09			
Mean		5		14		25		--			55	3.2	55
Percentage	60.4		41.5		22.6					100			
1927													
October	3.48	6	3.24	16	1.92	26	0.48	37	2.76	5.54	55	2.2	48
November	1.08	5	1.20	14	2.16	24	.24	37	1.80	3.38	47	2.5	55
December	.60	5	.60	14	.60	23	.24	37	.96	1.45	32	3.2	68
1928													
January	.36	5	.12	13	.12	26	.12	37	1.20	2.02	34	2.6	2/ 33
February	.60	5	.36	14	.48	26	.36	36	1.68	2.90	38	3.6	2/ 44
March	1.08	6	.60	19	.36	25	.12	36	3.60	6.17	47	3.6	2/ 31
April	2.04	5	1.92	16	1.20	25	.84	37	5.16	8.62	52	5.1	3/ 29
May	4.80	5	3.84	16	2.64	25	1.56	37	5.28	8.12	62	3.3	3/ 39
June	8.88	6	5.40	17	2.16	26	.24	37	10.68	12.72	68	3.8	3/ 22
July	10.08	6	7.20	17	3.84	30	1.92	37	13.08	11.00	74	2.4	3/ 43
August	7.68	6	6.72	17	4.92	27	3.36	36	10.68	8.39	70	2.6	3/ 62
September	5.76	6	3.96	17	2.28	27	.60	37	7.80	7.34	64	2.3	4/ 43
Total for water year	46.44		35.16		22.68		10.08		64.68	77.65			
Mean		6		16		26		37			54	3.1	43
Percentage	59.8		45.3		29.2		13.0		83.3	100			

1/ Pan covered with ice during most of December and up to January 9, 1927.
2/ Mean of 5 p.m. readings.
3/ Mean of 5 p.m. readings for 24 days.
4/ Mean of 5 p.m. readings for 21 days.

OWENS VALLEY, CALIFORNIA

Closed Basins

Determination of the safe yield from closed rock basins is of considerable importance to sections of the Southwest where reliance is placed upon ground water as the principal source of supply. The recharge into the basin results from percolation from stream flow and from precipitation. The normal loss is from evaporation from water surfaces and moist areas, transpiration from vegetation, and surface and underflow from the basin. Underflow is generally a slow movement through a limited cross section of alluvial material and may sometimes be omitted from consideration.

Under natural conditions the recharge and discharge will be about evenly balanced over a long period of time. In times of drought the moist area of the basin will contract owing to lower ground water, and in periods of above-normal precipitation it will expand and there will be increased flow out of the basin.

Under natural conditions the discharge by evaporation and transpiration may be considered as the theoretical yield which may be pumped from the basin without greatly changing ground-water levels. In actual practice, however, the safe yield is less than the theoretical owing to loss of water by plant use in low areas and evaporation of moisture from the soil surface.

Measurement of the quantity of water which may be safely extracted from a basin of the closed alluvial type may be arrived at through estimating the natural losses resulting from evaporation and from consumptive use by natural vegetation. The ground-water discharge by plants applied to areas of known depth to water will provide a measure of quantities recoverable for other uses.

The pioneer work of this nature by Lee (16, 17) in determining the safe yield of water in the Owens Valley, Calif., prior to the construction of the Los Angeles aqueduct, opened the way for other investigations described elsewhere in this report.

Saltgrass.--Consumptive use of water by saltgrass grown artificially in large tanks in Owens Valley was determined for various depths to water table. Evaporation from water and from moist soil surfaces was likewise determined. As a result of preliminary investigations six tanks were used for growths of saltgrass sod. In these tanks ground water remained fairly constant at predetermined depths except where it was so near the surface that there was a high rate of consumptive use. In the tank in which the water table was theoretically about 1 foot below the surface, the grass withdrew water more rapidly than it could be supplied from the connected reservoir tank, so that the water table dropped from near the 1-foot level in the winter months to below 2 feet in the summer.

The investigation disclosed a diminishing rate of consumptive use as depth to ground water increased, in practically a straight-line ratio. Reference to Table 35 shows the monthly and annual use of water by saltgrass for various depths to water table, ranging from an annual maximum of 48.80 inches where average depth to water table was 18 inches to an annual minimum of 13.43 inches where average depth to water table was 59 inches. Observations in the Owens Valley showed little saltgrass in localities where ground water exceeded 8 feet, indicating inability of the roots to function beyond this depth. It does not follow that this is the limit in all saltgrass fields. The maximum depth observed in southern California was 11 feet in clay soil.

Estimated Water Supplies

As a result of this investigation, Lee made estimates of evaporation and consumptive use of water losses for 54.59 square miles of high ground-water alkali and saltgrass lands, as shown in Table 36, and converted the consumptive use into equivalent stream flow. The average rate of discharge for the 54.59 square miles where depth to water did not exceed 8 feet was equivalent to a continuous flow of 2 cubic feet per second per square mile.

TABLE 35

CONSUMPTIVE USE OF WATER BY SALTGRASS IN TANKS IN OWENS VALLEY, CALIF., 1911 (16)

Month	Water used	Average depth to water table	Water used	Average depth to water table	Water used	Average depth to water table	Water used	Average depth to water table	Water used	Average depth to water table
	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches	Inches
January	0.56	9	0.26	23	0.44	36	0.30	48	0.15	60
February	.70	10	.37	16	.22	30	.07	40	.04	59
March	1.52	12	.70	20	.18	33	.11	45	.07	59
April	3.70	18	3.22	24	1.70	36	1.15	48	.33	59
May	5.62	20	6.03	24	4.70	36	3.04	49	1.11	60
June	6.30	25	6.48	28	6.03	41	4.40	40	2.22	60
July	8.52	26	8.40	24	9.11	37	5.00	41	2.81	60
August	8.74	30	10.50	24	8.58	36	4.63	47	3.22	59
September	6.81	29	5.74	19	5.62	32	3.07	46	2.22	58
October	4.29	17	2.04	20	2.33	33	1.55	47	.85	58
November	1.48	7	.74	22	1.00	34	.85	48	.26	58
December	.56	7	.41	24	.30	35	.44	49	.15	60
Year	48.80	18	44.89	22	40.21	35	24.61	46	13.43	59

TABLE 36

ESTIMATED CONSUMPTIVE USE OF WATER BY SALTGRASS AND ALKALI LANDS IN THE OWENS VALLEY, CALIF., 1911. (BASED UPON TANK INVESTIGATIONS.) (16 and 17)

Enclosing contours	Area	Average depth to water table	Water used			Equivalent stream flow
			Summer	Winter	Total	
Feet	Square miles	Feet	Inches	Inches	Inches	Second-feet
3	11.89	2.5	36.5	5.2	41.7	36.6
3 to 4	17.66	3.5	29.6	4.0	33.6	43.7
4 to 8	25.04	5.5	15.6	.2	15.8	29.1
Totals	54.59					109.4

This was the theoretical quantity of water which might be recovered for beneficial use if ground-water levels were lowered through pumping to depths beyond reach of the vegetation, and was the basis for construction of the $25,000,000 Los Angeles aqueduct.

SANTA ANA RIVER VALLEY, CALIFORNIA

River-bottom vegetation.--An investigation was made by Troxell (33) of the United States Geological Survey, along a 16-mile stretch of the Santa Ana River between Riverside Narrows and the Prado gaging station, California. Much of this area has relatively high ground water which contributes to and increases the flow of the river along its course. The river-bottom area is narrow, probably averaging less than half a mile in width. Within this strip ground water over a considerable area is found at less than 5 feet from the surface.

The vegetation was typical river-bottom growth ranging from large cottonwood trees to grass meadows. A vegetative survey showed 4,040 acres of bottom lands of which 137 acres were cultivated and 210 acres consisted of water surface. Of the remainder, heavy tree-cover of the water-loving type grew on 1,519 acres, while there were 751 acres of meadow. Table 37 shows the vegetative classification. Typical vegetative growth along the Santa Ana River is depicted in Plate IV-B.

TABLE 37

CLASSIFICATION OF VEGETATIVE COVER, SANTA ANA RIVER, CALIF.

Type of vegetation	Acres	Per cent
Heavy tree cover	1519	37.6
Grass	751	18.6
Light brush cover	481	11.9
Heavy brush cover	356	8.8
Bare sand	251	6.2
Swamp plants, sedges, etc.	242	6.0
Water surface	210	5.2
Cultivated	137	3.4
Light tree cover	93	2.3
Totals	4040	100.0

Natural losses of the area, determined as a result of the investigation, were computed on the basis of various tests and studies rather than actual consumptive-use measurements. Evaporation losses, stream flow at several gaging stations, temperature, ground-water fluctuations, and changes in ground-water storage were recorded during the summers of 1931 and 1932. Consumptive use of water was likewise estimated by means of ground-water fluctuations beneath a group of willows. The method of analysis of ground-water fluctuations has been previously discussed.

Consumptive use during two summer seasons from July 1 to September 30 averaged 66 per cent of the evaporation from a Weather Bureau pan or approximately the amount of evaporation from a body of water of extent equal to the area involved. The loss of ground water due to transpiration and evaporation averaged nearly 20 per cent of the annual inflow into the area in a 2-year period.

The percentage of loss during the summer was even greater. It was during these months, when water had the highest value for irrigation, that the entire flow of the river was diverted into canals for irrigation of citrus lands at points below the Prado measurement. From May to September natural losses of the river-bottom vegetation were 55 per cent of all the water entering the channel of the Santa Ana River in a length of 16 miles. Troxell (33) estimates natural losses, combining transpiration and evaporation, as equal to approximately 50 inches in depth annually.

As a measure of evaporation and transpiration losses, Table 38 has been compiled to show the effect of natural losses on stream flow, total monthly loss in acre-feet, and monthly consumptive use of water in acre-inches per acre.

TABLE 38

ESTIMATED NATURAL LOSSES BETWEEN RIVERSIDE NARROWS AND PRADO GAGING STATION, SANTA ANA RIVER, CALIF., 1930-31 AND 1931-32 (33)

Month	1930-31 Mean daily	1930-31 Monthly	1930-31 Per acre	1931-32 Mean daily	1931-32 Monthly	1931-32 Per acre
	Second-feet	Acre-feet	Acre-inches	Second-feet	Acre-feet	Acre inches
October	19.8	1220	3.62	19.5	1200	3.56
November	19.3	1150	3.42	13.1	780	2.32
December	13.7	844	2.51	9.0	555	1.65
January	14.6	895	2.66	15.2	935	2.78
February	9.7	540	1.60	9.3	535	1.59
March	20.8	1280	3.80	18.7	1150	3.42
April	22.7	1350	4.00	23.2	1380	4.10
May	28.0	1720	5.11	27.0	1660	4.93
June	33.9	2020	6.00	34.1	2030	6.03
July	41.6	2560	7.60	36.1	2220	6.59
August	35.6	2190	6.50	37.7	2320	6.89
September	28.4	1690	5.02	26.2	1560	4.63
Year	24.0	17459	51.84	22.4	16325	48.49

The results obtained agree in general with tank measurements conducted by the Division of Irrigation 20 miles away near Santa Ana, a general summary of which is given in Table 13. Here saltgrass growing with water near the surface used 36 to 42 inches annually. Tules and cattails represented an adjusted loss of 73 inches, willows used 45 inches, and wire rush 84 inches.

When it is considered that 1,519 acres of the Prado bottom lands had a heavy tree cover credited with being of the water-loving type, an average consumptive use of 50 inches per acre cannot be considered excessive.

SUMMARIES OF CONSUMPTIVE USE DATA

Results obtained through investigations described earlier in this report are arranged for convenience in summaries to show meteorological data and depths of water used by saltgrass, tules, cattails, and other varieties of native vegetation. They are presented as Tables 39 to 41.

TABLE 39

MEAN ANNUAL OR SEASONAL CONSUMPTIVE USE OF WATER BY SALTGRASS GROWN IN TANKS, AND PERTINENT METEOROLOGICAL DATA

Locality	Period of record	Evaporation from Weather Bureau pan	Temperature: Mean maximum	Temperature: Mean minimum	Temperature: Mean	Precipitation	Wind	Relative humidity	Depth to water table	Water used	Reference
		Inches	°F.	°F.	°F.	Inches	Miles per hour	Per cent	Inches	Inches	Table No.
Santa Ana, Calif.	May 1929 - Apr. 1932	66.58	74	49	62	12.29	2.2	--	12	42.72	2, 3
	May 1929 - Apr. 1932	66.58	74	49	62	12.29	2.2	--	24	35.31	2, 3
	May 1929 - Apr. 1932	66.58	74	49	62	12.29	2.2	--	36	1/ 23.79	2, 3
	May 1929 - Apr. 1932	66.58	74	49	62	12.29	2.2	--	48	13.37	2, 3
Isleta, N. Mex.	June 1936 - May 1937	--	69	38	54	10.89	-	49	8	31.59	24
Mesilla Valley, N. Mex.	June 1936 - June 1937	79.80	74	43	59	--	-	51	14	39.81	25
Escalante Valley, Utah	May - Oct. 1927	72.65	--	--	62	4.47	4.6	40	26	17.88	31
	May - Oct. 1927	72.65	--	--	62	4.47	4.6	40	23	22.59	31
San Luis Valley, Colo.	June - Oct. 1927	21.36	--	--	--	--	-	--	6	17.04	32
	June - Oct. 1928	26.04	--	--	--	--	-	--	4	20.64	32
	June - Oct. 1930	23.04	--	--	--	--	-	--	4	22.44	32
	June - Oct. 1931	25.68	--	--	--	--	-	--	3	20.64	32
	June - Oct. 1927	21.36	--	--	--	--	-	--	15	17.88	32
	June - Oct. 1928	26.04	--	--	--	--	-	--	14	17.76	32
	June - Oct. 1930	23.04	--	--	--	--	-	--	10	18.36	32
	June - Oct. 1931	25.68	--	--	--	--	-	--	12	23.88	32
	June - Oct. 1927	21.36	--	--	--	--	-	--	25	13.32	32
	June - Oct. 1928	26.04	--	--	--	--	-	--	24	15.60	32
	June - Oct. 1930	23.04	--	--	--	--	-	--	23	16.20	32
	June - Oct. 1931	25.68	--	--	--	--	-	--	25	19.08	32
	June - Oct. 1931	25.68	--	--	--	--	-	--	38	16.92	32
Los Griegos, N. Mex.	Oct. 1926 - Sept. 1927	80.09	--	--	55	6.77	3.2	55	5	48.36	34
	Oct. 1926 - Sept. 1927	80.09	--	--	55	6.77	3.2	55	14	33.24	34
	Oct. 1926 - Sept. 1927	80.09	--	--	55	6.77	3.2	55	25	18.12	34
	Oct. 1927 - Sept. 1928	77.65	--	--	54	7.03	3.1	43	6	46.44	34
	Oct. 1927 - Sept. 1928	77.65	--	--	54	7.03	3.1	43	16	35.16	34
	Oct. 1927 - Sept. 1928	77.65	--	--	54	7.03	3.1	43	26	22.68	34
	Oct. 1927 - Sept. 1928	77.65	--	--	54	7.03	3.1	43	37	10.08	34
Owens Valley, Calif.	Jan. - Dec. 1911	--	--	--	58	5.56	-	--	18	48.80	35
	Jan. - Dec. 1911	--	--	--	58	5.56	-	--	22	44.89	35
	Jan. - Dec. 1911	--	--	--	58	5.56	-	--	35	40.21	35
	Jan. - Dec. 1911	--	--	--	58	5.56	-	--	46	24.61	35
	Jan. - Dec. 1911	--	--	--	58	5.56	-	--	59	13.43	35

1/ Record for 11 months only - May omitted.

TABLE 40

MEAN ANNUAL OR SEASONAL CONSUMPTIVE USE OF WATER BY TULES AND CATTAILS GROWING IN WATER IN TANKS, AND PERTINENT METEOROLOGICAL DATA

Type of vegetation	Locality	Period of record	Evaporation from Weather Bureau pan	Temperature: Mean maximum	Temperature: Mean minimum	Temperature: Mean	Precipitation	Wind Miles per hour	Water used	Reference
			Inches	°F.	°F.	°F.	Inches		Inches	Table No.
Tules	Santa Ana, Calif.	May 1930 - Apr. 1931	66.00	75	48	61	11.62	2.2	177.78	2, 8
		May 1931 - Apr. 1932	63.24	74	48	61	14.86	1.9	1/ 162.99	2, 8
		May 1930 - Apr. 1931	66.00	75	48	61	11.62	2.2	117.69	2, 8
		May 1931 - Apr. 1932	63.24	74	48	61	14.86	1.9	1/ 109.80	2, 8
		May 1930 - Apr. 1931	66.00	75	48	61	11.62	2.2	160.96	2, 8
		May 1931 - Apr. 1932	63.24	74	48	61	14.86	1.9	184.00	2, 8
Cattails	Santa Ana, Calif.	May 1930 - Apr. 1931	66.00	75	48	61	11.62	2.2	111.08	2, 8
		May 1931 - Apr. 1932	63.24	74	48	61	14.86	1.9	1/ 117.49	2, 8
Tules	San Bernardino, Calif.	May 1930 - Apr. 1931	61.59	80	44	62	14.29	1.3	2/ 170.88	6, 8
		May 1931 - Apr. 1932	65.13	--	--	--	20.18	1.4	2/ 141.93	6, 8
Tules 4/	Victorville, Calif.	Jan. 1931 - Dec. 1932	3/ 82.46	74	36	55	9.02	1.8	3/ 272.24	11
		Jan. 1931 - Dec. 1932	3/ 82.46	74	36	55	9.02	1.8	4/ 84.45	11
		Jan. 1931 - Dec. 1932	3/ 82.46	74	36	55	9.02	1.8	4/ 78.45	11
Tules 4/	Temescal Creek, Calif.	Oct. 1929 - May 1930	--	--	--	--	--	-	4/ 68.10	15
Tules	Clarksburg, Calif.	Jan. - Dec. 1930	--	--	--	--	--	-	221.64	19
Cattails	Clarksburg, Calif.	Jan. - Dec. 1930	--	--	--	--	--	-	198.39	19
Tules 4/	King Island, Calif.	Jan. - Dec. 1932	--	--	--	--	--	-	4/ 103.56	20
Cattails 4/	King Island, Calif.	Jan. - Dec. 1932	--	--	--	--	--	-	4/ 90.00	20
Tules 4/	Parma, Colo.	June - Nov. 1936	30.80	75	37	56	7.13	1.0	4/ 38.77	23
Cattails 4/	Isleta, N. Mex.	June 1936 - May 1937	--	69	38	54	10.89	-	4/ 97.29	24
Cattails 4/	Mesilla Valley, N. Mex.	Jan. - Dec. 1937	79.15	76	44	60	--	-	4/ 120.83	25
Tules	Mud Lake, Idaho	June 1921 - Sept. 1923	--	81	45	63	3.22	4.9	51.92	30
Tules	Los Griegos, N. Mex.	Oct. 1927 - Sept. 1928	77.65	--	--	54	--	3.1	64.68	34

1/ Record for 11 months only - December omitted.
2/ Record for 11 months only - February omitted.
3/ Exposed to desert conditions.
4/ Tanks set in swamp for protection by surrounding growth.

TABLE 41

MEAN ANNUAL OR SEASONAL CONSUMPTIVE USE OF WATER BY SOME NATIVE VEGETATION, AND PERTINENT METEOROLOGICAL DATA

Type of vegetation	Locality	Type of study	Period of record	Evaporation from Weather Bureau pan	Temperature Mean maximum	Temperature Mean minimum	Temperature Mean	Precipitation	Wind	Depth to water table	Water used	Reference
				Inches	°F.	°F.	°F.	Inches	Miles per hour	Inches	Inches	Table No.
Wire rush	Santa Ana, Calif.	Tank	Aug. 1930 - July 1931	67.56	76	49	63	11.11	2.1	24	1/78.93	2, 4
Willow	Santa Ana, Calif.	Tank	May 1930 - Apr. 1931	66.00	75	48	61	11.62	2.2	24	52.70	2, 5
Bermuda grass	San Bernardino, Calif.	Tank	May 1929 - Apr. 1931	66.54	80	44	62	13.02	1.6	24	34.37	6, 7
		Tank	May 1929 - Apr. 1931	66.54	80	44	62	13.02	1.6	36	28.19	6, 7
Native brush	San Bernardino, Calif.	Field	Oct. 1927 - Sept. 1930	2/	--	--	65	25.91	-	--	21.64	9
		Field	Oct. 1927 - Sept. 1929	2/	--	--	65	17.08	-	--	17.08	9
Native brush	Mascoy, Calif.	Field	Oct. 1927 - Sept. 1929	2/	--	--	65	17.72	-	--	17.58	9
	Claremont, Calif.	Field	Oct. 1927 - Sept. 1930	2/	--	--	62	14.65	-	--	14.65	9
	Palmer Canyon, Calif.	Field	Oct. 1929 - Sept. 1930	2/	--	--	62	19.58	-	--	19.58	9
Native grass and weeds	San Bernardino, Calif.	Field	Oct. 1928 - Sept. 1929	2/	--	--	--	10.75	-	--	10.00	10
	Cucamonga, Calif.	Field	Oct. 1927 - Sept. 1930	2/	--	--	--	15.43	-	--	14.68	10
	Anaheim, Calif.	Field	Oct. 1927 - Sept. 1928	2/	--	--	--	12.58	-	--	12.58	10
	Ontario, Calif.	Field	Oct. 1927 - Sept. 1928	2/	--	--	--	13.40	-	--	13.40	10
	Winavilla, Calif.	Field	Oct. 1927 - Sept. 1928	2/	--	--	--	13.35	-	--	13.35	10
Moist-land vegetation	Temescal Canyon, Calif.	Field	May (30 days) 1929	--	--	--	--	--	-	--	12.90	14
Canyon-bottom vegetation	Coldwater Canyon, Calif.	Field	July - Oct. 1932	--	--	--	--	--	-	--	47.00	17,18
Sedge grass	Fort Collins, Colo.	Tank	May - Oct. 1930	--	--	--	--	--	-	6	60.22	22
		Tank	May - Oct. 1930	--	--	--	--	--	-	12	46.19	22
		Tank	May - Oct. 1930	--	--	--	--	--	-	18	53.63	22
Rushes	Fort Collins, Colo.	Tank	July - Oct. 1931	--	--	--	--	--	-	--	52.59	22
Sunflowers	Fort Collins, Colo.	Tank	July - Oct. 1931	--	--	--	--	--	-	12	39.42	22
		Tank	July - Oct. 1931	--	--	--	--	--	-	18	51.18	22
Redroot	Fort Collins, Colo.	Tank	May - Sept. 1932	--	--	--	--	--	-	18	31.69	22
Meadow grass	Parma, Colo.	Tank	June - Nov. 1936	30.80	75	37	56	7.13	1.0	0	36.27	23
		Tank	June - Nov. 1936	30.80	75	37	56	7.13	1.0	8	30.50	23
Sedge	Isleta, N. Mex.	Tank	June 1936 - May 1937	--	69	38	54	10.89	-	+ 3	76.94	24
Willow	Isleta, N. Mex.	Tank	June 1936 - May 1937	--	69	38	54	10.89	-	13	30.49	24
Greasewood	Escalante Valley, Utah	Tank	May - Oct. 1926	72.83	--	--	62	2.28	4.6	35	11.84	31
		Tank	May - Oct. 1927	72.65	--	--	62	4.47	4.6	26	25.20	31
River-bottom brush	Prado, Calif.	Field	Oct. 1930 - Sept. 1931	78.40	--	--	--	10.82	2.3	--	51.84	38
		Field	Oct. 1931 - Sept. 1932	76.29	--	--	--	17.87	2.3	--	48.49	38

1/ Record for 11 months only - January omitted.
2/ No records of evaporation available as early as 1927 but amount should be about 65 inches annually.

CHAPTER 6

RELATION BETWEEN CONSUMPTIVE USE AND DEPTH TO WATER TABLE

In all investigations involving determination of consumptive use of water by grasses in tanks in which a predetermined water table has maintained, there has been evidence of a straight-line relation between depth to water table and amount of water consumed. To show this relation graphically for those experimental stations where sufficient data exist, Figure 15 has been prepared with saltgrass the medium of the comparison. The plotted points do not always agree with the average; occasionally one is obviously out of line, but enough records have been found consistent to permit a close representation.

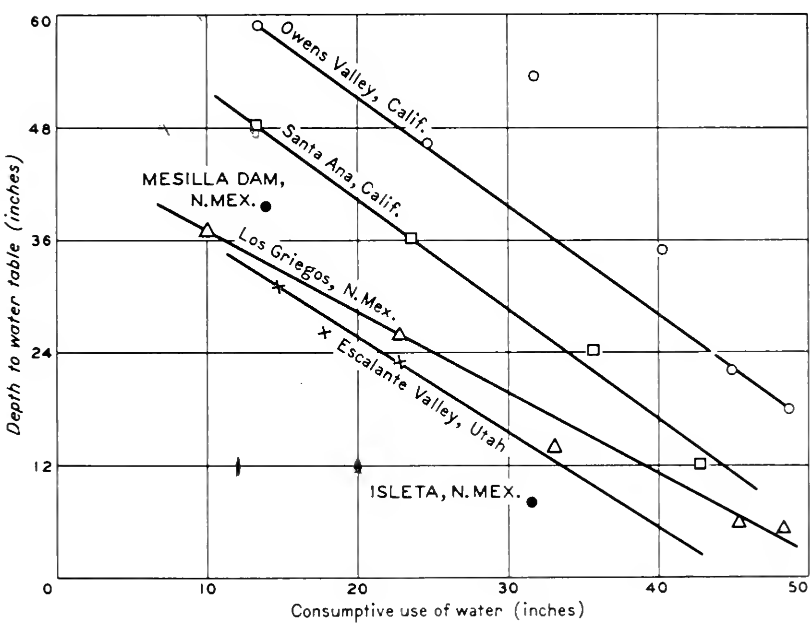


FIGURE 15.-- Relation of consumptive use of water by saltgrass in tanks to depth to water table.

In an analysis of this chart there are a number of factors to consider, the principal ones probably being climate and soil. Climate regulates consumptive use and length of growing season. The fineness of the soil determines the amount and limiting height of water held by capillarity above the water table and the probable depths to which saltgrass roots extend for moisture. As these investigations were conducted under conditions varying as to length of growing season and soil, the charts for each station would not be expected to show the same relation. However, in most cases they show the same general slope.

Where data are available, consumptive use is plotted for a 12-month period, although there is considerable variation as to the time each period begins. Thus the Owens Valley data begin in January and end in December; Santa Ana data are for May to April; Los Griegos from October to September; and Escalante Valley, Utah, from May to October. These differences are deemed unimportant, however, as long as a complete cycle of seasons is included. In his report of the Owens Valley study, Lee (16, 17) divided the year into summer and winter seasons and plotted the consumptive use-depth relation for each period separately. Without discussing the benefits of such division, it is apparent that the two methods disagree when used to indicate the limiting depth to which saltgrass roots appear to function. This has been given for Owens Valley as 7.7 feet for the period April 1 to September 30, and 7.0 feet from October 1 to March 31. If consumptive-use data had been plotted for the entire year, however, the limiting depth would appear to be somewhat less.

In comparison, the limiting depth for a 12-month period at Santa Ana appears to be 5.3 feet for fine sandy loam soil, and 3.8 feet at Los Griegos for clay loam soil. Consumptive-use data for Owens Valley and Santa Ana plot as parallel lines, yet the Owens Valley curve represents approximately 10 inches greater use of water for any given depth to water table.

Los Griegos curve also indicates a straight-line relation although it lies lower on the chart and departs from the parallelism of the previous curves. It indicates nearly 9 inches less consumptive use than at Santa Ana for a 24-inch depth to water and 12.5 inches less as the water table lowers to 36 inches.

It is evident from these curves that for given depths to water table, saltgrass in the Owens Valley has a greater consumptive use than at other places of investigation, with decreasing amounts at Santa Ana, Los Griegos, and in Escalante Valley.

CHAPTER 7

RELATION OF CONSUMPTIVE USE TO EVAPORATION

Throughout this report the relation between consumptive use and evaporation, first mentioned in the Introduction, has been stressed as a basis of estimating water used by plants when only evaporation is known. The relation varies month by month, reaching a maximum in summer and a minimum during the cooler months of the growing season. Thus, the relation for any period is an average which may have a considerable departure from the value for any single month. For the more water-loving species summer consumptive use exceeds evaporation, but for many dry-land plants it is less. Since consumptive use becomes less with increased depth to ground water, its relation to evaporation is partly governed by the position of the water table.

Few attempts have been made to determine, by experiment, the consumptive use-evaporation relation. The Victorville, Calif. investigation with tules, previously described, is probably the most significant and perhaps the only experiment undertaken directly for this purpose (4). The results indicated, for the particular region in which the investigation was carried on, that annual use of water by tules was equal to 95 per cent of the annual evaporation from a standard Weather Bureau pan with monthly values ranging from 57 to 122 per cent. For other areas in the same climatic territory where evaporation records are available, use of water by tules may be computed as a percentage of the evaporation. At Los Griegos, the annual use of water by tules was as low as 83 per cent of the evaporation.

A graphical comparison of monthly use of water by tules growing under natural conditions and evaporation from a Weather Bureau pan, in four southwestern localities, is shown in Figure 16. Table 42 gives the percentage relation for tules by months at various locations.

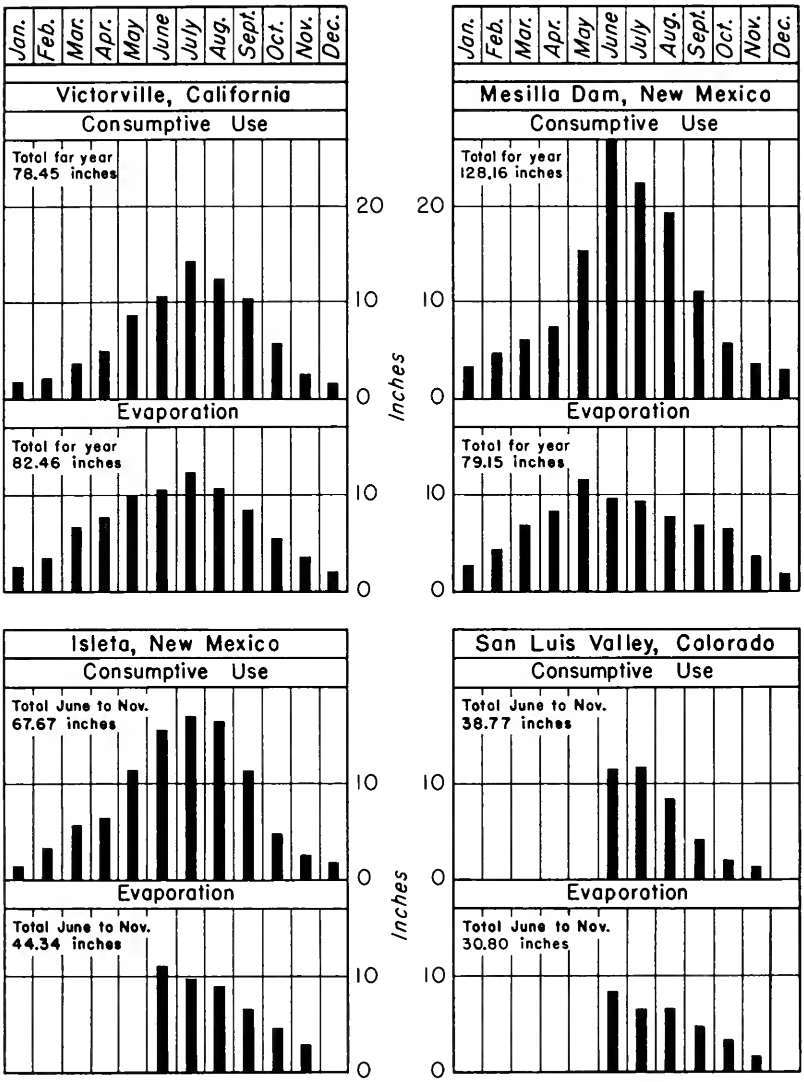


FIGURE 16.-- Comparison of consumptive use of water by tules in swamps and evaporation from a Weather Bureau pan.

TABLE 42

RELATION OF CONSUMPTIVE USE OF WATER BY TULES AND CATTAILS IN THEIR NATURAL ENVIRONMENT TO EVAPORATION FROM AN ADJACENT WEATHER BUREAU PAN

Month	Victorville, Calif.	King Island, Calif.		Parma, Colo.	Los Griegos, N. Mex.	Isleta, N. Mex.	Mesilla Dam, N. Mex. 1/
	Tules	Tules	Cattails	Tules	Tules	Cattails	Cattails
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
January	72	--	--	--	59	--	96
February	61	--	--	--	58	--	100
March	57	--	--	--	58	--	94
April	65	--	--	--	60	--	105
May	89	--	--	--	65	--	138
June	104	146	116	139	84	171	249
July	116	169	168	178	119	167	217
August	115	120	123	126	127	155	212
September	122	133	127	87	106	140	153
October	108	174	124	62	50	104	86
November	69	--	--	--	53	--	93
December	72	--	--	--	66	--	138
Year 2/	95	--	--	--	83	--	152
June to October, inclusive 2/	113	147	133	128	100	154	192

1/ Average for two tanks.
2/ Based upon total values.

In considering other native plants a high percentage of consumptive use to evaporation results from a high water table. This is demonstrated for saltgrass as shown in Table 43. Also, a comparison of consumptive use of water by saltgrass and evaporation is shown for four localities in Figure 17. Table 44 gives consumptive use-evaporation percentages for Bermuda grass, wire rush, willows, sedge, native meadow, and greasewood grown in tanks under different ground-water conditions.

Plates V to VIII show typical examples of different kinds of native vegetation growing under various soil, ground water, and other conditions and environments.

TABLE 43

RELATION OF CONSUMPTIVE USE OF WATER BY SALTGRASS IN TANKS TO EVAPORATION FROM AN ADJACENT WEATHER BUREAU PAN

Month	Santa Ana, Calif.				Garnett, San Luis Valley, Colo.				Los Griegos, N. Mex.				Isleta, N. Mex.	Mesilla Dam, N. Mex.	Escalante Valley, Utah	
	Average depth to water table, in inches															
	12	24	36	48	4	12	25	38	6	16	26	37	8	14	26	31
	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent
January	57	32	87	14	--	--	--	--	18	6	6	6	--	16	--	--
February	58	32	67	12	--	--	--	--	21	12	16	12	--	26	--	--
March	44	31	64	10	--	--	--	--	18	10	6	2	--	16	--	--
April	62	48	57	17	--	--	--	--	24	22	14	10	--	24	--	--
May	54	29	--	4	--	--	--	--	59	47	32	19	--	18	--	--
June	72	53	22	10	108	90	60	57	70	42	17	2	49	39	25	12
July	85	63	28	27	102	106	89	72	92	66	35	18	60	87	33	14
August	81	62	27	33	113	111	86	75	92	80	59	40	62	87	23	43
September	72	63	29	30	76	88	82	76	78	54	31	8	58	93	24	26
October	64	58	32	28	71	50	46	46	63	58	35	9	38	77	18	8
November	63	51	59	15	--	--	--	--	32	36	64	7	--	40	--	--
December	72	48	97	18	--	--	--	--	41	41	41	16	--	38	--	--
Year 1/	68	50	2/ 42	19	--	--	--	--	60	45	29	13	--	50	--	--
June to October, inclusive 1/	76	60	27	25	97	93	74	66	80	59	34	15	55	76	25	22

1/ Based upon total values.
2/ For 11 months.

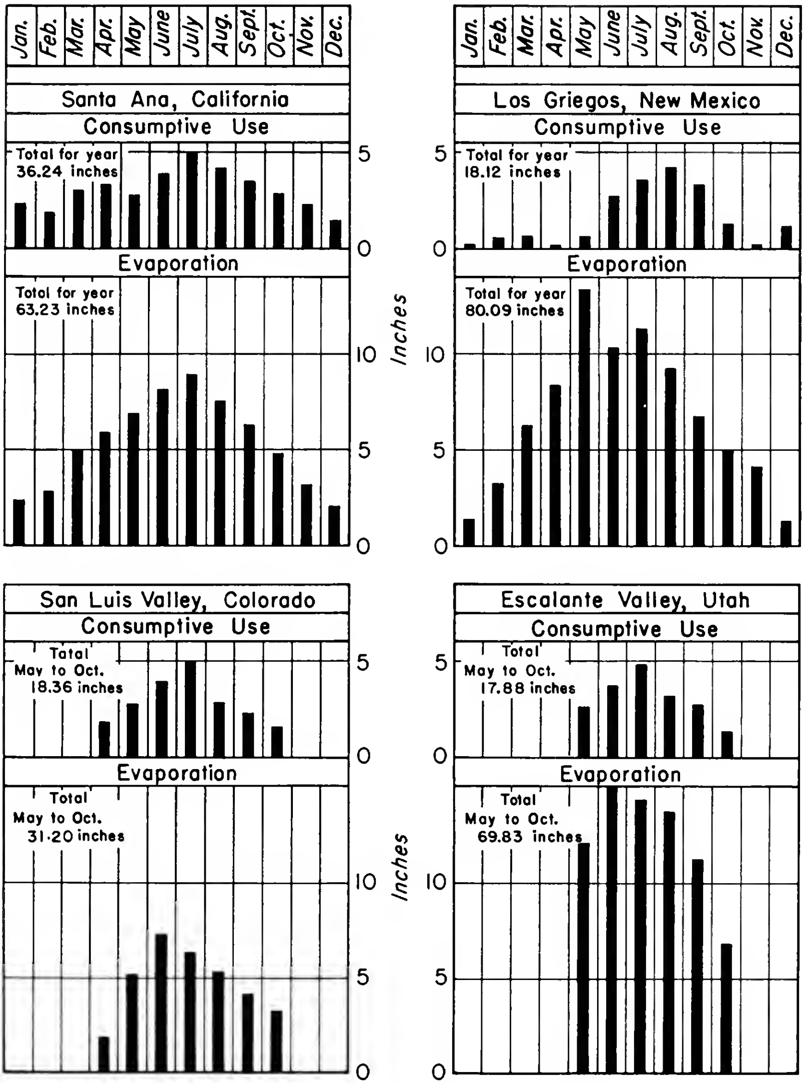


FIGURE 17.-- Comparison of consumptive use of water by saltgrass where approximate depth to ground water is 24 inches, and evaporation from a Weather Bureau pan.

TABLE 44

RELATION OF CONSUMPTIVE USE OF WATER BY BERMUDA GRASS, WIRE RUSH, WILLOW, SEDGE, NATIVE MEADOW GRASS, AND GREASEWOOD, IN TANKS, TO EVAPORATION FROM AN ADJACENT WEATHER BUREAU PAN

	San Bernardino, Calif.		Santa Ana, Calif.		Isleta, N. Mex.		Parma, Colo.	Escalante Valley, Utah
	Bermuda grass 1/		Wire rush	Willow	Willow	Sedge 1/	Native meadow 2/	Grease-wood
	Average depth to water table, in inches							
Month	24	36	24	24	11	In water	8	25
	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent	Per cent
January	17	28	92	--	--	--	--	--
February	16	20	108	73	--	--	--	--
March	27	15	117	68	--	--	--	--
April	52	41	129	95	--	--	--	--
May	59	42	125	69	--	--	--	--
June	71	62	128	72	34	126	82	32
July	72	61	154	86	42	140	137	46
August	71	56	170	98	53	164	120	43
September	63	54	173	114	63	126	145	40
October	39	27	176	98	64	102	61	27
November	29	25	157	83	--	--	--	--
December	24	20	213	64	--	--	--	--
Year 3/	52	42	145	--	--	--	--	--
June to October, inclusive 3/	65	54	158	92	48	134	110	39

1/ Average of a 2 years' record.
2/ Average for two tanks.
3/ Based upon total values.

PLATE V

A. Dense growth of bank vegetation using water from an irrigation canal in Imperial Valley, Calif.

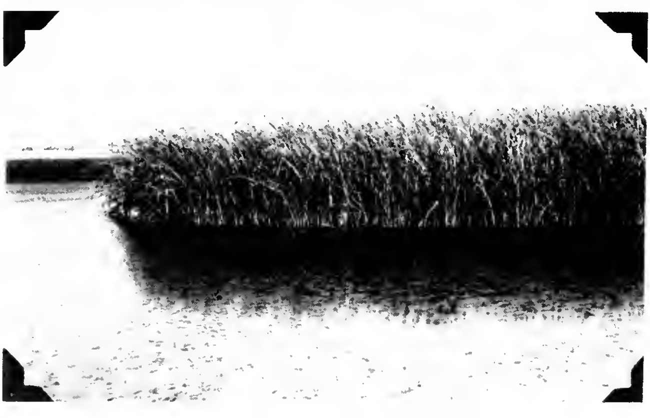
B. Wild sunflower plant in California. Sunflowers are remarkably thrifty for long periods in very dry places.

C. Mesquite in the Coachella Valley, Calif., illustrating size of bush. This is found in areas where ground water is within reach of root systems. The size is an indication of depth to water table; high ground water results in tall, dense growth.

PLATE VI

A. Tall, dense cottonwood and willow growth along dry bed of San Luis Rey River, San Diego County, Calif. Much of the surface flow sinks into the gravels and is absorbed by vegetation.

B. Typical swamp area. Tules use large amounts of water.



C. Tules 6 to 8 feet high, growing in open water.

PLATE VII

A. Creosote bush and other vegetation in the desert, illustrating the habit of wide spacing between plants owing to the scarcity of moisture in the soil.

B. Eucalyptus grove on eroded bank, illustrating depth of rainfall penetration at about 7 feet as indicated by dark shadowy line below the light colored gravel strata. Note tree roots extending through the gravel into finer soil.

PLATE VIII

A. Chapparal, illustrating extensive root system exposed by flood.

B. Johnson grass (Sorghum halepense) growing in young orange grove, Calif., where soil was unusually moist.

CHAPTER 8

SUMMARY

Precipitation in arid regions is largely consumed by the native vegetation, and desert plants are adapted to an extreme economy in their use of water. As precipitation increases, the dominant type of growth changes in response to the augmented water supply. In areas of high ground water are found those plants which send their roots to the water table or into the adjoining capillary fringe. Also, there are plants which live with their roots in water and are responsible for a considerable draft upon the general water supply of the region.

In closed basins having little or no outflow, the consumptive use of the native vegetation growing therein is a practical measure of the amount of underground water recoverable from the basin for other uses. This may be determined by study of native vegetation, the position of the water table, and the quantity of water each species uses annually.

Investigations of use of water by various species of native vegetation have been made under different conditions of climate and depth to water table. The species studied have been limited principally to grasses, small shrubs and water-loving plants adapted to growth in metal tanks. The difficulty of growing larger vegetation in tanks is obvious.

Depth to water table is an important factor in the quantities of water consumed by vegetation. A high water table results in increased growth and consumptive use. As depth to water becomes greater, vegetation uses decreasing amounts in practically a straight-line ratio, provided the soil within the root zone is reasonably homogeneous. As the limiting depth at which it is possible for the roots to function is approached, vegetation typical of the area becomes progressively smaller and scarcer and gradually changes from one dominant type to another.

There are four general methods by which consumptive use of water by native vegetation may be determined: tank studies, soil-moisture investigations, stream-flow studies and water-table fluctuations. Tank data on use of water by native vegetation are available for several kinds of native vegetation in western States.

The most satisfactory method of water-table control in tanks appears to be that using the Mariotte supply tank as developed by the Division of Irrigation. This equipment is automatic and permits regular observations of water consumed by tank growth.

Annual consumptive use of water by saltgrass varies from more than 40 inches when the water table is 12 inches from the surface to as little as 10 inches when depth to water exceeds 3 to 4 feet. Other factors than depth to water table also influence these values, as is evident from the considerable differences in water used for the same depth to water table at different locations in western States where investigations have been made.

Wire rush appears to be a heavy user of water when a plentiful supply is available, but the number of investigations with this plant are insufficient for conclusive data.

Willows usually grow where the roots extend into the groundwater region, and they appear to use the approximate equivalent of evaporation from a water surface. Investigations with willows are limited, and this relation may vary for different localities.

Tules and cattails grow with their roots in water and consume greater quantities than other varieties. Sedges compare in consumptive use with other aquatic growth.

The natural growth of brush and weeds found on outwash slopes in arid and semiarid regions depends entirely upon precipitation for moisture. As this varies widely from season to season it is evident that there is no definite water requirement for such vegetation. In years of light precipitation all moisture entering the ground is consumed within the root zone, but as precipitation increases to proportions unnecessary for plant life, moisture passes beyond the roots as a contribution to the underground-water supply.

Weeds growing along ditch banks or in irrigated fields are consumers of large quantities of water. Many weeds are adapted to the use of a limited water supply, but if water is abundant they use increased amounts. Canal bank growth, such as willows, alders, and tules, are also consumers of large quantities of water, but is sometimes useful as a means of canal bank protection.

Vegetation grown in tanks must be surrounded by similar growth if consumptive-use measurements correctly represent losses in open fields. Unnatural exposure of tank growth to sun and wind results in increased losses that may lead to erroneous results. Too often this very important factor has been overlooked in extending tank data to field losses. In considering reduction factors to be applied to data obtained from fully exposed tanks, it seems probable that there is little difference in consumptive use between tank growth and field growth of the various native grasses. Investigations have shown, however, that actual swamp consumptive use of water by tules and cattails lies between 40 and 50 per cent of the consumptive use as indicated by growth in tanks outside their natural environment. Factors for other species probably are found between 50 and 100 per cent.

Riparian growth along streams, as willows, alders, sycamores, and cottonwoods, obtain moisture from underground water traveling toward stream channels or from waters percolating from the stream bed. They have first use of the water supply in the stream. Regardless of the showing of a considerable use of water by vegetation and an inadequate water supply for much of the western area, it is not the purpose of this report to advocate destruction of vegetation.

Daily water-table fluctuations in areas of high ground water are usually the result of consumptive use by the overlying vegetation. This is evident from the fact that fluctuations increase as the plants approach their maximum growth and decrease as they mature. Fluctuations respond to those factors of weather which cause greater or less transpiration.

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STATE OF CALIFORNIA

When the Department of Public Works was created in July, 1921, the State Water Commission was succeeded by the Division of Water Rights, and the Department of Engineering was succeeded by the Division of Engineering and Irrigation in all duties except those pertaining to State Architect. Both the Division of Water Rights and the Division of Engineering and Irrigation functioned until August, 1929, when they were consolidated to form the Division of Water Resources.

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*Biennial Report, State Water Commission, December 1, 1916, to September 1, 1918.
*Biennial Report, State Water Commission, September 1, 1918, to September 1, 1920.

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*Bulletin No. 4—Proceedings Second Sacramento-San Joaquin River Problems Conference, and Water Supervisors' Report, 1924.
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*Bulletin No. 2—Irrigation Districts in California, 1887-1915.
Bulletin No. 3—Investigations of Economic Duty of Water for Alfalfa in Sacramento Valley, California, 1915.
*Bulletin No. 4—Preliminary Report on Conservation and Control of Flood Waters in Coachella Valley, California, 1917.
*Bulletin No. 5—Report on the Utilization of Mojave River for Irrigation in Victor Valley, California, 1918.
*Bulletin No. 6—California Irrigation District Laws, 1919 (now obsolete).
Bulletin No. 7—Use of Water from Kings River, California, 1918.
*Bulletin No. 8—Flood Problems of the Calaveras River, 1919.
Bulletin No. 9—Water Resources of Kern River and Adjacent Streams and Their Utilization, 1920.
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*Biennial Report, Department of Engineering, 1910-1912.
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*Biennial Report, Department of Engineering, 1916-1918.
*Biennial Report, Department of Engineering, 1918-1920.

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DIVISION OF WATER RESOURCES

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*Bulletin No. 1—California Irrigation District Laws, 1921 (now obsolete).
*Bulletin No. 2—Formation of Irrigation Districts, Issuance of Bonds, etc., 1922.
Bulletin No. 3—Water Resources of Tulare County and Their Utilization, 1922.
Bulletin No. 4—Water Resources of California, 1923.
Bulletin No. 5—Flow in California Streams, 1923.
Bulletin No. 6—Irrigation Requirements of California Lands, 1923.
*Bulletin No. 7—California Irrigation District Laws, 1923 (now obsolete).
*Bulletin No. 8—Cost of Water to Irrigators in California, 1925.
Bulletin No. 9—Supplemental Report on Water Resources of California, 1925.
*Bulletin No. 10—California Irrigation District Laws, 1925 (now obsolete).
Bulletin No. 11—Ground Water Resources of Southern San Joaquin Valley, 1927.
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Bulletin No. 13—The Development of the Upper Sacramento River, containing U. S. R. S. Cooperative Report on Iron Canyon Project, 1927.
Bulletin No. 14—The Control of Floods by Reservoirs, 1928.
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Bulletin No. 20—Kennett Reservoir Development, an Analysis of Methods and Extent of Financing by Electric Power Revenue, 1929.
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Bulletin No. 24—A Proposed Major Development on American River, 1929.
Bulletin No. 25—Report to Legislature of 1931 on State Water Plan, 1930.
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