SDA FOREST SERVICE RESEARCH PAPER RM—68

MARCH 1971

characteristics and processes of soil piping in gullies

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Abstract

Soil piping processes and soil development were studied as a result of combined pipe and gully actions. Soils from gully side slopes with and without pipes showed a highly significant difference in exchangeable sodium percentage (ESP). Piping soils had a layer permeability 2 to 12 percent of that of soils without pipes. Both soils were fine textured. The interior of one soil pipe was thoroughly inspected, surveyed, and photographed from inlet to outlet. Based on the survey, and chemical and mechanical analyses, it is proposed that soil pipes on the Alkali Creek watershed developed mainly from soil cracks. Other causes such as rodent holes or dead root canals are presumed possible, but were not verified. Gullies, high exchangeable sodium percentage, low gypsum content, and fine-textured soils with montmorillonite clay appear to be prerequisites to the formation of soil pipes on the study area.

ESP was significantly higher in piping soils in place than in those fallen from the gully side slopes. ESP decreased also with increasing time since fall. Natural reclamation of the fallen soils led to processes initiating gully stabilization.

KEY WORDS: Gullies, soil erosion, soil permeability, soil stabilization.

USDA Forest Service
Research Paper RM-68

March 1971

Characteristics and Processes of Soil Piping in Gullies[1]

by

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[1]Part of this study was included in a dissertation submitted in partial fulfillment of the requirements for the degree of Ph.D. to Colorado State University, June 1967.

This study was made in cooperation with the Rifle Ranger District of the White River National Forest, Glenwood Springs, and Region 2 Office of the U. S. Forest Service, Denver, Colorado.

Helpful suggestions on chemical analyses were given by Drs. Donal D. Johnson and Willard R. Schmehl, Professors of Soils, Colorado State University.

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Burchard H. Heede

Present Knowledge

The piping of soils has been recognized on different continents for several decades. This type of erosion, in which the soil is carried away by water running through holes in the ground, has also been called pseudokarst, tunneling erosion, and pothole erosion.

A thorough knowledge of the processes involved in soil piping is necessary for successful and economical control projects, especially in the Southwest where soil pipes occur frequently. This paper presents a comparison of soils from sites with and without pipes. On the basis of chemical and mechanical analyses, permeability tests, topographic surveys, and thorough visual inspections, some of the older hypotheses on soil piping are verified, others rejected. Soil piping was observed on the study area for more than 4 consecutive years. During this time a complete topographic survey of a soil pipe, pictures of its interior, and analyses of soil and sediment samples from the interior and from flows through the pipe were made. These observations indicated that piping may not only lead to a karstlike topography along gullies, but may indeed help induce reclamation of the soils. Based on this hypothesis, a second study was initiated to show the influence of piping on soil reclamation in gullies.

Literature

The literature on soil piping and hypotheses on the piping processes were thoroughly reviewed by Brown (1961) and therefore, need not be repeated here. Where pertinent, older investigations will be referred to in the text. Reviewed here will be only that literature which relates soil characteristics to soil piping.

The role of sodium in the processes of dispersion and flocculation of soils was studied some 40 years ago on the high plateau of Colorado, Utah, and Wyoming, and in the sediment load of Colorado River water (Breazeale 1926). This study demonstrated that erosion hazards may be drastically increased by the presence of sodium, which increases the dispersibility of soils. In recent field experiments on the erodibility of some South African soils, Hiemstra (1965) could distinguish between relatively stable (less erodible) and unstable soils by their sodium content. While stable soils contained extractable sodium cations of 0.1 meq./100g., unstable soils had between 0.2 and 1.2 meq./100g.

The influence of sodium on the dispersion and permeability of soils has been studied by several researchers. They demonstrated that the type of sodium compound as well as the level of saturation of the soil influence soil permeability. Thus, Ramdas and Mallik (1947) found in India that a 5 percent solution of sodium chloride and a 1 percent solution of sodium carbonate each increased permeability four times. In England, Quirk and Schofield (1955) saturated soils with sodium ions by passing molar sodium chloride solution through them for 12 hours. When this solution was replaced by more dilute solutions of sodium chloride, in each case permeability decreased with time throughout the observation period of 5 hours. This decrease was thought to result from swelling, and then deflocculation.

In canal sealing studies, clays with high sodium content were found to produce a desirable high degree of dispersion of the channel soils (Dirmeyer and Skinner 1964). Swelling and dispersion, along with other processes, are associated with the structural breakdown of soils. Their combined effects can be expressed in an air-water permeability ratio.

This ratio was introduced by Reeve (1953) as an expression of the stability of soil structure, who found that the permeability ratio increased exponentially with increasing exchangeable sodium (Reeve et al. 1954). When the ratio was tested later on seven different soils, it was shown again that exchangeable sodium has a marked effect on the stability of soil structure (Brooks and Reeve 1959).

The importance of sodium in soil piping processes has been considered by only a few investigators (Brown 1961, Fletcher et al. 1954). These authors advanced the hypothesis that sodium is a contributing factor to the severity of piping, but not a necessary constituent for the occurrence of pipes. They were led to the second thought by the range in values of sodium at locations where piping is prevalent. Parker and Jenne (1967), without presenting data, state that high percentages of exchangeable sodium can be responsible for the occurrence of pipes, but that large amounts are not prerequisite in all cases, and conclude that such cases of piping may occur "due to subsidence, loess, and possibly other low-density previously unsettled earth materials." Nearly all investigators stated that the processes of soil piping lead to a widening of gullies. Leopold et al. (1964) reported soil pipes to be an important element in the headward extension of discontinuous gullies. Where pipes were located up-valley from the head cut, the up-valley progression of the head cut was accelerated by the piping processes. Since, as these authors observed in New Mexico, the pipes often extend into the ungullied alluvium for distances of several hundred feet, tributary gullies will form by the collapse of tunnels extending from the gully side walls.

Natural reclamation of soils was first reported from the Solonetz regions of southern Russia (Vilenskii 1957) where, due to increases in steppe or meadow vegetation, the soils were enriched in organic matter and calcium. This enrichment, in turn, led to a gradual transformation toward chernozemic and chestnut soils.

Apparently absent from the literature on piping are references to (a) surveys of soil pipe geometry, both external and internal, (b) analyses of soils from pipe walls, (c) local variations in soil characteristics as related to presence or absence of pipes, (d) frequency and magnitude of pipe flows, (e) character of sediment yielded from pipes, (f) chronology of pipes, and (g) influence of pipes on soil development.

The Study

Study Area

The study area is located on the upper Alkali Creek watershed of the Rifle Ranger District, White River National Forest, 20 miles south of the town of Silt, Colorado. The area is part of the Uinta Basin of the Colorado Plateau Province, and represents a dissected plateau with strong relief. Gullies carry water only during spring snowmelt and intense summer storms. Rocks of the watershed are tertiary sandstones and shales of the Wasatch formation, which consists chiefly of variegated clay shale and irregular, crudely bedded sandstone (Fox and Nishimura 1957). In general, the soils are predominantly formed from fine-textured, loose, unconsolidated shales with an admixture of sand from beds of sandstone. Although the regolith is generally rather thin, alluvial deposits in excess of 6-foot depth are found on the main valley bottom. Soil piping is most extensive here. The area is representative of the oakbrush-sagebrush grasslands of the Western Slope of the Rocky Mountains in Colorado. Precipitation, the only climatic factor measured on the study area, averaged 18.5 inches in 1962 and 1963.

Study Method

The study consisted of two parts. The first, an investigation of soil piping processes themselves, lasted from 1962 to 1967. The second part, concerned with soil development as a result of combined piping and gully processes, was terminated in 1968.

Processes

For the study of piping processes, three soil pipes were selected whose inlets and outlets could be clearly identified. For two of the pipes, catchment devices were designed to collect the water and sediment leaving the pipes (fig. 1). These devices consisted of a large, flat funnel connected to two 55-gallon drums. The upper side of the funnel which could be removed for cleaning, prevented rain or snow from entering the system. The lower edge of the funnel was placed flush with the bottom of the soil pipe without changing the general charac-

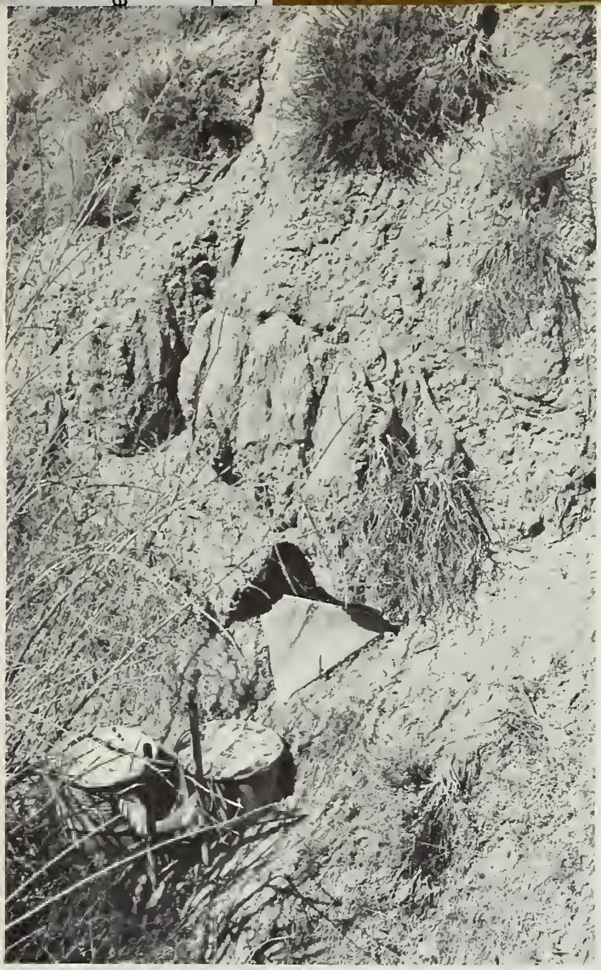


Figure 1.--Collector funnel with catchment barrels installed at outlet of soil pipe 1, which is 3 feet above gully bottom.

teristics of the outlet. When an observer was present, flow was collected with an ordinary milk bottle. Soil samples were collected from gully side slopes with and without soil pipes. The side slopes were sampled at different elevations to demonstrate development of soil characteristics with depth.

The full interior length of a pipe was surveyed and photographed, and soil samples were taken from interior walls. To minimize danger, it was surveyed in autumn when the soils were dry. The narrowness of pipes on Alkali Creek made the survey a difficult one-man task (fig. 2). Thirteen samples

Figure 2.--Floor plan and section of soil pipe 1. The cross section of the gully shows the layout of the pipe relative to the channel. Note that the height of the pipe is much larger than its width, and that the pipe outlet is above the gully bottom.

were removed from the interior of the pipe. All soil and sediment samples were subjected to chemical and mechanical analyses, and permeability tests. For the latter, fragmented samples were used (Dirmeyer and Skinner 1964). The Soils Testing Laboratory at Colorado State University chemically and mechanically analyzed the soils according to the procedures outlined in USDA Agriculture Handbook 60 (U. S. Salinity Laboratory Staff 1954). Sediment concentrations were calculated for the pipe-flow samples.

Soil Development

For the investigation on reclamation of soils, samples were collected from each of four locations with a piping side slope and soils fallen from these slopes. The fallen material was categorized into soil blocks, small colluvial cones, and soils fallen on the side slope opposite from the piping bank.

Soil blocks were formerly parts of Solonetz columns that had broken from the piping slopes. These blocks (each 1 cubic foot or more in volume) were almost intact, although they showed small seams and cracks caused by the impact of the drop. The time since fall was known to have been not much greater than 3 years.

The small colluvial cones consisted of soil particles ranging in diameter from sand to about 1 inch. The cones were formed below small chutes on the piping slopes by deposition of soil particles that had been moved by gravity, frost action, animals, and other forces.

Soils fallen on opposite side slopes contributed the largest volumes—as much as 15 cubic yards.

The original soil columns of the alluvial soils were completely shattered when dropped or, in one case, destroyed by erosion a few years later. Normally, vegetation grew on these dumps. To some extent, the loose material below and opposite

Figure 3.--Inlet of soil pipe 1 on sliding surface of gully side slope (see fig. 2). Length of ruler is 5 inches. Note the crusting and sugaring of the clayey alkaline soil.

from the piping slopes represented different degrees of both destruction of the original soil structure and mixing of the piping soils. The material fallen from the wall opposite the piping slopes showed the strongest degree of aggregate destruction and mixing. The material from colluvial cones showed less change. Soil blocks were little changed. For the purpose of this study, piping side slopes were classed as intact.

Results

Layout of a Representative Soil Pipe

Soil pipe No. 1 was selected for detailed surveys because its size allowed physical inspection of the pipe interior, and additional data on soils, sediment, and flows were available. The pipe was also regarded as representative of many others on the area. The pipe did not follow a straight line from the pipe inlet to the gully (fig. 2). Height within the pipe was two to six times greater than width. This ratio is typical for pipes investigated in the study area. Also typical is the pipe gradient from inlet to outlet. The pipe begins with a nearly vertical segment, then enters into a 45-degree reach, and ends with a gentle gradient of a few degrees. The inlet of the pipe was located outside the gully until the side slope slid into the gully, about 3 years before the survey. The cause of the slide is unknown. The inlet is now on the gully side slope (fig. 3) 3 feet above gully bottom. Not one pipe was found on the area with its outlet close to channel floor elevation. This pipe is located entirely in alluvial soil with very pronounced strata (fig. 4).

Figure 4.--Interior of soil pipe 1, 12.5 feet from the pipe outlet. Pronounced strata of the alluvial soils are typical for this pipe. The 6-inch long ruler is on the floor of the pipe. Roots in the lower layers are from sagebrush growing on the gully side slope.

Characteristics of Piping and Nonpiping Soils

Piping soils had a significantly higher exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) than nonpiping soils (table 1). ESP is the degree of saturation of the soil exchange complex with sodium, and may be calculated by the formula:

$$ESP = \frac{\text{Exchangeable sodium (meq./100 g. soil)}}{\text{Cation exchange capacity (meq./100 g. soil)}} \times 100$$

SAR is calculated from:

$$SAR = \frac{Na^{+}}{\sqrt{(Ca^{++} + Mg^{++})/2}}$$

where the ionic concentrations of the saturation extract are expressed in terms of milliequivalents per liter. While all exchangeable sodium percentages for nonpiping gully side slopes were less than 1.0, those for the piping slopes were greater than 1.0 and averaged 12.0. Susceptible soils also differed from nonpiping soils in pH and gypsum content. Because the higher pH of piping soils is due to their higher ESP's, pH must be regarded as a dependent variable. The highly significant difference in gypsum appears not to be meaningful because the amount of gypsum is too low to exert a tangible flocculating influence on the predominantly sodium-influenced soil. Larger segments of the gullies were sampled intensively for gypsum, but no greater concentrations were found. Calcium carbonate was present, but under the prevailing conditions was probably not effective because of its small amounts and low solubility.

Piping soils had a statistically greater conductivity than stable soils, but the conductivity, a measure of soluble salt in the soil, was not high enough in the majority of these soils for them to be considered saline. With the exception of one sample, analyses of the cations present in the saturation extract of the piping soils showed a great excess of soluble sodium over calcium and magnesium. Sodium ion concentration averaged 12.2 milliequivalents (meq.) per liter (standard error of the mean 2.6) while mean calcium plus magnesium ion concentration was 1.4 meq./l. (standard error 0.2) for 12 samples. Potassium ions were not found in significant amounts.

With such high soluble sodium levels relative to those of calcium and magnesium, the piping soils contained sufficient sodium to insure dispersion when water moved through them. In contrast, the stable soils did not contain enough sodium for dispersion

Table 1.--Comparison of soils with and without pipes

Soils	Exchangeable sodium percentage	Sodium adsorption ratio	pH (1:5)	Gypsum	Conductivity at 25° C.	Moisture at saturation	Sand	Silt	Clay	Textural class	Number of samples
				meq./ 100 g.	mmhos/ cm.	- - - Percent - - -					
Without pipes (Stable)											
Average	[2]<1.0	0.4	7.6	0.7	0.5	45.1	25.4	26.8	47.8	Clay	19
Standard error of the mean	[2] --	.07	.14	.06	.05	1.35	2.53	1.33	2.13		
With pipes (Unstable)											
Average[1]	12.0**	10.7**	8.9**	1.6**	1.7*	38.7	30.7	23.5	45.8	Clay	13
Standard error of the mean	2.27	2.0	.17	.19	.37	3.16	4.05	2.39	2.87		

[1]Statistically significant differences between soils with and without pipes: **highly significant; *significant.

[2]For ease of statistical calculations, a mean of 1.0 instead of <1.0 and a standard error of 0.0 were used.

and swelling to take place. Since both piping and nonpiping soils were clay, there was no significant difference in the mechanical analyses. Soil moisture at saturation is dependent on the amount of clay in these soils, and therefore was also not significantly different.

Nonpiping side slopes had a more gentle gradient and were well covered by vegetation. In contrast, piping gully side slopes were steep, unstable, had a "sugary" soil surface, and usually had no or sometimes very sparse vegetation.

To trace the origin of the sodium in the soils, samples from shale of the Wasatch formation, underlying the alluvial soils, were analyzed. Values for ESP and SAR were high in all samples (table 2) and indicate that the shale delivered most of the sodium to the soils. Gypsum content was low, as in the alluvial soils. The shale had high pH values due to the influence of the sodium.

Soil samples from four different levels were collected and analyzed to test whether chemical characteristics and/or particle size distribution of the soils with pipes differed with depth (table 2). With the exception of the sample from 1-foot depth at pipe 1, all values for ESP were greater than 1.0. All pipes showed some continuous decrease of sodium with depth after the maximum value was obtained about half-way between brink of bank and gully bottom. Yet, none of the lower levels had values close to those of stable gully side slopes, and there was no tendency for greater soil dispersion adjacent to or beneath the pipe outlets. Gypsum content was very low in all samples. Variations in the mechanical composition of the soils by depth were small. Soils from the inlet and outlet of pipe 1 showed close agreement between ESP, gypsum content, and texture, and the values did not deviate significantly from those of the depth samples. Samples from the interior of pipe 1 at a location about 10 feet below the ground surface and 12.5 feet inside the gully side slope, as measured from the pipe outlet, were also high in exchangeable sodium and low in gypsum (table 2).

It is noteworthy that cloudburst storms did not produce pipe flows. The pipes supported flows only during spring snowmelt. Two samples from these flows carried large sediment loads with much greater concentrations of sodium (140 p.p.m.) than calcium (10 p.p.m.) or magnesium (18 p.p.m.). Since the loads were derived from soils of the piping slopes, the sediment deposits in the catchments below pipes had ESP values greater than 1.0, high pH, weak conductivity, and low gypsum content (table 2). The deposits were relatively high in silt content due to the ease of removal by flows of small magnitudes.

Table 2.--Supplementary soil analyses, with mean and standard error (S.E.)

Source of soil	Exchangeable sodium percentage		Sodium adsorption ratio		Conductivity at 25°C.		Gypsum		pH		Number of samples
	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	
					mmhos/cm.		meq./100g.				
Shale parent material	17.9	1.5	15.7	1.5	0.8	0.1	0.9	0.49	9.7	0.09	4
Gully side slopes:											
Brink	11.2	9.5	11.2	9.3	1.1	.8	.1	.04	--	--	6
Midway	26.7	1.9	25.6	2.4	1.7	.3	.2	.06	--	--	6
Pipe outlet	16.0	3.4	14.2	3.3	.8	.2	.1	.03	--	--	6
Bottom	11.4	3.8	10.0	3.2	.5	.2	.1	.03	--	--	6
Alluvial layers inside pipe	10.1	1.2	8.7	1.0	2.6	.5	.2	.03	9.5	0.03	13
Pipe inlet	13.1	2.8	11.1	2.5	1.9	.6	1.8	1.0	8.6	.4	2
Pipe outlet	14.8	7.5	13.3	7.0	2.2	.8	1.4	.2	8.9	.2	2
Sediment from pipe flow	7.2	1.6	6.2	1.3	--	--	--	--	8.6	.0	2
Deposited below pipes[1]	10.3	.4	8.7	.4	.9	.07	.1	.01	9.4	.04	10

" -- " indicates not applicable.
[1]From snowmelt flow during springs of 1964 and 1965 from soil pipe 1.

Characteristics of Piping Soils in Place and Fallen

If ESP is expressed as a function of soil disturbance (fig. 5), the decrease from undisturbed soils (piping slopes) to the most disturbed soils (falls on slopes opposite from piping banks) is statistically significant. According to conventional practice (U. S. Salinity Laboratory Staff 1954), the determination of Solonetz soils is based on ESP and conductivity. It was therefore not surprising to find that occurrence of Solonetz was greatest in the least disturbed soils.

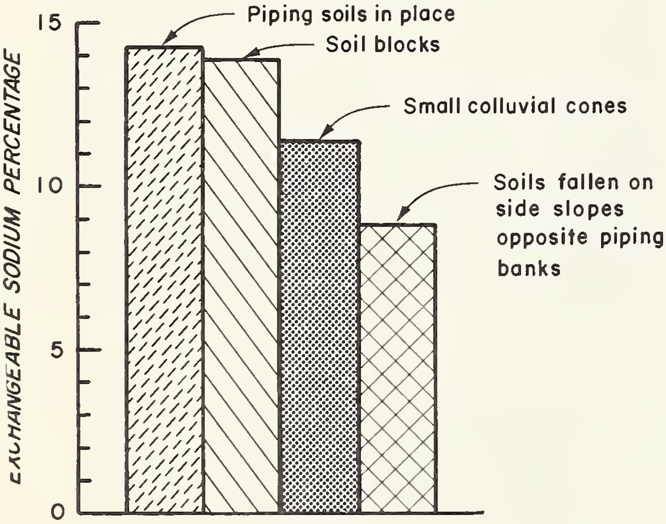


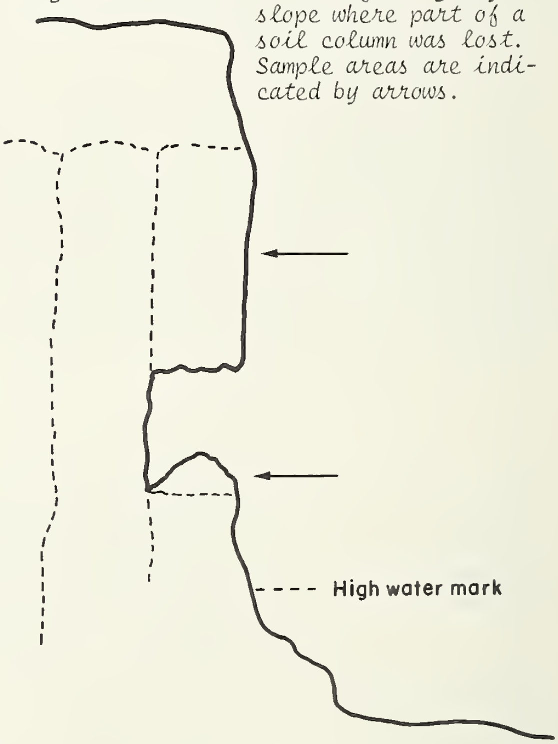
Figure 5.--Exchangeable sodium percentage as a function of in place and fallen piping soils.

To demonstrate the development of ESP values between soils related to each other beyond doubt, two sites were selected for sampling where part of Solonetz soil columns had broken out naturally from the gully side slopes about 1 year before sampling. In each case, an opening about 9 inches high had formed in the column (fig. 6). On the bottom of the opening, loose material from the column above accumulated in small piles. The piles were above the high-water marks of the gully flows during the previous 2 years. ESP of the columns above the openings and the soil in the piles were as follows:

Soil columns	Soil piles
17.4	13.9
16.5	16.0

In each case, values for ESP decreased with disturbance. This finding corresponds with results obtained from a recent study on deep plowing of Solonetz soils in Canada (Bowser and Cairns 1967). Deep plowing, representing physical destruction of the original soil structure, led to an increased exchangeable-calcium to exchangeable-sodium ratio.

Figure 6.--Cross section of the gully side slope where part of a soil column was lost. Sample areas are indicated by arrows.



For one location, time scales for occurrences of soil falls were established and ESP and conductivity of the saturation extract expressed as a function of age (fig. 7). In view of the relatively short periods involved (up to about 3 years), the decreases with time are substantial—almost 50 percent. Such a decrease in conductivity reflects a decrease of the salt complex in the soils. The rapid decrease of the salts must be explained primarily by leaching. The time intervals of figure 7 should be regarded as approximations to the nearest year.

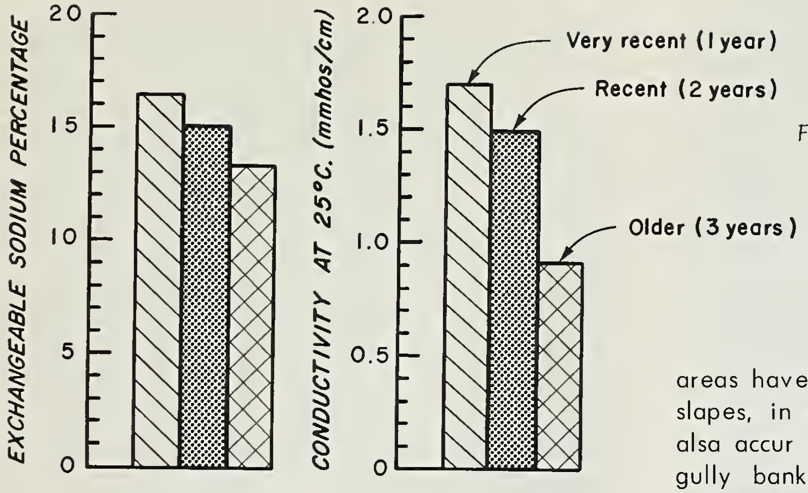


Figure 7.--Conductivity and exchangeable sodium percentage related to age of soil fall.

Discussion

Soil Piping Processes

Of the many hypotheses advanced on the causes and development of pipes, rodent burrows (Carroll 1949), canals formed by dead roots (Carroll 1949), land denudation by overgrazing (Downes 1946, Fletcher and Carroll 1948, Kingsbury 1952) and soil cracks (Downes 1946, Brown 1962), were most frequently mentioned. There is little doubt that rodent holes, root canals, and deep soil cracks may lead to the formation of pipes on Alkali Creek watershed if a sufficient hydraulic gradient for runoff is provided by a lower base level such as represented by gullies. But based on the following reasoning, it is suggested that on the Alkali Creek watershed a dispersing agent such as sodium must be present in the soils as a prerequisite.

Older studies on the area have shown that the clay has montmorillonite structure (Brown 1961). This type of clay is characterized by a strong rate of swelling and shrinking, and soils containing this clay mineral tend to develop cracks. Since the clay content is high in all soils of Alkali Creek watershed, soil cracks were not confined to areas with sparse or no vegetation, but were also found in areas with dense vegetation cover. These latter areas have nonpiping, relatively stable gully side slopes, in spite of the fact that deep soil cracks also occur there. Pipes do develop, however, on gully banks and side slopes where the ESP is greater than 1.0, although the exact breaking point at which pipes may develop cannot be given. All pipes detected on the watershed were located close to the gullies. No pipe inlets were found at a distance greater than 25 feet from the present edge of the gully.

The shape and alinement of soil pipe 1 (fig. 2), typical of pipes in the area, indicated that the pipe followed a former soil crack. The pipe was narrow (fig. 8) and, if viewed from within, showed

Figure 8.--Upstream view inside soil pipe 1 at a location 18 feet from gully side slope. The ruler is 6 inches long. Note the narrowness of pipe relative to its height, which indicates former cleavage line in the clayey alluvial soils. The pipe continues with a sharp bend to the left.

the seam of a continuous crack on its ceiling, which appeared to be the remnant of the original line of cleavage. Since the soils of gully side slopes and banks dry out much faster than those of undissected areas away from gullies, cracks will start at the gullies. Later runoff follows these cracks down to the channel. Where sodium content reaches a certain level, the clayey-silty soils are easily dispersed and carried into the gully. This process leads to a widening of the crack at its bottom where the water runs. Once the hole is sufficiently wide, the crack above the widening closes due to gravitational action and a so-called soil pipe has been formed. The capability of the soils for arching is illustrated by a natural soil bridge (fig. 9). In contrast, where a dispersing agent is not available, erosion in the cracks is so slow that the cracks will close again during swelling of the soils.

Wetting of the soils may be as important as dispersion for the piping processes. Laboratory experiments demonstrated that the layer permeability of soils with ESP values greater than 1.0 ranged between 1.6 percent and 11.8 percent of that of soils with ESP less than 1.0 (fig. 10). This means that wetting and, with this, swelling of the sodium soils is much slower than of nonsodium soils, and suggests that cracks in the sodium soils remain open much longer. Also, more water is available for flows through the cracks where the ESP is higher because of decreased infiltration and increased surface runoff. The increased flow will cause increased erosion in these cracks.

Figure 9.--Upstream view of a gully on Alkali Creek watershed. Length of rod placed under natural soil bridge is 5.5 feet. Unstable gully side slopes with soil piping typically alternate with stable slopes indicated by a vegetation cover in the right foreground and in the background of gully. Bridge appears to be remnant from an older soil pipe.

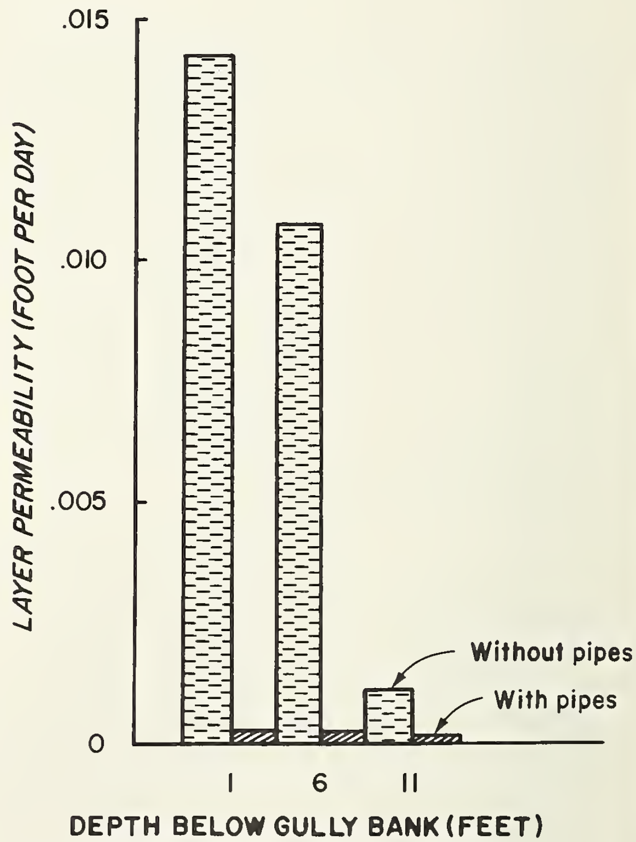


Figure 10.--Layer permeability of gully side slopes, with and without soil pipes by depth below bank of gully.

At first, the development of the pipe gradient from extremely steep to very gentle appeared puzzling. The question arose as to what caused the breaks in gradient, especially where the flow seemed to head deterministically toward the gully and did not continue its downward movement. Since the soils of the lower part of the gully side slopes remain moist for a much longer period of time and dry at a rate much slower than those of the upper part, soil cracks will start above the moist zone where drying is very rapid after the last runoff from spring snowmelt (fig. 11). Thus, it can be assumed that the original configuration of a soil crack provides the longitudinal profile characteristic for the pipe. Surface runoff, entering a crack, will be well loaded with sediment when it reaches the low part of the pipe. Due to the gentle gradient there, velocities of flow will decrease, and in turn, the load-carrying capacity of the water decreases. Thus, the rate of erosion on the bottom of the lower pipe is small and, in time, aggradation will occur instead of degradation. Strata of high dispersion in a soil profile may also act as impermeable layers and thus could be a cause for the changes in longitudinal gradients of pipes. The occurrence of an impermeable substratum was proposed by earlier research (Downes 1946). Yet our analysis showed that the exchangeable sodium percentage decreased at lower depths (table 2). Layer permeability values for samples from gully side slopes on piping soils did not decrease for depths greater than 1 foot below the soil surface (fig. 12).

Figure 11.--The outlet of soil pipe 3, located about 4 feet above the gully bottom, during the spring snowmelt of 1963. Recent pipe flow, exhausted by lack of snow outside of the gully, caused the erosion on the gully side slope below the outlet. The increased slope gradient below the pipe outlet raised the load-carrying capacity of the pipe flows and thus made this erosion possible. Snows in the headwaters still feed the flow in the gully. Note the wetting of the gully side slope to the approximate elevation of the pipe outlet. Ruler is 4 inches long.

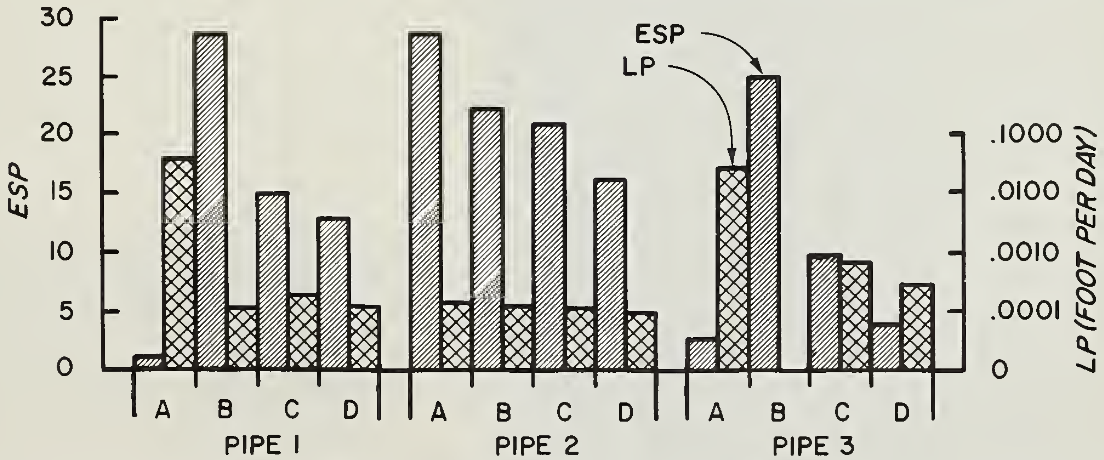


Figure 12.--Exchangeable sodium percentage (ESP) and layer permeability (LP) of piping soils, by depth, for three soil pipes.
A = 1 foot below ground surface
B = midway between ground surface and pipe outlet
C = bottom elevation of pipe outlet
D = 1 foot below bottom of pipe outlet

Natural Reclamation of the Piping Soils

While the analysis of the samples from stable gully side slopes showed that all samples were derived from normal soils, part of the samples from piping side slopes represented Solonetz, if conventional guidelines (U.S. Salinity Laboratory Staff 1954) were applied. These guidelines propose a division of soils into sodium and nonsodium at 15 percent exchangeable sodium. This practice has been questioned since experiments have shown that, as the exchangeable sodium increases, the permeability to solutions, considerably less concentrated than the threshold concentration, decreases continuously (Quirk and Schofield 1955). The threshold concentration, which has no absolute value, was defined as that concentration of salt that causes 10 to 15 percent decrease in soil permeability—the concentration where factors which can cause drastic reduction in permeability are becoming operative. Most of the piping soils of the study area can be classified as soils with a tendency toward the formation of Solonetz, if we accept Gedroits' concept on the causes for Solonetz formation. Gedroits stated that the direct cause for such development is the adsorption of sodium by the soils while displacing exchangeable calcium and magnesium. That such displacement has occurred or is taking place at present, appears to be indicated by the large sodium ion concentration relative to the concentration of calcium and magnesium ions. In contrast to Russian Solonetz, the soils of the study area exhibit no or very weak horizons. Thus, our soils are of a much younger age. The youthfulness is also illustrated by very pronounced alluvial strata (see fig. 4). Yet, as is the case with Russian columnar Solonetz, our soils are also divided into well-defined columns below the surface soil layer (fig. 13). After

Gedroits, K. K. Solenetz, their origin, properties and melioration. 1928. Cited by Vilenskii (1957).

Figure 13.--This soil column was taken from a gully side slope with pipes. The section of the column constitutes a hexagon; its longest side measures 6 inches (there was some destruction during transport).

spring snowmelt, when the soils dry ropidly, the hitherto nonstructured soil moss is dissected into structured columns with polygonic cross sections. Most of the polygons hove six sides; lengths of sides up to 8 inches were meosured. Identical to the Russian Solonetz, the summits of the columns hove locquered surfoces, opparently from the drying of colloidol solutions on them.

Piping gully side slopes of the Alkoli Creek wotershed sheor off repeotedly during rains ond periods of heavy snowmelt, leoving neorly verticol cliffs. The soil mosses ore deposited on the opposite side slope, and force future gully flows agoinst the piping bonk (fig. 14). This leods to undercutting of the piping side slope, ond results in more bonk cleovage. With time, the tholweg migrotes owoy from the deposition side slopes, ond it oppeors thot these slopes become stoble. Growth of vegetation on the deposition slopes is fovored by increased soil moisture. More woter will infiltrote into the slopes due to the gentler slope grodient formed by the deposits. The soluble solts, o lorge proportion of which ore sodium, moy olso be leoched more eosily from the soils after their mechonicol disturbonce. As sodium is leached from the soil, the pH will decreose ond colcium will be more soluble ond ovoilable for plont growth. The greoter colcium influence will also stimulote flocculotion ond will speed the leoching process. While the leaching of sodium undoubtedly benefits the estoblishment of vegetotion becouse the osmotic pressure in the soils decreoses with decreosing solt concentrotion, calcium mode ovoiloble by the plonts, in turn, will speed the leoching processes. Thus, gully side slope stobilizotion moy progress ropidly, once plonts become estoblished.

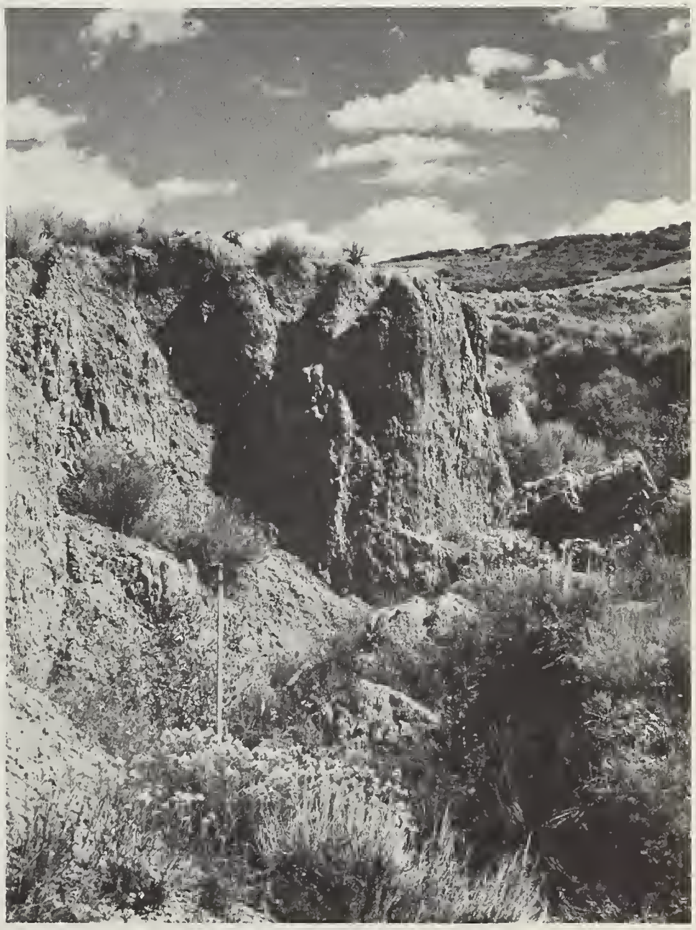


Figure 14.--Piping gully side slopes break off in vertical cleavage lines. The soil masses are dumped on the opposite side slope. These slopes of deposition are invaded by vegetation, while the gully flows are forced toward the piping slopes. The length of the rod is 5.5 feet.

Field observations indicate that gullies with piping side slopes move laterally into the piping bank, and that lateral gully movement continues as long as piping banks are available. Since most of the material from the piping slopes falls on the opposite side slope of the gully, stabilization will occur there. Inspections showed that stable slopes are found on all aspects, and no aspect was favored. Typically for the study area, the gully side slopes opposite from pipes 1, 2, and 3 were classified as stable, with very little surface soil movement. It must be assumed that the soils with relatively high ESP values exist as lenses, a depositional form typical of alluvium. Once a gully has moved laterally through such a lens, the former piping bank may become stabilized, if deep cutting of the gully or other hydraulic adjustments such as meandering are not at work. The final stage of this development may resemble that of old age of a karst topography on a somewhat smaller scale. Our investigations did not permit the delineation of such areas on Alkali Creek watershed, although general observations indicated that they may exist. The study did show, however, that in each case, gully side slopes covered by fallen piping soils were in the process of stabilization.

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Exchangeable sodium percentage showed a highly significant difference between soils with and without pipes. Layer permeability of piping soils was only 2 to 12 percent of that of soils without pipes. The interior of one soil pipe was thoroughly inspected, surveyed, and photographed. Soil pipes on the Alkali Creek watershed probably developed mainly from soil cracks. Gullies, high exchangeable sodium percentage, low gypsum content, and fine-textured soils with montmorillonite clay appeared to be prerequisite to the formation of pipes. Soil piping appears to lead ta natural reclamation of the soils, which in turn introduces stabilization processes of gully side slopes.

KEY WORDS: Gullies, soil erosion, soil permeability, soil stabilization.

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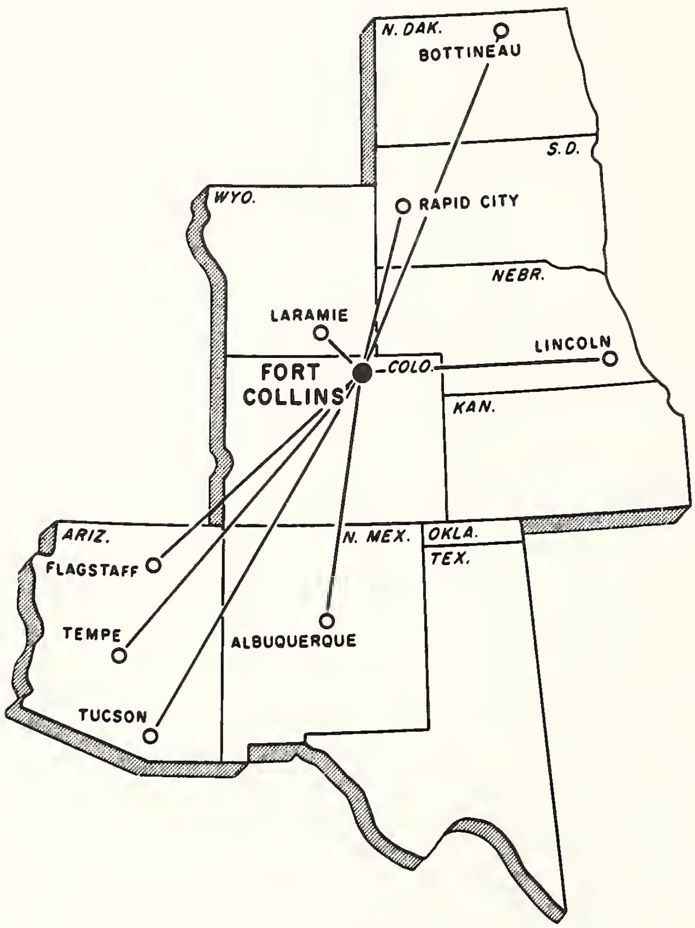
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