Hyde Forbes.

DEPARTMENT OF THE INTERIOR
Hubert Work, Secretary

U. S. GEOLOGICAL SURVEY
George Otis Smith, Director

WATER-SUPPLY PAPER 577

PLANTS AS INDICATORS OF GROUND WATER

BY

OSCAR EDWARD MEINZER

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PLANTS AS INDICATORS OF GROUND WATER

By Oscar Edward Meinzer

INTRODUCTION

PLANTS THAT HABITUALLY FEED ON GROUND WATER

Perhaps the most outstanding feature of the flora of the desert is its relation or lack of relation to the water table. On the one hand are the plants which are adapted to extreme economy of water, which depend on the rains that occur at long intervals for their scanty water supplies, and which during prolonged periods of drought maintain themselves in a nearly dormant condition. These plants are known as xerophytes (from Greek roots meaning "dry plant"). On the other hand are the plants that habitually grow where they can send their roots down to the water table or to the capillary fringe immediately overlying the water table and are thus able to obtain a perennial and secure supply of water. These plants have been called phreatophytes.[1] The term is obtained from two Greek roots and means a "well plant." Such a plant is literally a natural well with pumping equipment, lifting water from the zone of saturation.

The terms "ground water," "zone of saturation," "water table," and "capillary fringe" are used in this paper as previously defined by the writer.[2] The term "ground water" is used by the writer and, so far as could be determined, by the authorities that are

[1] Meinzer, O. E., Outline of ground-water hydrology, with definitions: U. S. Geol. Survey Water-Supply Paper 494, p. 55, 1923. In so far as the writer is informed, the term "phreatophyte" was first used by him in a mimeographed edition of the paper which was later issued in revised form as Water-Supply Paper 494. See also Meinzer, O. E., Plants as indicators of ground water: Washington Acad. Sci. Jour., vol. 16, pp. 553–564, 1926. The principal ecologic groups of plants that have been recognized by botanists are hydrophytes, which grow in water or at least with their roots under water; the halophytes, which can endure large amounts of salt or alkali in the soil water on which they live; the xerophytes, which are able to survive on very small and irregular supplies of water; and the mesophytes, which are not adapted to endure any of these extremes. In proposing the name phreatophyte the writer did not imply that this group should find a separate place in the old classification, but rather believed that it would overlap some of the other groups. The term "helophyte" has been used for marsh plants, which are more or less intermediate between hydrophytes and mesophytes, but this term could not be used to designate the phreatophytes without violating its past usage and introducing much confusion. (See, for example, Warming, Eugen, Oecology of plants, p. 185, Oxford, 1909.)

[2] Op. cit. (Water-Supply Paper 494), pp. 21, 22, 26.

quoted, to designate the water in the zone of saturation—that is, below the water table.

The plants that feed on ground water form a fairly definite and well-recognized group in the desert regions and a much less definite group in the humid regions, where water supplies from other sources are more abundant. In the most arid regions the plants that feed on ground water stand in sharp contrast to the desert plants that do not utilize water from the zone of saturation. However, in passing into less arid and then into more and more humid regions the control of the water table becomes progressively less rigid, until even the plants that have been most dependent on it are able to live in all sorts of situations entirely beyond its reach.

Even in the desert regions many if not all ground-water species will spread more or less to localities where their roots do not reach the water table, such as irrigation ditches, irrigated fields, streams, and dry washes that are far above the water table, or even alluvial slopes and hillsides. It is also true that plants of species that do not habitually utilize ground water may do so under certain circumstances and may flourish, at least for a time, on such a water supply. Moreover, there is not always a wholly definite distinction between ground water and other soil moisture, because of the existence of a great variety of perched and temporary water tables and of gravity water that may be in transit from the surface to the water table. However, these exceptions and complicating conditions do not alter the important fact that there are certain plant species which habitually feed on ground water and others which do not, and that in the arid regions there is a very real and conspicuous distinction between these two groups. This distinction is, indeed, often more real than appears on casual observation, for some of the ground-water plants are closely related to species of the other group which resemble them, and frequently plants of one of these related species growing in dry localities are mistaken for stunted individuals of the ground-water species. Moreover, in many places clumps of a ground-water species growing outside of the recognized shallow-water belts do not form exceptions to the rule but instead faithfully indicate the presence of ground water near the surface where it would otherwise not be suspected.

EVIDENCES OF THE GROUND-WATER HABIT

The evidence that plants of certain species possess the ground-water habit or adaptation whereas those of other species do not possess it may be grouped as follows: (1) Observations of the root habit of different species, showing their relation or absence of relation to the water table and showing the ability of some species to send roots to great depths; (2) experiments with certain species in which the quantities of water they absorb from the zone of saturation are measured or the effects of their growth in lowering the water table are recorded; (3) determinations of soil moisture during dry periods in an arid region, showing that certain species grow chiefly or exclusively with their roots penetrating into soil which contains moisture that could not have been supplied by rains but must have risen from the zone of saturation, whereas other species are found chiefly or exclusively with their roots in dry soil that is not moistened by ground water; (4) observations in arid regions of the relation or absence of relation of the period of growth of different species to the rainy season, showing that certain species (commonly growing where the ground water is beyond the reach of the plant roots) become dormant after the supply of soil moisture derived from the rains has been exhausted, whereas other species (growing where the ground water is within reach) continue to grow actively throughout the summer; and (5) observations in arid regions of the depth to the water table, showing that certain species are confined almost completely to areas with specific depth limits, whereas others show no relation to the water table and may grow where the water table is at a great depth or where ground water is entirely absent.

1. There are widely scattered data as to the depths and habits of the roots of plants that utilize ground water, in contrast to those that do not, though most of these data are not so definite as could be desired. A few striking facts as to the depths to which the roots may go for water are given elsewhere in this paper. (See especially fig. 15, p. 91.) A study of the subject, especially with reference to forest trees, has been made by Cannon,[3] who makes the following statement:

> It is now well established, at least for a portion of the Southwest, that there may be a very intimate relation between the occurrence of certain species of trees and the character of their roots, having regard to the depth at which perennial water may be found. Here trees occur along streamways, while the near-by upland may be treeless. The humidity of the two areas may not be very unlike, nor the rainfall, nor yet the temperature. The great difference, which is often striking, lies mainly in the soil conditions, particularly with regard to the depth to the ground water. On the bottoms the water table lies within reach of the roots of trees, while on the more elevated land it is far below them. * * *
>
> The problems which deal with the presence of trees are primarily physiological and have mainly to do with the absorption and conservation of water. Each of these capacities varies with the species. Of the root relations, that of

[3] Cannon, W. A., The root habits of desert plants: Carnegie Inst. Washington Pub. 131, 1911; Some relations between root characters, ground water, and species distribution: Science, new ser., vol. 37, pp. 420–423, 1923; Tree distribution in central California: Pop. Sci. Monthly, vol. 85, pp. 417–424, 1914.

the root-and-water table is of prime importance, owing to the fact that the soil horizon tapped by the roots of trees derives by capillarity, from the level of the ground water, its perennial supply of moisture.

Striking examples have been observed by the writer of the depths to which the roots of trees of a certain species will go for a reliable supply of water in one of the rugged limestone regions of Cuba. In spite of the heavy precipitation in this region the trees in exposed localities have great difficulty in obtaining enough water, because of the lack of soil and the cavernous character of the limestone. Wherever possible the roots descend through crevices or over escarpments of the rocks, and in one place they were seen extending vertically down over a sheer cliff about 100 feet into a perennial stream where it emerges from a cavern. These long roots have functional rootlets only at their lower ends, where they dip into the water.

2. The experiments which definitely demonstrate that plants of certain species feed on ground water are of two kinds. In one plants are grown in tanks that are filled with soil in which a water table is maintained at a certain level by adding measured quantities of water from below, to replace the water that is removed by the transpiration of the plants or by both transpiration and evaporation, as in the experiments by Lee [4] with salt grass and recently by Walter N. White, of the Geological Survey, with greasewood, salt grass, and alfalfa. In the other a record of the fluctuations of the water table is obtained by means of a water-stage recorder installed in a well in a tract where the plants under investigation are growing naturally. This method was devised by G. E. P. Smith,[5] who demonstrated that the water table under a forest of mesquite trees declines during periods of growth but not at night, on cloudy days, or at times when the mesquite trees shed their leaves. Similar records have been obtained by Smith on tracts of cottonwood, salt grass, and sacaton, and recently by Mr. White on unirrigated alfalfa in the desert and on salt grass and greasewood.

3. Determinations of soil moisture which show that certain species utilize ground water during the dry periods while others do not were made in connection with the investigation of the indicator significance of vegetation in Tooele Valley, Utah.[6] The following quotation from the Tooele Valley report summarizes the contrasting results for greasewood, a well-known ground-water plant, and shad scale, a very common desert plant which is not dependent on ground water:

It is significant that moisture available for the growth of plants [excess of moisture content over wilting coefficient] was present in considerable quantity

[4] Lee, C. H., An intensive study of the water resources of a part of Owens Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 294, pp. 53–60, 1912.

[5] Personal communication.

[6] Kearney, T. H., and others, Indicator significance of vegetation in Tooele Valley, Utah: Jour. Agr. Research, vol. 1, pp. 365–417, 1914.

during the months of June and July in all but the surface foot in the greasewood-shad scale association, while in the shad scale association during the same months there was a marked deficit of available water to a depth of 4 feet. The relatively high moisture content is correlated with the relatively slight elevation above the level of water in the lake and with a consequently high ground-water table. * * *

Greasewood prefers an ample and permanent supply of moisture within reach of its roots, and its strong, deeply penetrating taproot enables it to reach moisture in places where the surface soil is dry and the ground-water table is at a considerable depth. * * * Shad scale, on the other hand, does not thrive with its roots in wet soil, and its presence is usually a reliable indication that at least the surface foot is dry during the greater part of the summer.

4. The fact that certain species which utilize ground water grow throughout the summer while other species are dormant except in the rainy season is a matter of common observation. It is summed up as follows in the Tooele Valley report:[7]

In those parts of the valley where the ground water is beyond the reach of the plant roots the vegetation becomes dormant after the moisture stored in the soil by the winter and spring rains has been exhausted. Herbaceous plants ripen and die, at least to the ground, while the woody species, losing much of their foliage and reducing their transpiration to a minimum, enter a resting condition which is nearly as complete as that which is brought about by the low temperatures of winter. * * * In the lower part of the valley, where the ground-water table is high and the soil is moist throughout the summer nearly or quite to the surface, active growth continues until it is terminated by frosts.

For the same reason alfalfa, which has adaptations for utilizing ground water, will, if well established in an area of shallow water, continue to grow through the driest season when other field crops that do not have such adaptations utterly perish.

Observations made by Douglass[8] on the relation between tree rings and ground water give interesting evidence of the ground-water habit in some trees and of a difference between various species of trees in this respect, as is shown by the following statement:[9]

It was found that dry-climate trees which grew in basins with a large and constant water supply, and this refers especially to the Sequoias, usually produced rings without much change in size from year to year. This character of ring is called "complacent." The opposite character is the "sensitive" ring, where a decided variation is shown from year to year. Sensitive trees grow on the higher elevations, where the water supply is not reliable and the tree must depend almost entirely on the precipitation during each year. Such trees grow near the tops of ridges or are otherwise separated from any collection of water in the ground. In case of the basin trees one could be sure that a ring was produced every year, but owing to the lack of individual-

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[7] Kearney, T. H., and others, op. cit., p. 370.

[8] Douglass, A. E., Some aspects of the use of the annual rings of trees in climatic study: Smithsonian Inst. Rept. for 1922 (Pub. 2731), pp. 223–239, 1924; Some topographic and climatic characters in the annual rings of the yellow pines and Sequoias of the Southwest: Am. Philos. Soc. Proc., vol. 61, pp. 117–122, 1922; Climatic cycles and tree growth: Carnegie Inst. Washington Pub. 289, 1919.

[9] Smithsonian Inst. Rept. for 1922, pp. 230, 231, 1924.

ity in the rings for certain years it was difficult to compare trees together and produce reliable data. In case of the sensitive trees growing in the uplands there was so much individuality in the rings that nearly all of the trees could be dated with perfect reliability, but in extreme cases the omission of rings in a number of trees required special study. * * * Trees growing in the dry climate of Arizona at an altitude where they have the utmost difficulty in getting water to prolong life become extraordinarily sensitive. In the same tree one finds some rings several millimeters across and others microscopic in size or even absent. * * * The great sensitiveness of the yellow pines as compared with the best Sequoias is evident in any brief comparison of dated specimens.

5. The numerous observations made by the writer and others, as cited in this paper, of the relation between the depth to the water table and the occurrence of certain plant species in arid regions give convincing and abundant evidence of the ground-water habit in some species and its absence in others. In the arid regions of the western part of the United States tracts of shallow ground water occur in three principal situations—(1) in the canyons and other localities in

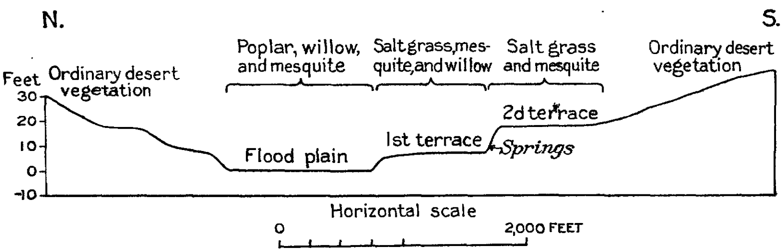
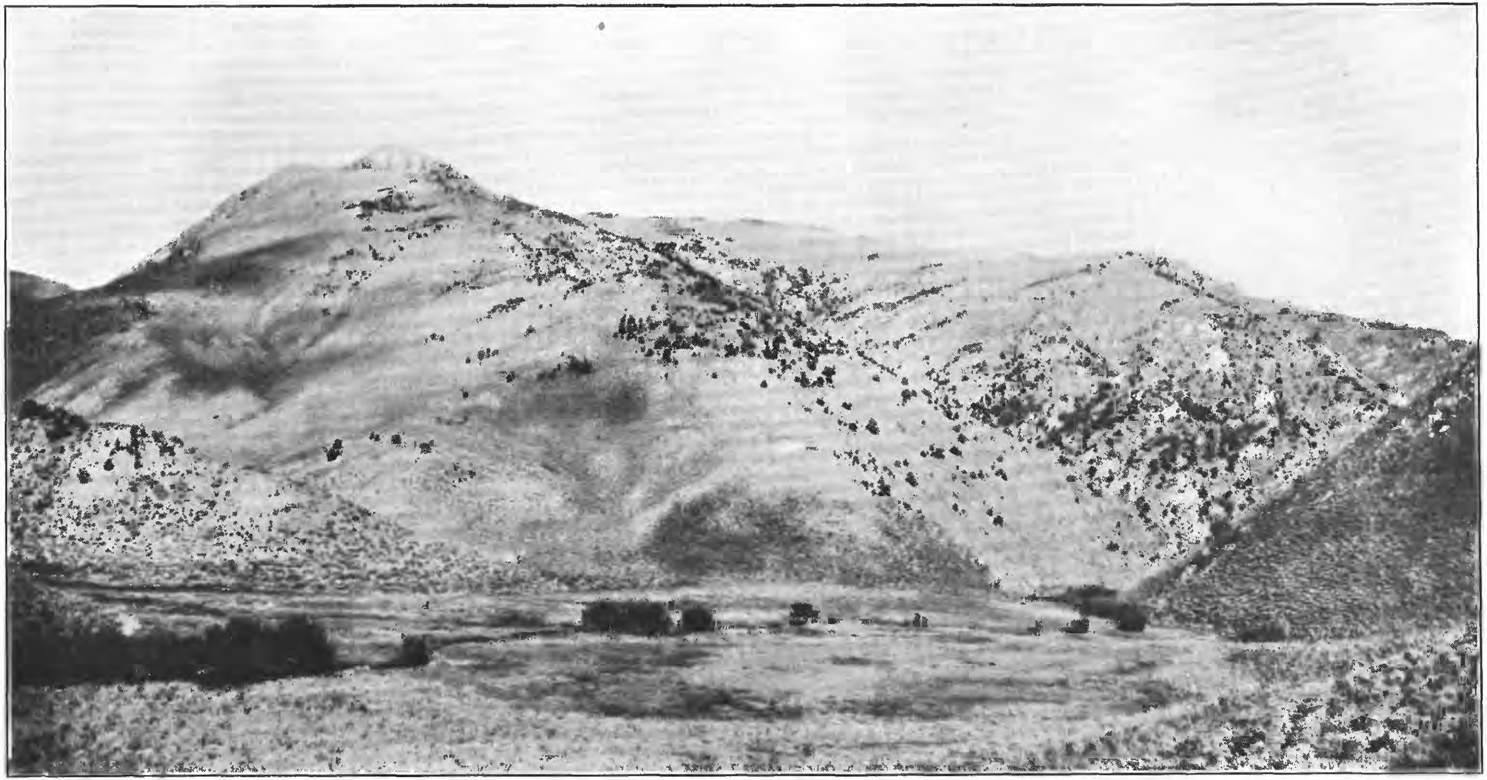


FIGURE 1.—Profile across Mohave River valley at Camp Cady, Calif., showing distribution of ground-water plants. After D. G. Thompson. (See pl. 2.)

the mountains where the water is held up by impermeable bedrock near the surface, (2) in the lowest parts of the principal basins or intermontane valleys, and (3) at certain intermediate points where barriers to the ground water occur. The largest areas of plants that feed on ground water are in the valley lowlands, but distinctive plants of this group also grow in higher tracts where they are reliable indicators of ground water. The native plants found in these tracts of shallow ground water are not the same species as grow elsewhere in the desert but consist of a few distinctive species which dominate the shallow-water tracts and are absent or have only very sparse growth in other parts of the desert region where the water table is not near the surface. (See pls. 1 and 2 and fig. 1.)

As a rule in the interior lowland of a large desert basin these ground-water species occupy a zone of shallow ground water surrounding a central playa that is virtually destitute of all vegetation. The unfavorable conditions that make the playa barren need not be discussed here further than to say that some of the worst features are the alkaline character of the soil and in large parts its clayey



UPPER VALLEY OF BIRCH CREEK, IN THE TOYABE MOUNTAINS, NEV., SHOWING AREA OF SHALLOW GROUND WATER AS INDICATED BY THE VEGETATION

MOHAVE RIVER VALLEY AT CAMP CADY, CALIF., SHOWING ZONES OF VEGETATION DUE TO DIFFERENT DEPTHS TO GROUND WATER

Desert brush in the foreground, zone of salt grass supplied by ground water on the lowland back of the desert brush, and zone of poplar, willow, and mesquite on the flood plain back of the salt grass zone. (See fig. 1.) Photograph by D. G. Thompson texture, which renders it impermeable to ground water and results in violent variations of moisture conditions, ranging from extreme aridity to complete submergence in times of heavy freshets.

The zone of shallow ground water surrounding the playa can generally be subdivided into several concentric belts of vegetation, in each of which one or more ground-water species is dominant. The successive belts vary in texture and alkalinity of soil as well as in depth to the water table. These differences in the soil have an important modifying influence on the type of vegetation and on the limits of the successive belts, and they have received much more attention than the ground-water conditions with respect to their effect on vegetation. However, the main factor in the control of the vegetation over the area of shallow ground water is the depth to the water table. This conclusion is definitely proved by the existence of otherwise similar basins which, on account of subterranean leakage, do not have shallow ground water in their interior lowlands. In these basins there may be a barren central playa with clayey, alkaline soil, surrounded by belts of soil having essentially the same texture as that of the soil in the basins that have shallow water, yet the familiar ground-water plants are essentially absent and the ordinary desert species extend to the margins of the playa. Doubtless there are some differences in the amount and distribution of the alkali in the soil resulting from the absence of shallow ground water, but in view of the characteristic growth of ground-water plants in many well-drained areas of shallow ground water it is certain that the absence of these species in the basins having deep ground water is not due to a difference in soil alkali.

Good examples of desert basins that do not have shallow ground water are Coal Valley, Nev., described by Carpenter,[10] and Alkali Spring Valley, Nev., described by the writer.[11] In Coal Valley no water was found in a well drilled to a level 200 feet below the playa, and drought-resistant plants, such as shadscale, extend to the edge of the playa. In Alkali Spring Valley the water in a dug well at the edge of the playa was found to stand 47½ feet below the surface, and no ground-water plants were found except greasewood, which may go to this depth for ground water. These basins are in striking contrast to the numerous basins in the same region that have areas of shallow ground water with their distinctive vegetation—as, for example, Big Smoky Valley, Nev.[12]

[10] Carpenter, Everett, Ground water in southeastern Nevada: U. S. Geol. Survey Water-Supply Paper 365, pp. 68, 69, 1915.

[11] Meinzer, O. E., Geology and water resources of Big Smoky, Clayton, and Alkali Spring Valleys, Nev.: U. S. Geol.. Survey Water-Supply Paper 423, pp. 148–150, 1917.

[12] Idem, pp. 86–104.

In appraising the evidence that certain desert plants possess the ground-water habit and others do not, it should be remembered that the several lines of evidence are mutually corroborative and together bear much more weight than any one of them, because they all agree in selecting the same species as ground-water plants.

HISTORY OF THE SUBJECT

As might be surmised, the subject of plants as indicators of ground water is by no means a new one. Vitruvius,[13] a Roman architect and engineer, who lived about the time of Christ and who is credited with being the first writer to advocate the modern theory of the origin of ground water, makes the following statement on the subject:

> Besides these there are other indications of places where water can be found—namely, the presence of small rushes, willows which are not planted, alder trees, vitex, reeds, ivy, and all other such plants which occur and thrive only in places where there is water. One must not rely on these plants, however, if they occur in marshes, which, being lower than the surrounding country, receive and collect and for some time retain rain waters that fall on the near-by fields in winter; but if these plants occur naturally in places that are not marshes, one can seek for water in these places. [Translated from Paramelle.]

Somewhat similar statements are found in the writings of Pliny,[14] in the first century A. D., who virtually quoted Vitruvius, and in those of Cassiodorus, in the sixth century, who obtained his ideas largely from a professional water finder who came to Rome from the arid regions of Africa.

Paramelle cites an article in the "Globe" of November 4, 1848, which discusses briefly the value of certain trees and smaller plants for locating ground water. Paramelle himself, while recognizing the relation between certain types of vegetation and the occurrence of ground water, did not regard the vegetation as of practical value in locating ground-water supplies, as is shown by the following quotation from his well-known book on ground water,[15] the first edition of which appeared in 1856:

> When the thalweg of a valley is uncultivated and one sees there growing naturally willows, poplars, alders, osiers, rushes, reeds, wild mint, silver weed, ground ivy, and other water-loving trees or plants, one should presume that the course of water [water table?] is not deep in that place. However, as these kinds of plants thrive in all humid terranes they can only serve to indicate the presence of ground water in so far as they are on a thalweg or at the bottom of a hollow. Pliny himself had already observed that the search

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[13] Vitruvius Pollio, Marcus, De architectura, quoted by Paramelle, Abbé, L'art de découvrir les sources, 4th ed., p. 396, Paris, 1896.

[14] Naturalis historia, book 31. (First published in Latin in Vienna in 1469. See "The natural history of Pliny" translated by John Bostock and H. T. Riley, vol. 5, p. 489, London, 1856.)

[15] Paramelle, Abbé, op cit., p. 148.

for springs by inspection of certain plants which thrive only in humid places is not very safe, and he calls these signs erroneous indications (augurium fallax). [Translated.]

The subject was treated more thoroughly in a publication by Amy [16] in 1861. His statements in this regard are evidently based on his own observations and appear to be reasonably accurate, although he may have overestimated the practical value of vegetation for finding ground water. He suggests the possibility also of using vegetation as an indicator of depth to and quality of ground water, but calls attention to the facts that the indications vary from place to place with differences in soil and topography and that vegetation and other surface indications do not show ground water where it lies at considerable depth. He gives the scientific names of numerous species of plants that indicate ground water. These species belong to 14 different families or orders and include birches, alders, willows, and poplars, and also sedges, rushes, cat-tails, and grasses, among which he mentions reed grass (*Phragmites*).

Vitruvius and the other writers above mentioned discussed this subject in connection with other and even less tangible methods of locating ground water, such as color and dampness of the soil, mists rising from the ground early in the morning, and sponges becoming moist when placed in shallow holes in the ground. Obviously all this borders closely on divining, or water witching, and it is greatly to the credit of Vitruvius, Pliny, and Cassiodorus that none of these ancient writers recognized divining or any other magical method for locating ground water.[17] Although the means suggested by Vitruvius as aids in finding ground water may not have had much practical value in the relatively humid country in which he lived, yet they were obviously based on outdoor observations and were serious efforts to discover sound and practicable methods at a time when the science of geology was still a complete blank.

The foregoing review shows that the study of plants as indicators of ground water has made very little progress in European countries. Most of the French and German treatises on ground water either do not mention the subject at all or else dispose of it very briefly, except a book by Mager,[18] which not only treats this subject at length but also champions the divining rod and other devices. The reason for this neglect of the subject by European hydrologists is not hard to find—it is simply because the subject does not have

[16] Amy, F., Voyages d'un hydroscope, ou l'art de découvrir les sources, Paris, 1861.

[17] Raymond, R. W., The divining rod: Am. Inst. Min. Eng. Trans., vol. 11, pp. 415–416, 1883; U. S. Geol. Survey Mineral Resources, 1882, pp. 610–626, 1883.

[18] Mager, Henri, Les moyens de découvrir les eaux souterraines et de les utiliser, pp. 310–319, Paris, 1912.

and can not be made to have much scientific or practical importance in humid regions. It is significant in this connection that Cassiodorus became interested in the subject through an "aquilege" who came to the court of Theodoric from Africa. "Because of the great aridity of the terranes of his country," wrote Cassiodorus, "the art of discovering springs is there cultivated with the greatest care."

References to plants that depend on ground water are found in many publications relating to arid regions in foreign countries, but no systematic search of this literature was made in connection with the present investigation. In so far as the writer knows, no comprehensive study of the subject has been made anywhere outside the United States. In describing the desert region of Southwest Africa, Wagner [19] makes the following statements:

> Trees and plants sometimes afford invaluable assistance [in locating successful wells], the position of master joints or of belts of fissured or decomposed rock, along which underground water percolates, being not infrequently indicated at the surface by lines of trees or shrubs, known as "aars." One of the most reliable indicators of the existence of water below such aars is the *Acacia horrida* (sweet thorn). Other trees and plants which betray the presence of ground water at shallow depths are the ebony tree (*Euclea pseudebenus*), the karree tree (*Rhus lancea*), the tamarisk (*Tamarix austroafricans*), and the inkbush (*Suaeda fruticosa*). In the Namib the narra bush (*Acanthosicyos horrida*) is the best indicator.

The desert region of the United States has been estimated to cover about half a million square miles, or about one-sixth of the entire area of the country.[20] In this region the relation of the native vegetation to ground water is a subject of great scientific and practical importance. For many years the region has received much attention from both hydrologists and botanists. It is therefore surprising that this subject should have received but little thorough systematic study in the desert region of the United States and should be covered by only a meager and unsatisfactory literature. The explanation probably lies in the fact that the subject is in the border land between hydrology and botany and has not been preempted by workers in either science. The ground-water geologists who have worked in the region, realizing their lack of training in botany, have avoided getting very deeply involved in the subject; on the other hand, the botanists who have worked in the region, unfamiliar with the principles of ground-water hydrology, have for the most part

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[19] Wagner, P. A., The geology and mineral industry of Southwest Africa: South Africa Geol. Survey Mem. 7, pp. 22, 116, 1916.

[20] Meinzer, O. E., Routes to desert watering places in California and Arizona: U. S Geol. Survey Water-Supply Paper 490–A, p. 1, 1920.

failed to realize the significance of the subject or have purposely avoided going so far afield from their familiar precincts.

The theory that plants in general, especially forest trees, draw upon the ground-water supply has been expressed by numerous authorities—for example, Ototzky,[21] Storer,[22] McGee,[23] Bownman,[24] and Zon.[25] Most of these writers have not been much concerned as to whether the trees and other plants actually withdraw water from the zone of saturation or whether they deplete the ground-water supply by absorbing the soil water before it can seep down to the water table, although they generally seem to imply actual removal from the saturated zone. As a rule, they have not been interested in distinguishing between different species in this respect. McGee conceived the idea that agricultural crops throughout the Great Plains and other semiarid regions are supplied largely by ground water that rises from the zone of saturation by capillarity, but this suggestion is not well supported by the known facts.

The idea that plants of certain species more than others utilize water from the zone of saturation has been recognized, or at least suggested by several eminent botanists. Coulter,[26] a leading authority on botany in this country, states that "there is what may be called a water level in soils, and it is important to note the depth of this level beneath the surface," and that "the depth of the water level helps to determine plant societies." Warming[27] states that "it would appear that the most potent and decisive factor [in the differences in vegetation in various parts of such a country as Denmark] is the amount of water in soil, and this in turn depends upon the depth to the water table and upon the physical characters of soil." He also calls attention to the zonal arrangement of the vege-

[21] Ototzky, P., Les eaux souterraines, leur origine, leur régime et leur distribution, Deuxième partie, Les eaux souterraines et les forêts, principalement dans les plaines de latitudes moyennes, St. Petersburg, 1905 (published in Russian); Influence de forêts sur les eaux souterraines; Annales sci. agronomique, 2d ser., 3d year, vol. 2, pp. 476–477, 1897; Influence des forêts sur les eaux souterraines: Idem, 2d ser., 5th year, vol. 1, pp. 300–316, 1899; Die Grundgewässer under den Wäldern (abstract by Prof. K. Keilhack): Geol. Centralbl., Band 2, Jahrgang 1902, pp. 630–631; Le niveau de l'eau souterraine sous bois et hors en 1902, dans les landes de Gascogne; Annales sci. agronomique, 3d ser., vol. 1, No. 2, pp. 116–119, 1907.

[22] Storer, F. H., Agriculture in some of its relations with Chemistry, pp. 47–114, New York, 1887.

[23] McGee, W J, Field records relating to subsoil water: U. S. Dept. Agr. Bur. Soils Bull. 93, 1913.

[24] Bowman, Isaiah, Forest physiography, pp. 41–54, New York, 1911.

[25] Zon, Raphael, How the forests feed the clouds, in Caldwell, O. W., and Slosson, E. E., Science remaking the world, pp. 212–222, New York, 1924.

[26] Coulter, J. M., Plants, a textbook of botany, p. 163, New York, 1900.

[27] Warming, Eugen., Oecology of plants, pp. 45, 97, 131, 132, Oxford, 1909. The first edition of this treatise was published in Danish in 1895.

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tation around every lake and pool and states that "differences of a few centimeters in the level of the water table suffice to evoke wide distinctions in the vegetation." He bases these statements largely on the work of other botanists, especially Fielberg, Raunkiär, and Massart.

In 1891 a botanical reconnaissance of the Mohave Desert and Death Valley regions, in California, was made by Coville.[28] He described the zonal arrangement of the vegetation surrounding alkaline marshes or playas and divided the plants found in the desert into two significant classes—those of humid habitat and those of arid habitat. The list of plants of humid habitat probably comes nearer to being a catalog of desert ground-water plants than anything else that has been published in this country. However, such abundant ground-water plants as greasewood and rabbit brush are included in the list of desert plants of arid habitat. Coville recognized three kinds of soil moisture—hydrostatic, capillary, and hygroscopic—and defined hydrostatic moisture as "free water, such as that which rises in a well or stands beneath a swamp"—that is, ground water, as defined in this paper. He mentioned mesquite as an indicator of ground water where it occurs at depths of a few yards, and alkali sacaton (*Sporobolus airoides*) and other plants as indicators where it occurs at depths of only a few feet. He dismissed the subject, however, with the following statement: "Such sources of water are, however, not to be considered in a discussion of the desert proper. Capillary moisture also exists in the vicinity of springs and permanent underground water supplies; but in such cases, like the hydrostatic moisture from which it arises, it has no connection with the true desert vegetation."

The Desert Botanical Laboratory of the Carnegie Institution of Washington was established at Tucson, Ariz., in 1903, to study the relation of plants to an arid climate and to substrata of unusual composition. The botanists of this laboratory in their investigations have generally recognized the relation of certain species to the water table, and the subject has been studied by Spalding[29] and especially by Cannon.[30] Recent papers by Markle,[31] Weaver,[32] and

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[28] Coville, F. V., Botany of the Death Valley expedition: Contr. U. S. Nat. Herbarium, vol. 4, pp. 23, 31, 32, 35, 38, 39, 47, 1893.

[29] Spalding V. M., Distribution and movements of desert plants: Carnegie Inst. Washington Pub. 113, pp. 5–17, 1909.

[30] Cannon, W. A., op. cit.

[31] Markle, M. S., Root systems of certain desert plants: Bot. Gazette, vol. 64, pp. 177–205, 1917.

[32] Weaver, J. E., The ecological relations of roots: Carnegie Inst. Washington Pub. 286; 1919; Root development of field crops: McGraw-Hill Book Co., N. Y., 1926.

Clements,[33] do not contain much that is applicable to the present subject.

One of the pioneers in the modern development of this subject is G. E. P. Smith, irrigation engineer in the University of Arizona, with whom is associated J. J. Thornber, botanist. As early as 1915 Smith made the statement that he had long held the hypothesis that the water absorbed and transpired by mesquite and other trees constitutes the principal loss from the ground-water reservoir.

A thorough and valuable investigation of the indicator significance of native plants in Tooele Valley, Utah,[34] was made by the United States Department of Agriculture. In this investigation the relation of the principal ground-water plants, such as greasewood, to the water table was recognized, and much precise information was obtained bearing on the present subject. No specific study was made of this relation, however, as no data were obtained on the position of the water table, the chemical character of the ground water, or the alkali or moisture content of the soil below the depth of 4 feet. Much valuable work has more recently been done by Shantz, Aldous, Piemeisel, and others[35] on the general subject of the indicator significance of native plants in the arid and semiarid regions of the United States, including some reference to ground water. Much of this recent work has been done in connection with the classification of the public domain by the Geological Survey with respect to its irrigability and its value for arid farming and grazing.

In most of the older water-supply papers of the United States Geological Survey dealing with discharge of ground water no mention is made of discharge by plants or indeed by evaporation from the soil, showing that these processes of ground-water discharge were not recognized or that their importance was not appreciated. In recent years, however, in the investigations by the Geological Survey of ground water in the desert regions, the great importance of these processes has been fully recognized and attention has necessarily been given to the plants that feed on ground water. The reports that have resulted from these investigations contain considerable

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[33] Clements, F. E., Plant indicators, the relation of plant communities to process and practice: Carnegie Inst. Washington Pub. 290, 1920.

[34] Kearney, T. H., and others, Indicator significance of vegetation in Tooele Valley, Utah: Jour. Agr. Research, vol. 1, pp. 365–417, 1914.

[35] Shantz, H. L., Grassland and desert shrub: Atlas Am. Agr., pt. 1, The physical basis of agriculture, sec. E, Natural vegetation, 1924. Aldous, A. E., and Shantz, H. L., Types of vegetation in the semiarid portion of the United States and their economic significance: Jour. Agr. Research, vol. 28, pp. 99–127, 1924. Shantz, H. L., and Piemeisel, R. L., Indicator significance of the natural vegetation of the southwestern desert region: Jour. Agr. Research, vol. 28, pp. 721–801, 1924.

specific information on the subject.[36] However, the work was done by geologists, who were not equipped to study the botanical phases of the subject.

QUESTIONS THAT DESERVE FURTHER STUDY

Questions in regard to the ground-water plants that should receive more thorough study are as follows: What are the species that habitually depend on the zone of saturation? To what extent and under what circumstances do these species grow where they can not reach the zone of saturation? To what extent will other species utilize water from the zone of saturation, and to what extent are they killed if the water table rises to their roots? Do the ground-water plants develop root systems in the capillary fringe, or do they send their roots into the zone of saturation? Do they avoid the alkali in the soil by sending their roots into or nearly to the zone

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[36] Reference is made especially to the following publications:

Ball, S. H., A geologic reconnaissance in southwestern Nevada and eastern California: U. S. Geol. Survey Bull. 308, p. 22, 1907.

Mendenhall, W. C., Some desert watering places in southeastern California and southwestern Nevada: U. S. Geol. Survey Water-Supply Paper 224, pp. 20, 21, 1909.

Meinzer, O. E., Ground water in Juab, Millard, and Iron Counties, Utah: U. S. Geol. Survey Water-Supply Paper 277, pp. 24, 25, 110, 128, 1911.

Lee, C. H., An intensive study of the water resources of a part of Owens Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 294, p. 77, 1912.

Meinzer, O. E., and Kelton, F. C., Geology and water resources of Sulphur Spring Valley, Ariz.: U. S. Geol. Survey Water-Supply Paper 320, pp. 171–187, 1913.

Meinzer, O. E., and Hare, R. F., Geology and water resources of Tularosa Basin, N. Mex.: U. S. Geol. Survey Water-Supply Paper 343, pp. 193–206, 306–311, 1915.

Carpenter, Everett, Ground water in southeastern Nevada: U. S. Geol. Survey Water-Supply Paper 365, pp. 13, 36, 45, 48, 59, 66, 69, 71, 73, 78, 1915.

Gregory, H. E., The Navajo country—a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Water-Supply Paper 380, pp. 130–131, 1916.

Schwennesen, A. T., Ground water in the Animas, Playas, Hachita, and San Luis Basins, N. Mex.: U. S. Geol. Survey Water-Supply Paper 422, pp. 50–53, 144–149, 1918.

Meinzer, O. E., Geology and water resources of Big Smoky, Clayton, and Alkali Spring Valleys, Nev.: U. S. Geol. Survey Water-Supply Paper 423, pp. 92–104, 159–161, 1917.

Waring, G. A., Ground water in Pahrump, Mesquite, and Ivanpah Valleys, Nev. and Calif.: U. S. Geol. Survey Water-Supply Paper 450, pp. 55, 56, 66, 1921.

Clark, W. O., and Riddell, C. W., Exploratory drilling for water and use of ground water for irrigation in Steptoe Valley, Nev.: U. S. Geol. Survey Water-Supply Paper 467, pp. 15, 38, 39, 1920.

Brown, J. S., Routes to desert watering places in the Salton Sea region, California: U. S. Geol. Survey Water-Supply Paper 490–A, p. 13, 1920.

Thompson, D. G., Routes to desert watering places in the Mohave Desert region, California: U. S. Geol. Survey Water-Supply Paper 490–B, pp. 98, 99, 110, 1921.

Brown, J. S., The Salton Sea region, California—a geographic, geologic, and hydrologic reconnaissance, with a guide to desert watering places: U. S. Geol. Survey Water-Supply Paper 497, pp. 16–19, 112–118, 1923.

Ross, C. P., The Lower Gila region, Arizona—a geographic, geologic, and hydrologic reconnaissance, with a guide to desert watering places: U. S. Geol. Survey Water-Supply Paper 498, pp. 15, 16, 1923.

Bryan, Kirk, The Papago country, Arizona—a geographic, geologic, and hydrologic reconnaissance, with a guide to desert watering places: U. S. Geol. Survey Water-Supply Paper 499, pp. 156, 157, 1925.

Thompson, D. G., The Mohave Desert region, California—a geographic, geologic, and hydrologic reconnaissance, with a guide to desert watering places: U. S. Geol. Survey Water-Supply Paper 578 (in preparation).

of saturation, where they may obtain less concentrated water? To what extent do the different species indicate the quality of the ground water? How do they adapt themselves to the fluctuations of the water table? What are the conditions where there is a gravelly subsoil, with a very thin capillary fringe, as compared with a loam subsoil that has a thick capillary fringe? What are the maximum and minimum limits of depth to the water table for different species? What is the greatest depth from which ground water is lifted by plants? In species that habitually send their roots to considerable depths, what adaptations have the young plants for enduring drought until they can get their roots down to the capillary fringe? Do plants of this kind propagate by runners so that the young plant can be nursed by the parent plant until it can get its roots down to the water? What changes take place in the physiology and growth of such plants when their roots reach ground water? Are the ground-water plants economical or wasteful of water, or are some economical and others wasteful, or have they adaptations which permit them to be economical or wasteful according to circumstances? How does the depth to the water table affect the rate at which a given species will lift water? What methods can be employed to determine for a given region the quantity of ground water that is annually discharged by the vegetation and that could be utilized by pumping from wells? What are the prospects of increasing the agricultural production of the arid and semiarid regions by developing ground-water plants of economic value?

ACKNOWLEDGMENTS

The writer is deeply indebted to A. E. Aldous, of the Geological Survey; to H. L. Shantz, of the Department of Agriculture; and to J. J. Thornber and G. E. P. Smith, of the University of Arizona, for their critical examination of this paper and for the many valuable suggestions which they made; also to Kirk Bryan and D. G. Thompson, of the Geological Survey; A. E. Douglass, of the University of Arizona; and R. L. Piemeisel, of the Department of Agriculture, all of whom made valuable contributions to this investigation. Many of the photographs of plants in their natural habitat used in this paper were taken by D. G. Thompson or J. S. Brown in connection with their field work on desert watering places.

PRINCIPAL SPECIES OF PLANTS THAT HABITUALLY FEED ON GROUND WATER

ARRANGEMENT OF SPECIES

Before discussing the subject further it is desirable to describe the principal ground-water plants with reference to what is known of their relation to the water table. As the subject has not been systematically studied no attempt will be made to give a complete list of species. However, for the purposes of hydrology it is not so necessary to have a complete list of species as to recognize the comparatively few species that tend to form the dominant vegetation in their natural habitat. The descriptions of specific plants are practically limited to definite observations made by the writer or others of the relation of the species to the water table. This method unavoidably results in uneven treatment of the different kinds of plants and probably in the omission of some species that ought to be included.

No attempt is made to arrange the species that are described in strictly systematic order. In general the plants that indicate water very near the surface are described first and those that indicate successively greater depths to the water table are described later, except that the trees and woody bushes are described last even though they grow where the ground water is very near the surface.

No detailed descriptions are given of the species that are discussed, but more or less technical descriptions of most of them can be found in one or more of the following publications:

Coulter, J. M., Manual of the botany of the Rocky Mountain region from New Mexico to the British boundary, New York and Chicago, 1885.

Coulter, J. M., and Nelson, Owen, New manual of botany of the Rocky Mountains, New York, 1909.

Coville, F. V., Botany of the Death Valley expedition: Contr. U. S. Nat. Herbarium, vol. 4, pp. 55–233, 1893.

Parish, S. B., Plant ecology and floristics of Salton Sink: Carnegie Inst. Washingon, Pub. 193, pp. 104–114, 1914.

Shantz, H. L., and Zon, Raphael, Natural vegetation: U. S. Dept. Agr. Atlas Am. Agr., pt. 1, sec. E, 1924.

Sudworth, G. B., Forest trees of the Pacific slope, U. S. Forest Service, 1908.

Tidestrom, Ivar, Flora of Utah and Nevada: Contr. U. S. Nat. Herbarium, vol. 25, 1925.

Wooton, E. O., and Standley, P. C., Flora of New Mexico: Contr. U. S. Nat. Herbarium, vol. 19, 1915.

Wooton, E. O., and Standley, P. C., The grasses and grasslike plants of New Mexico: New Mexico Coll. Agr. and Mechanic Arts Bull. 81, 1912.

RUSHES, SEDGES, AND CAT-TAILS

Several species of rushes (*Juncus*), sedges (*Scirpus*), and cat-tails (*Typha*) commonly grow along the margins of shallow bodies of surface water and are frequently found in the pools and currents of water produced by springs. To some extent they also grow where the water table stands a short distance below the surface, and in these situations they may properly be regarded as ground-water plants. They generally though not invariably indicate water of good quality.[37]

[37] Mendenhall, W. C., op. cit. (Water-Supply Paper 224), p. 20.

In Tooele Valley, Utah, *Juncus balticus* was found in association with salt grass where the water table is near the surface.[38] A number of species of rushes, sedges, and cat-tails are given in Coville's list of desert plants of humid habit, and detailed information as to their occurrence in the desert regions are given both in Coville's catalog of species[39] and in the catalog of plants in the Salton Sink by Parish.[40]

As the plants of this type grow largely where the water is visible at the surface or where there are other evident signs of water their value as indicators is accordingly limited, but even in these places they may serve a useful purpose in attracting attention to the localities where the water occurs. They are, moreover, valuable in indicating areas where a perennial supply of ground water is present in distinction from wet areas produced by temporary supplies of surface or ground water, where such plants can not as a rule survive the dry periods.

REEDS AND CANE

The common reed, or giant reed grass (*Phragmites communis*) is found along streams and ponds and also in many places where there is no surface water but where the ground water is not far below the surface. It occurs in the main area of shallow ground water in the lower basin of Big Smoky Valley, Nev., and in the Rye Patch, near Tonopah (p. 18), but it was not seen except where the ground water is near the surface. It was observed in the Mohave Desert region,[41] where the water table was only 3 or 4 feet below the surface.

Wild cane is listed by both Ball[42] and Brown[43] as a reliable indicator of shallow ground water. It was observed by Brown in Coachella Valley, Canebrake Canyon, and a few other places in the Salton Sea region, California. It may grow to a height of 10 feet or more as a tall jointed stalk with green leaves at the top, thus attracting attention to localities where water can be found.

WILD RYE

The species of wild rye commonly called giant rye grass or giant wild rye (*Elymus condensatus*), which in some places grows 10 feet high, is widely distributed through the West. It was observed in areas of shallow ground water in Nevada, particularly in the so-called Rye Patch, in Ralston Valley, east of Tonopah. Ball,[44] who made a geologic reconnaissance in southwestern Nevada and adjacent parts of California, in 1905, in describing signs of water in

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[38] Kearney, T. H., etc., op. cit., p. 407.
[39] Coville, F. V., op. cit.
[40] Parish, S. P., op. cit.
[41] Thompson, D. G., op. cit.
[42] Ball, S. H., op. cit. (Bull. 308), p. 22.
[43] Brown, J. S., op. cit. (Water-Supply Paper 497), p. 113.
[44] Ball, S. H., op. cit. (Bull. 308), pp. 22, 24.

the desert, states that "where rye grass and cane grow there is water at the surface or at a moderate depth." Hillman,[45] in a discussion of the forage value of this species states: "The plants do not occur on the dryest hills but on rather lower land. The grass is frequently met in the subalkaline parts of the valleys and at the entrances to the mountain canyons." In Steptoe Valley, Nev., giant wild rye was found by Clark and Riddell[46] in tracts where the depth to the water table does not exceed 12 feet. In Tooele Valley, Utah, the same species was found in the greasewood-shadscale association where the water table is at only moderate depth but not extremely near the surface.[47] In areas of somewhat more abundant precipitation giant wild rye apparently grows where the water table is not within reach. Thus a good growth of this species is reported by Aldous in association with sagebrush in upland tracts of San Pete Valley, Utah, where the average annual precipitation is about 15 inches. The wheatlike rye grass (*Elymus triticoides*) is reported by Thornber as a ground-water plant, growing invariably in rich valley soils where the ground water is relatively near the surface.

Both the giant reed grass and the giant rye grass are abundant in the Rye Patch, in Ralston Valley, Nev., in association with salt grass, big greasewood, and rabbit brush. At the Rye Patch were sunk the wells that furnished the first adequate water supply for the city of Tonopah, the water being pumped through a pipe line 11 miles long and lifted a height of 600 feet. The Rye Patch is situated along the axis of a desert valley about 50 miles long, at a point where an underground barrier is believed to be formed by lava beds. So far as known, it is the only area of shallow ground water along the axis of this large valley and affords a conspicuous example of a very valuable water supply that was located by the presence of ground-water plants. In the first wells that were sunk the water level was originally 8 feet below the surface but is now somewhat lower. In some places in the Rye Patch ground water stands within 5 feet of the surface. The precise depth to the water table at the points where the reed grass and wild rye are growing was not determined.[48]

Certain plants of the character of wild rye are also found in areas of shallow ground water in the humid eastern part of the country, as, for example, near Washington, D. C., where they indicate localities in which fairly permanent water supplies can be obtained by digging shallow wells.

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[45] Hillman, F. H., Field notes on some Nevada grasses: Nevada Agr. Exper. Sta., Bull. 33, p. 11, 1896.

[46] Clark, W. O., and Riddell, C. W., op. cit. (Water-Supply Paper 467), p. 39.

[47] Kearney, T. H., and others, op. cit., pp. 400–401.

[48] Meinzer, O. E., op. cit. (Water-Supply Paper 423), pp. 95, 124–126.

SALT GRASS

One of the most widespread and trustworthy of all plants as an indicator of ground water is the common salt grass (*Distichlis spicata*). It is described by Wooton and Standley [49] as "a coarse perennial with stiff leaves and stems, a rather strict panicle, sometimes a little branched, with flattened spikelets of about 10 or a dozen flowers. It is a sod-forming grass, spreading by underground stems." (See fig. 2.) Doubtless if full information were available it would be found that salt grass is growing in many places that are watered from other sources than ground water or in clayey soils with considerable moisture but without a definite water table. The fact will always remain, however, that throughout a vast desert region in the western part of the United States this species is normally a ground-water plant, that it faithfully shows the presence and approximate extent of literally hundreds of areas of shallow ground water, and that it can be used with great confidence as an indicator of ground water by anyone who has a reasonable amount of experience and judgment. (See pl. 3, *A*.)

Salt grass has been described as a ground-water plant in California,[50] Arizona,[51] New Mexico,[52] Utah,[53] Nevada,[54] Nebraska,[55] and Wyoming,[55] but it also occurs in other Western States.[56]

In an intensive study by Lee [57] of the discharge of ground water in the Independence district of Owens Valley, Calif., it was found that the belt of grass and alkali land in this district from which ground water is discharged covers about 55 square miles, or 35,000 acres. (See fig. 3.) Most of this belt is covered with salt grass, which grows where the depth to ground water does not exceed about 8 feet. In about 12 square miles of this belt the average depth to the water table is less than 3 feet, in about 18 square miles it is be-

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[49] Wooton, E. O., and Standley, P. C., The grasses and grasslike plants of New Mexico: New Mexico Agr. Exper. Sta. Bull. 81, pp. 120, 121, 1912.

[50] Mendenhall, W. C., op. cit. (Water-Supply Paper 224), p. 21. Lee, C. H., op. cit. (Water-Supply Paper 294), pp. 14, 77, 84, 85. Thompson, D. G., op. cit. (Water-Supply Paper 490–B), p. 98. Brown, J. S., op. cit. (Water-Supply Paper 497), p. 113. Shantz, H. L., and Piemeisel, R. L., op. cit., p. 762.

[51] Gregory, H. E., op. cit. (Water-Supply Paper 380), p. 131. Shantz, H. L., and Piemeisel, R. L., op. cit., p. 798.

[52] Meinzer, O. E., and Hare, R. F., op. cit. (Water-Supply Paper 343), pp. 193, 198. Wooten, E. O., and Standley, P. C., op. cit. pp. 120, 121.

[53] Kearney, T. H., and others, op. cit., pp. 407, 408.

[54] Ball, S. H., op. cit., p. 24. Meinzer, O. E., op. cit. (Water-Supply Paper 423), pp. 95, 100. Waring, G. A., Ground water in Reese River basin and adjacent parts of Humboldt River basin, Nev.: U. S. Geol. Survey Water-Supply Paper 425, p. 110, 1919; Ground water in Pahrump, Mesquite, and Ivanpah Valleys, Nev. and Calif.: U. S. Geol. Survey Water-Supply Paper 450, p. 66, 1921. Clark, W. O., and Riddell, C. W., op. cit. (Water-Supply Paper 467), p. 39.

[55] Meinzer, O. E., Ground water for irrigation in Lodgepole Valley, Wyo. and Nebr.: U. S. Geol. Survey Water-Supply Paper 425, p. 48, 1919.

[56] Aldous, A. E., and Shantz, H. L., op. cit., p. 111. Shantz, H. L., op. cit., p. 26.

[57] Lee, C. H., op. cit. (Water-Supply Paper 294), pp. 14, 80, 84, 85, 131; pl. 25.

tween 3 and 4 feet, and in about 25 square miles it is between 4 and 8 feet. The annual fluctuation of the water table in this belt as observed in 122 wells ranged from about 1.5 to 4 feet and averaged 3.14 feet.

FIGURE 2.—Salt grass (*Distichlis spicata*). After Wooton and Standley

The discharge of ground water by transpiration from salt grass and other vegetation and by evaporation from the soil was found to average about 2 feet a year over the area and to vary inversely about as the depth to the water table, down to depths of 8 feet (p. 86).

In Figure 3 lines indicating equal depth to ground water are drawn to show depths of 8, 4, and 3 feet. In the vicinity of the 8-foot line salt

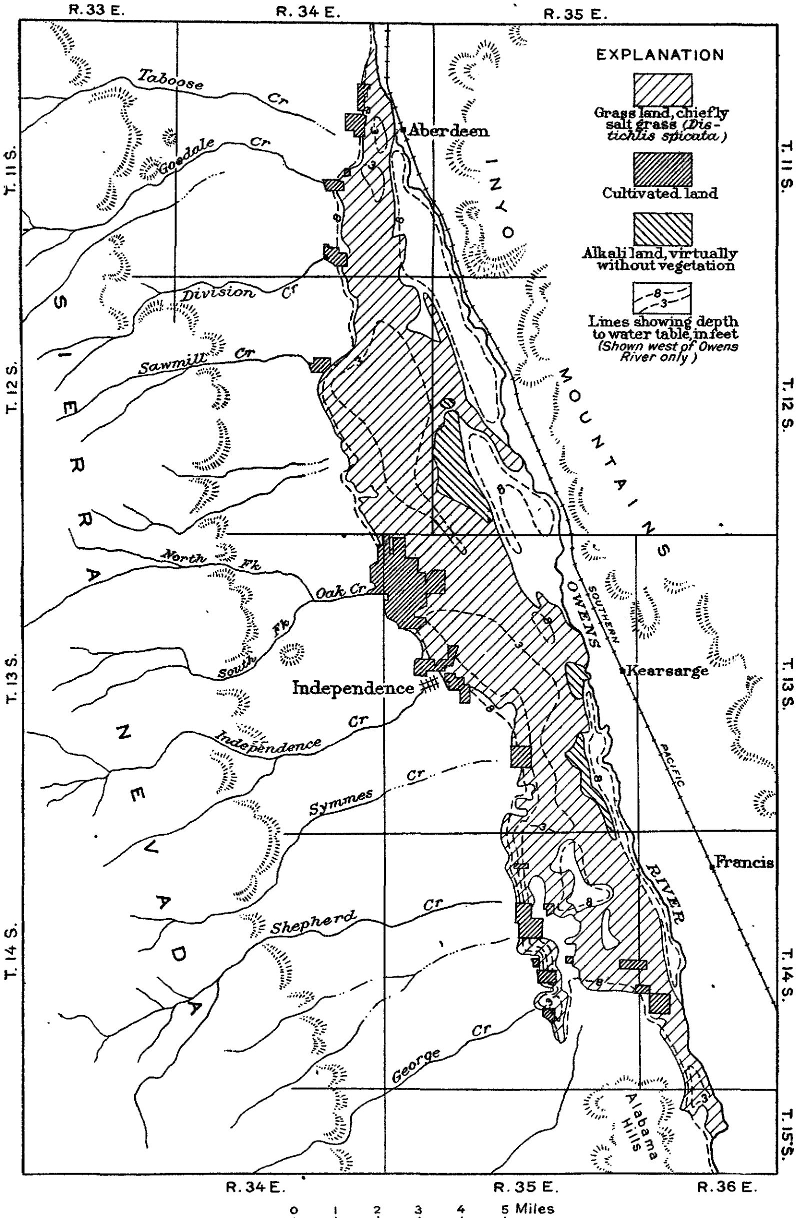

FIGURE 3.—Map of Independence district of Owens Valley, Calif., showing area of ground-water discharge. (After Lee, C. H., op. cit. (Water-Supply Paper 294), pl. 25)

grass begins to appear and gradually becomes dominant with increasing depth to the water table. Farther east, near and within the area inclosed by the 4-foot line, it grows luxuriantly. Within the 3-foot line fresh-water grasses thrive where there is sufficient surface water to leach out and carry away most of the alkali, but the salt grass grows well even where the soil contains considerable alkali.

In 15 localities in Big Smoky Valley, Nev., in which salt grass was growing, the depth to the water table was found to range from 2 to 11.7 feet in the fall, when the water table was about at its lowest level for the year.[58] In Clayton Valley, Nev., in the same season salt grass was dominant in a zone bordering the playa in which the depth to the water table did not greatly exceed 10 feet, but it was evident that the salt grass extended slightly beyond the 10-foot limit.[59]

In many places salt grass covers the ground virtually to the exclusion of other vegetation. However, out of 18 localities in Big Smoky Valley there were only 2 in which salt grass was growing alone; in 9 localities it was associated with rabbit brush, in 7 with greasewood, and in 1 or 2 each with pickleweed, alkali sacaton, salt bush (*Atriplex torreyi*), willow, poplar, and sagebrush. In Ralston Valley it is associated with greasewood, rabbit brush, wild rye, and giant reed grass. In Clayton Valley it is associated with pickleweed, rabbit brush, and seepweed.

In Tooele Valley, Utah, salt grass is a leading species on the grass flat, which lies between the greasewood-shadscale belt and the salt flats bordering Great Salt Lake. The grass flat covers a gently sloping or nearly level expanse and appears to be lower in altitude than some of the ridges and hillocks situated between it and the shore of the lake. The area is thus somewhat analogous to a coastal lagoon and may have had a similar origin. During the greater part of the year it has a very moist soil, obviously because the water table is close to the surface. Salt grass is more or less abundant in all parts of the grass flats and also penetrates the salt flats, where in some places it is associated scatteringly with pickleweed and in other places it forms dense mats. In the wetter portions of the grass flat salt grass is the principal component of a meadowlike vegetation, with *Juncus balticus*, *Suaeda erecta*, *Puccinellia airoides*, and *Glaux maritima* as chief associates and with numerous other species scatteringly present.[60]

Mexican salt grass (*Eragrostis obtusiflora*) has been observed at the margins of the playas in southwestern New Mexico[61] and southeastern Arizona.[62] In regard to this species Wooton and Standley

[58] Meinzer, O. E., op. cit. (Water-Supply Paper 423), p. 100, pl. 12.
[59] Idem, pp. 144, 145.
[60] Kearney, T. H., and others, op. cit., pp. 405, 407, 408, 413.
[61] Wooton, E. O., and Standley, P. C., op. cit., p. 120.
[62] Meinzer, O. E., and Kelton, F. C., op. cit. (Water-Supply Paper 320), pp. 172–181, 184, 186.

state that "it might easily be mistaken for ordinary salt grass, which it resembles in many respects, but the inflorescence is somewhat different. It is of some importance in the region mentioned and may occur elsewhere, having been overlooked on account of its similarity to ordinary salt grass." Mexican salt grass was observed at 13 localities in Sulphur Spring Valley, Ariz., at which the depth to the water table was known. In these localities the depth to the water table ranged from 4 to 15 feet in the fall of a dry year, when the water table was doubtless at a low stage. Out of 27 localities there were 2 in which this grass was growing alone, whereas in 21 it was associated with alkali sacaton, in 4 with seepweed, in 3 with mesquite, in 2 with chamiso, and in at least 4 with grama grass.

SACATON

Sporobolus airoides, a species of sacaton that is known by several common names, including tussock grass, alkali sacaton, red-top sacaton, fine-top sacaton, purple top, bunch grass, and salt grass, is a coarse grass, 2 to 3 feet high, with stems forming large tufts, clothed below by dead sheaths. (See fig. 4.) In late summer the feathery purple panicles of this grass are a characteristic feature of the vegetation. It is reported to occur from California to Nebraska and southward into New Mexico and Texas.[63]

Studies of this grass in relation to its environment in Tooele Valley, Utah, and Sulphur Spring Valley, Ariz., indicate that it is commonly a ground-water plant in these valleys, but not much tangible information is at hand as to whether in some localities it parts company with the water table. It is one of the two species that were especially mentioned by Coville[64] as indicators of ground water in Death Valley. He states that this grass "has come to be of special importance to the desert traveler, for it indicates the presence, within a few feet of the surface, of water sufficiently fresh to drink."

In Tooele Valley it grows in association chiefly with rabbit brush, forming the so-called *Sporobolus-Chrysothamnus* community, which covers a large part of the grass flat. Either of these species may occur where the other is absent, but as a rule they are closely associated. Salt grass is also usually more or less abundant in this community. The *Sporobolus-Chrysothamnus* zone is bordered on the outside by the greasewood-shadscale zone and on the inside by the salt-grass zone. In the few tests of soil moisture that were made in the *Sporobolus-Chrysothamnus* zone considerable excess of moisture over that represented by the wilting coefficient was generally found from the first or second foot down, suggesting the extension of the

[63] Coulter, J. M., op. cit., p. 411. Kearney, T. H., and others, op. cit., pp. 406, 407.
[64] Coville, F. V., op. cit., p. 35.

capillary fringe virtually to the surface and the water table at a depth of only a few feet. The association of alkali sacaton with salt grass and rabbit brush indicates a depth to the water table not

FIGURE 4.—Alkali sacaton or tussock grass (*Sporobolus airoides*). (After Wooton and Standley, op. cit., p. 77)

exceeding 10 or 15 feet. The alkali content of a number of soil samples taken where this grass was growing was found to be very moderate, averaging only about one-third of 1 per cent.

In Sulphur Spring Valley the zone of ground-water vegetation surrounding the barren playa is divided more or less definitely into belts, seepweed being dominant next to the playa, then Mexican salt grass associated with seepweed, then alkali sacaton with the salt bush chamiso, and finally mesquite. The alkali sacaton is prominent, occurring throughout a wide belt. It was found in 24 localities where the depth to the water table and the alkali content of the soil were determined. In these localities the depth to the water table at a low stage ranged from 4 to 27 feet, but in 19 of them it was not more than 15 feet, and in 11 it was not more than 10 feet. Alkali sacaton was also found in a few localities where the depth to the water table was not known but was estimated to be greater than 27 feet. In 9 of the 24 localities it was found in association with mesquite along the outer edge of the sacaton belt, in 11 it was found in association with Mexican salt grass in the inner part of the sacaton belt or within the salt-grass belt, and in 2 it was found in association with seepweed. The soil at the sacaton localities that were investigated generally contains only moderate amounts of alkali. The belt in which this species is dominant has rather definite limits and is closely related to the water table. Its luxuriance in this belt shows clearly that it habitually feeds on water from the zone of saturation; apparently, however, it has spread in some localities to high land where its roots do not reach down to the capillary fringe. In southwestern New Mexico some alkali sacaton was reported by Schwennesen where the water table was estimated to be as much as 100 feet below the surface.[65]

Another species of sacaton (*Sporobolus wrightii*), also known as coarse-top sacaton to distinguish it from fine-top sacaton, or alkali sacaton, occurs widely throughout the arid regions in localities where considerable water is available. There is evidence that it grows in places where the soil is periodically well moistened by flood waters, but also in places where it feeds on ground water. The record furnished by a water-stage recorder maintained by G. E. P. Smith over a well in a sacaton tract shows that in this locality the coarse-top sacaton is a ground-water plant. J. J. Thornber[66] states that in Arizona the species typically depends on ground water.

PICKLEWEED, SAMPHIRE, SEEPWEED, AND OTHER SUCCULENT ALKALI-RESISTANT PLANTS

The succulent alkali-resistant bush here called pickleweed (*Allenrolfea occidentalis*) fringes the barren playas in many desert basins and is an indicator of shallow ground water. (See figs. 5 and 9.) In Big Smoky Valley, Nev., it occurs in association with salt grass

[65] Schwennesen, A. T., op. cit. (Water-Supply Paper 422), p. 144.
[66] Personal communication.

and also adjacent to the barren playas on alkaline soil beyond the limits of the salt grass. In one locality where this species is growing the depth to the water table was found to be only 2 feet.[67]

In the Tularosa Basin, N. Mex., *Allenrolfea occidentalis* is associated with salt grass in the area of alkaline soil and shallow ground water [68] and occurs also on soil that is too alkaline, too dense, or too

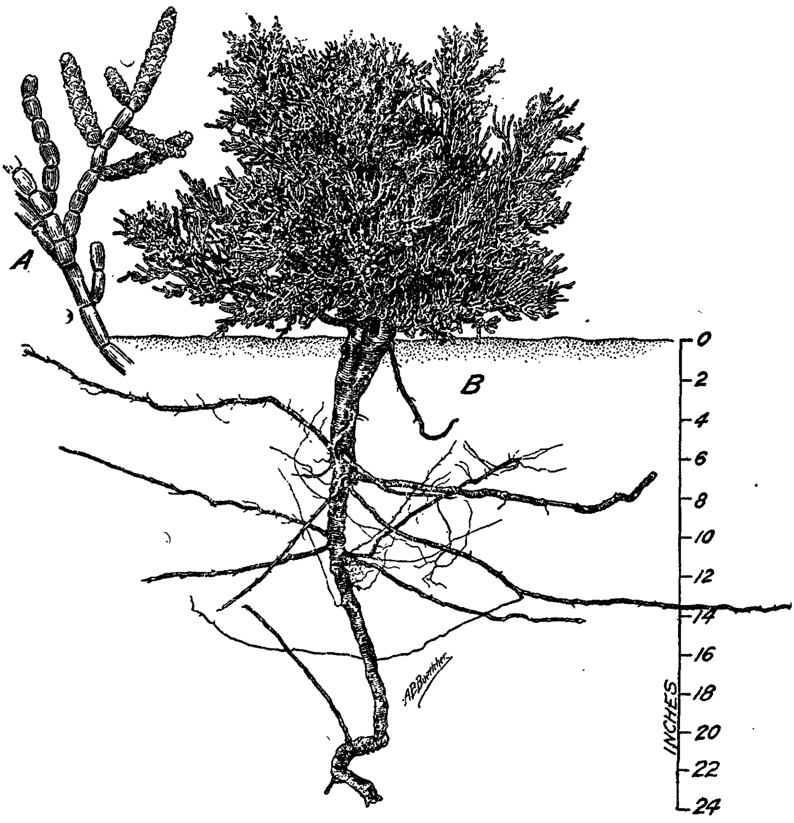

FIGURE 5.—Pickleweed (*Allenrolfea occidentalis*). (From Kearney, T. H., and others, op. cit., fig. 11.) *A*, Detail of a fruiting branch showing the cylindrical, fleshy, practically leafless stems; *B*, a plant showing the large tap root and rather scanty lateral roots characteristic of this species.

frequently submerged for salt grass. In this basin it was observed in four localities in which the depth to the water table in the fall ranged from 1.3 to 6 feet; also in a locality in which the depth was 11 feet and in another in which it was 20 feet.[69] In these last two localities the soil was shown by analysis to contain large amounts of alkali. It would be instructive to ascertain whether in these locali-

[67] Meinzer, O. E., op. cit. (Water-Supply Paper 423), pp. 95, 100.

[68] Meinzer, O. E., and Hare, R. F., op. cit. (Water-Supp'y Paper 343), pp. 193–199.

[69] Idem, pp. 306–311.

ties the plant sends its roots down to the capillary fringe or whether it has spread beyond its limits as a ground-water plant upon the highly alkaline soil. The long taproot of this species suggests that it may be able to obtain ground water from considerable depths, although it is most abundant where the water table is very near the surface.

Allenrolfea occidentalis is described by Parish [70] as occurring, in association with *Dondia torreyana*, on the most alkaline soil of the large flat extending northward from the Salton Sea, where the soil is commonly moist from rising ground water.

In the report on Tooele Valley, Utah,[71] is given the following detailed and exceedingly instructive description of the salt flat that borders Great Salt Lake and of the occurrence of *Allenrolfea occidentalis* and associated species on this flat:

Along the margin of Great Salt Lake there is a belt of low land which varies in width from about 4 miles, near the axis of the valley, to a mere fringe on the east and west sides where the mountain ranges approach the lake shore. Much of this area is covered with water at times but in summer presents a dazzling white surface due to the heavy crust of salts. These flats are divided into shallow basins of greater or less extent, separated by low ridges and hummocks. All but the lowest of these elevations are occupied by the greasewood-shadscale association, while the basins and flats when not altogether devoid of vegetation support a few extremely halophytic species which occur either as scattered individuals or in crowded colonies.

The two environments are ecologically quite distinct. * * * Greasewood occurs not only on the higher ridges in association with shadscale but also on the lower hummocks and at the edges of the depressions in association with *Allenrolfea*. Shadscale, on the other hand, is not found in the depressions, nor do the typical salt-flat species occur on the higher ridges.

The vegetation of the flats and depressions comprises several communities, each characterized by the presence of a single species—*Allenrolfea occidentalis*, *Salicornia utahensis*, and *Salicornia rubra*. The first of these is by far the most abundant and widely distributed. These three species appear to be the most salt-resistant of the flowering plants of this region, taking possession of the land left bare by the recession of the lake as soon as its salt content has been reduced sufficiently from the point of saturation with the excessively saline lake water to permit the growth of any flowering plant.

In the *Allenrolfea* community the dominant species, *Allenrolfea occidentalis*, is a shrubby plant with numerous cylindrical, jointed, fleshy, practically leafless branches and a large taproot. In Tooele Valley it rarely exceeds a height of 2 feet. There is considerable variation in the habitat of this plant, but it develops most characteristically on low hummocks on the salt flats and near the bases of the higher ridges, usually preferring a slightly better drained and less saline soil than the species of *Salicornia*. In places, however, it is seen scattered over the surface of the flats, the dark brownish-green tufts of *Allenrolfea* contrasting strikingly with the pure white of the saline incrustation. The thinness of the stand is shown by a plat of a typical 10-meter

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[70] Parish, S. B., op. cit., pp. 92, 93.

[71] Kearney, T. H., and others, op. cit., pp. 408–412.

quadrat in which were growing only 110 individual plants of *Allenrolfea occidentalis*, the only species present. Often, as shown in this plat, *Allenrolfea* forms a pure community. On higher and better-drained ground, however, it is frequently associated with greasewood (*Sarcobatus vermiculatus*) and with *Suaeda* [*Dondia*] *moquinii*, while in the wetter depressions it often mingles with *Salicornia utahensis*. Plants of greasewood, when growing with *Allenrolfea*, are usually stunted and sickly looking. * * *

It is clear from the tests made of the moisture equivalent, wilting coefficient, and salt content of the soil that the presence of this plant is an almost invariable indicator that the soil (1) contains moisture available for growth, at least below the surface foot, throughout the summer; and (2) is excessively saline to a depth of at least 4 feet.

Salicornia utahensis is a nearly leafless plant with fleshy, jointed stems. It resembles small plants of *Allenrolfea* but is readily distinguished by the light blue-green color and by the fact that the branches are opposite, while in *Allenrolfea* they are alternate. It spreads by creeping rootstocks and forms pure colonies of greater or less size, which sometimes cover the bottoms of depressions, sometimes occupy hummocks elevated but a few inches above the general surface of the flats. In this case the appearance is much like the *Allenrolfea* hummocks, except that the latter are higher and the plants are larger and darker colored. This *Salicornia* is also found in association with *Allenrolfea* and with *Distichlis*.

No determinations were made of the moisture equivalent and moisture content of the soil where this community occurs, but two borings carried to a depth of 30 inches and 12 inches, respectively, showed that abundant moisture was present throughout that depth, as would be expected from the slight elevation of the land above the water surface of the lake.

Salicornia rubra, a small, shallow-rooted annual species of *Salicornia*, is found most abundantly in pure communities along drainage channels in the salt flats. The patches of *Salicornia rubra* are very conspicuous late in the summer, owing to the bright-red color then assumed by the plants. Scattered individuals of this species were also observed far out on the otherwise bare salt flats.

The species of seepweed that is also called iodine weed and inkweed (*Dondia torreyana*, also identified as *Dondia moquinii* and *Suaeda torreyana* or *moquinii?*) is a perennial shrub, commonly having a purplish color and found in Nevada, California, and other States, on alkaline soil where more than an ordinary supply of moisture is available. It frequently occurs adjacent to the greasewood zone on land that is somewhat more alkaline and lies a little closer to the water table. In Clayton Valley, Nev., it occurs, in association with salt grass, rabbit brush, and pickleweed, near the playa, in a zone in which the depth to the water table does not greatly exceed 10 feet. In Ralston Valley it occurs with greasewood along the margin of the shallow-water tract. In Big Smoky Valley, however, it appears not to be a reliable indicator of ground water, for it grows in places that are far above the water table, such as the undrained areas on the landward side of ancient beach ridges where storm waters accumulate.

In Sulphur Spring Valley, Ariz., is found an alkali-resistant bush commonly called burroweed and identified as a species of *Suaeda* (*Dondia*). It grows in the belt of shallow ground water and alkaline soil immediately surrounding the barren playa, in association with Mexican salt grass, and also in clumps at the margin of the playa where the surface is otherwise destitute of vegetation. In three localities of *Dondia* investigated in Sulphur Spring Valley the depth to the water table at a low stage ranged from 4 to 7 feet. In one locality, where the depth to the water table was not determined but was estimated to be 15 feet, this species was found, though not as the dominant vegetation.[72]

Two other species of alkali-resistant plants that indicate ground water were mentioned by Mendenhall[73] as growing in California—lowland purslane (*Sesuvium portulacastrum*) and wild heliotrope (*Heliotropicum curassavicum*), locally called "Chinese pusley." The lowland purslane grows in moist soils and indicates ground water but usually water of poor quality. The wild heliotrope is described by Coulter[74] as occurring along the seacoasts and also on saline soils in the interior. Mendenhall states that it grows only in moist soils, but as it has strong alkali-resistant powers the ground water on which it feeds may be brackish.

YERBA MANSA

Yerba mansa, a perennial herb which somewhat resembles the plantain weed in appearance has been listed as a ground-water plant in southern California by both Lee[75] and Thompson.[76] Lee states that it formerly grew in association with salt grass in the valleys of the western slope of San Diego County, Calif., where the water table commonly stood within 5 feet of the surface. Thompson observed it in the vicinity of Newberry Spring, in the Mohave Desert region, where the water table is only 3 or 4 feet below the surface.

RABBIT BRUSH AND RELATED SPECIES

One of the most conspicuous of the ground-water indicators in Nevada, Utah, and adjacent regions is the well-known desert bush commonly called rabbit brush or broom sage. The principal ground-water species of rabbit brush (*Chrysothamnus graveolens*) is a shrub with slender, whiplike branches that have small, narrow leaves.

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[72] Meinzer, O. E., and Kelton, F. C., op. cit. (Water-Supply Paper 320), pp. 172–181, 184, 186.

[73] Mendenhall, W. C., op. cit. (Water-Supply Paper 224), p. 20.

[74] Coulter, J. M., Manual of the botany of the Rocky Mountain region, from New Mexico to the British boundary, p. 258, 1885.

[75] Ellis, A. J., and Lee, C. H., Geology and ground waters of the western part of San Diego County, Calif.: U. S. Geol. Survey Water-Supply Paper 446, p. 110, 1919.

[76] Thompson, D. G., op. cit. (Water-Supply Paper 578).

In late summer it is made conspicuous by numerous small heads of yellow flowers which resemble those of golden rod.[77] In the Mohave Desert region, Calif., *Chrysothamnus mohavensis* was observed by Thompson[78] as a ground-water plant. Rabbit brush has been described as a ground-water plant in Big Smoky,[79] Ralston,[80] Clayton,[81] and Steptoe[82] Valleys, Nev.; in Tooele Valley[83] and Sevier Desert,[84] Utah; and in Owens Valley[85] and the Mohave Desert region,[86] Calif.

It is one of the most common plants in the shallow-water areas of Big Smoky Valley. It prefers the parts of these areas that have some drainage but also grows in very alkaline soil and is a fairly reliable indicator of shallow ground water. The zone of dominant rabbit brush is in a general way bordered on the inside by the salt-grass zone and on the outside by the greasewood zone. In seven localities of rabbit brush that were investigated the depth to the water table at a low stage ranged from 2.5 to 12 feet, and in another locality the depth was estimated to be 14 feet. In all eight of these localities the rabbit brush was associated with salt grass, and in all except one it was also associated with greasewood. In two of the localities it was associated with sagebrush (*Artemisia tridentata*), which does not depend on ground water. The alkali in the soil of a few of the localities that were tested ranged from 0.20 to 3.15 per cent and averaged a little over 1 per cent.

In the Sevier Desert and some other tracts of shallow ground water in western Utah rabbit brush grows in close relation to greasewood but generally on somewhat better-drained and less alkaline soil. On some of the low ridges formed by abandoned river channels the greasewood is largely displaced by rabbit brush, and some abandoned channels can be traced long distances by such bands of yellow-topped brush winding through the monotonous expanse of greasewood. In Tooele Valley, where rabbit brush grows in association with alkali sacaton and salt grass, the alkali content of the soils that were tested is only very moderate. A considerable excess of moisture over that needed to prevent wilting suggests the presence of the capillary fringe and the existence of the water table probably within 10 feet of the surface. In studies made in Steptoe Valley,

[77] Kearney, T. H., and others, op. cit., p. 406.
[78] Thompson, D. G., op. cit.
[79] Meinzer, O. E., op. cit. (Water-Supply Paper 423), pp. 95, 98, 100, 159–161.
[80] Idem, p. 125.
[81] Idem, p. 145.
[82] Clark, W. O., and Riddell, C. W., op. cit., p. 39.
[83] Kearney, T. H., and others, op. cit., pp. 406, 407.
[84] Meinzer, O. E., op. cit. (Water-Supply Paper 277), pp. 24, 110.
[85] Lee, C. H., op. cit. (Water-Supply Paper 294), p. 77; The determination of safe yield of underground reservoirs of the closed-basin type: Am. Soc. Civil Eng. Trans., vol. 78, pp. 238, 250, 1915.
[86] Thompson, D. G., op. cit.

Nev., the conclusion was reached that in general rabbit brush occupies tracts where the depth to the water table is between 8 and 15 feet.

Small individuals of rabbit brush or of a plant resembling rabbit brush are widely distributed over the alluvial slopes far above the water table. In Tooele Valley the species *Chrysothamnus marianus* occurs in the shadscale association far above the water table and almost certainly without any relation to it. Further investigation is needed to determine to what extent the species *Chrysothamnus graveolens* parts company with the water table. Quite without such an investigation, however, there is generally little difficulty in determining the localities where the luxuriant and abundant individuals of rabbit brush are true indicators of shallow ground water.

The rayless goldenrod (*Bigelovii hartwegii*) appears to behave much like the rabbit brush, and the writer may have confused these two species in his observations. Apparently both have a tendency to occupy ground on which the native vegetation has been destroyed by grazing or cultivation, and both will grow in dry situations as small plants but will make a notably ranker growth where ground water is within reach.

ARROW WEED, BATAMOTE, AND JACATE

Arrow weed (*Pluchea sericea*) is a tall, straight-stemmed shrub that seldom branches and grows in rather dense thickets. Its wood was used by the Indians to make arrows.[87] It is reported to be a ground-water indicator in the Mohave Desert region, California, by Thompson,[88] and in the Salton Sea region, California, by Brown,[89] who states that although it is a reliable indicator of ground water it is likely to grow where the depth to the water table is several feet and possibly as much as 25 feet. Usually, however, a heavy growth signifies water within 5 or 10 feet of the surface. Thompson noted it growing abundantly along the flood plain of Colorado River near Needles, where the depth to water was only a few feet. Brown states that arrow weed is common along dry arroyos where there is a shallow subsurface flow and in basins where ground water is near the surface. It also grows freely beside pools and running streams.

The batamote bush (*Baccharis glutinosa*) is regarded by G. E. P. Smith as an indicator of ground water. In a letter he makes the following remarks in regard to it:

> There are several other plants which I think you should list. One of them is the batamote, of which there are three varieties. While it will grow in my

[87] Aldous, A. E., and Shantz, H. L., op. cit., p. 113.

[88] Thompson, D. G., op. cit. (Water-Supply Paper 490-B), p. 98; also Water-Supply Paper 578.

[89] Brown, J. S., op. cit., p. 113.

dooryard, if planted where it can steal water, yet it does not seem to belong there, but when growing along the bottom lands with its feet in the water it becomes a very large shrub or bush—almost a tree. It is often associated with arrow weed.

The shrub called jacate (*Hymenoclea monogyna*) commonly forms thickets in the valley lands of Arizona and in places attains a height of 8 to 10 feet. It generally indicates the occurrence of ground water near the surface.

SALTBUSHES

The different species of saltbush differ widely in their habitat and associates. Shadscale (*Atriplex confertifolia*) is a well-known and widely distributed desert plant that generally depends directly on the moisture from rain and snow and apparently has little tendency to utilize ground water except possibly in certain localities.

In his catalog of plants in the Salton Sink, Parish [90] lists eight species of *Atriplex*, three of which he describes as growing in damp or wet soil, evidently signifying moisture due to rising ground water. These are *Atriplex lentiformis*, *Atriplex polycarpa*, and *Atriplex canescens*. He describes them as growing on the extensive alkaline flats that stretch from Indio to the borders of the Salton Sea, near Mecca, in association with *Dondia torreyana* and *Allenrolfea occidentalis*. He states that over much of the area the water table is sufficiently high to permit the capillarity of the soil to raise the water nearly or quite to the surface. He further states that these five species do not grow intermingled, or at most are intermingled only on the borders of the portions respectively occupied by each, the *Dondia* and *Allenrolfea* occupying the most alkaline soil. He describes the three species of *Atriplex* and their occurrence as follows:

> The three species of *Atriplex* above named hold possession of the larger part of this area, their distribution being determined by the amount of water in the soil. Those parts in which the water content is greatest is occupied by *Atriplex lentiformis*. This is a vigorous species with leaves broader and greener than those of the others. It grows either in thickets close as a hedge, or isolated in great domes, 6 to 8 feet and exceptionally even 12 or 15 feet in height and base diameter. The same requirement of a very damp soil is manifested elsewhere in its position about springs and on river banks.
>
> Where the soil is somewhat drier *Atriplex polycarpa* forms a nearly pure stand. Its habit of growth is similar to that of *Atriplex lentiformis*, but mostly in thickets and less frequently in dense entangled individuals, in neither case much over 3 feet in height.
>
> The third species, *Atriplex canescens*, has great ecological adaptability, so that while reaching its best development on the drier margins of these flats, it also is frequent in the most arid soils.

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[90] Parish, S. B., op. cit., pp. 92, 93, 107, 108.

The occurrence of several species of *Atriplex* and their relation to seepweed (*Dondia torreyana*) in the Santa Cruz Valley, near Tucson, Ariz., are described by Spalding[91] as follows:

> In the lowest part of the salt spots, where the drainage is most defective, *Suaeda moquinii* [*Dondia torreyana*] is characteristic and in some cases is well nigh exclusive in its occupation of the soil. Commonly, however, there are associated with it a few other plants, especially one or more species of *Atriplex*. Thus, *Atriplex lentiformis* grows luxuriantly, even where the so-called black alkali, chiefly sodium carbonate, forms a heavy crust, and both *Atriplex nuttallii* and *Atriplex elegans* are of frequent occurrence in low spots where the accumulation of alkali has reached a high percentage.
>
> Beyond this association, and outside of it, *Atriplex canescens*, in many cases, is conspicuously present. Its range, however, extends over the flood plain and even beyond it, so that although closely related genetically, it can not be referred to the more restricted association of saltbushes, which have the salt spots as their habitat. Thus a zonal arrangement, often well marked, is produced, in which the center may be quite bare of plants, while around it, in successive concentric zones, are (1) *Suaeda moquini* and *Atriplex nuttallii*, (2) *Atriplex polycarpa*, (3) *Atriplex canescens* and various other species which belong around or outside the limits of the salt spot proper.

Atriplex canescens is described by Kennedy[92] as "a robust, shrubby perennial from 4 to 10 feet high, native of the high valleys and plains of Wyoming, Nevada, Arizona, New Mexico, and western Texas. * * * It has proved its adaptability to soils impregnated with white alkali and also withstands small amounts of black alkali. Its resistance to cold adds greatly to its value."

In Tularosa Basin, N. Mex.,[93] a lowland area of about 650 square miles has as its dominant vegetation a saltbush, presumably *Atriplex canescens*,[94] which is known by the Mexican inhabitants as chamiso but is often incorrectly called "sagebrush" by the English-speaking settlers. The soil throughout this chamiso zone consists largely of gypsum but as a rule contains only moderate amounts of alkali, although in some places the alkali content is large. In 19 localities of chamiso that were investigated the depth to the water table was determined in 8 and estimated in 11 localities. In the 8 localities the depth to the water table ranged from 13 to 62 feet; in the 19 localities it ranged, according to the estimates, from 8 to 62 feet. In 2 localities it was 10 feet or less, in 4 it was between 10 and 20 feet, in 8 it was between 20 and 30 feet; in 2 it was between 30 and 40 feet; and in 1 each it was 45, 60, and 62 feet. In 3 of the localities chamiso was associated with pickleweed, and in 8 it was associated

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[91] Spalding, V. M., op. cit., p. 13.

[92] Kennedy, P. B., Saltbushes: U. S. Dept. Agr. Farmers' Bull. 108, p. 12, 1900.

[93] Meinzer, O. E., and Hare, R. F., op. cit. (Water-Supply Paper 343), pp. 193–199, 306–311.

[94] Coville, F. V., and MacDougal, D. T., Desert Botanical Laboratory of the Carnegie Institution: Carnegie Inst. Washington Pub. 6, pp. 5–8, 1903.

with mesquite. In general the chamiso belt is bordered on its lower margin by the belt of pickleweed and salt grass and on its upper

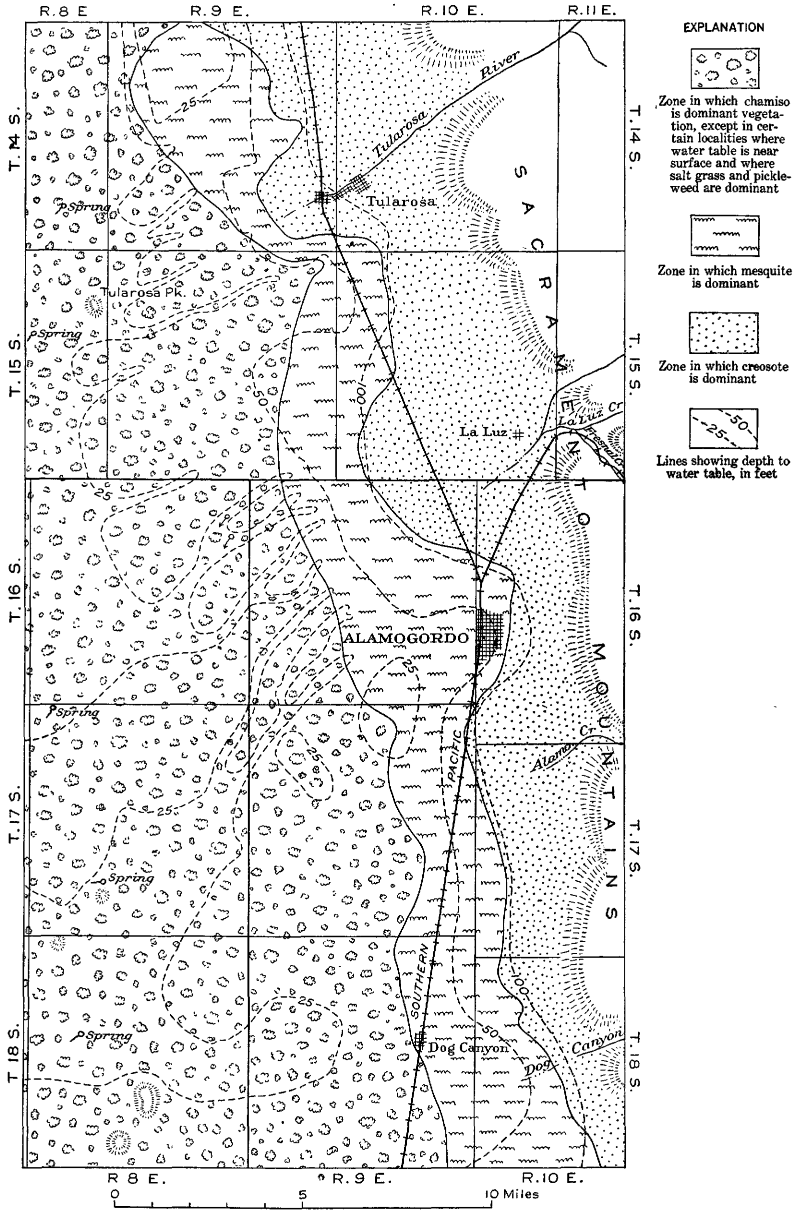


FIGURE 6.—Map of a part of the east slope of Tularosa Basin, N. Mex., showing areas in which mesquite is the dominant plant and their relation to ground water. In general chamiso is the dominant plant on the lower or west side of the mesquite areas and creosote bush on the upper or east side. (After Meinzer, O. E., and Hare, R. F., op. cit. (Water-Supply Paper 343) pl. 2)

margin by the mesquite belt. In parts of the east side of the basin the belt of dominant chamiso extends up to the region where the depth to the water table is about 30 to 35 feet, but there are many exceptions to this rule, and in some places it extends above the 50-foot line. (See fig. 6.) On the west side the relation of this belt to the depth to the water table is still more irregular and complicated, as is shown in Figure 7. In general it is bounded on the upper side by the mesquite belt, but in the interstream areas, where the soil is doubtless more gypseous than in the areas that are periodically flooded by storm waters from the mountains, the mesquite belt may be interrupted and the chamiso may extend as the dominant vegetation up the alluvial slope, beyond the line where the depth to water is 100 feet, and may be dominant in tracts above the mesquite belt. In some of the smaller basins of central New Mexico chamiso is found, as in the Tularosa Basin, on the lowland tracts that have only moderate depths to water but are especially noteworthy for their intensely gypseous soils. Obviously this species is well adapted to a gypseous soil, and its occurrence in these basins is largely controlled by the distribution of this soil.

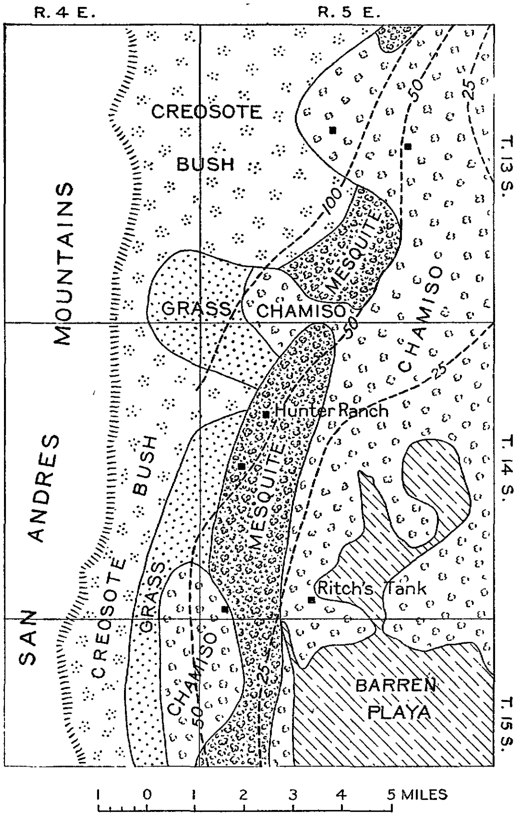


FIGURE 7.—Map of a part of the west slope of Tularosa Basin, N. Mex., showing belts of vegetation and their relation to ground water. Numbers on dashed lines indicate depths to the water table in feet. (After Meinzer, O. E., and Hare, R. F., op. cit., fig. 46)

In Sulphur Spring Valley, Ariz., a saltbush called chamiso (species not definitely determined but presumably *Atriplex canescens*) is found to a moderate extent in the shallow-water area, chiefly in association with alkali sacaton between the burroweed-saltgrass belt on the lower side and the mesquite belt on the upper side. In five localities that were studied in which chamiso was growing the observed or estimated depth to the water table ranged from 8 to 25 feet, and in three of them from 10 to 20 feet. The chamiso was associated with alkali sacaton in all five localities, with mesquite in two, and with Mexican salt grass in two. The chief interest in the chamiso of this valley lies in the fact that the soil is not gypseous but contains black alkali (sodium carbonate and sodium bicarbonate). In the five localities the amount of alkali in the soil ranged from rather low to moderately high. In all three localities of which the soil alkali was analyzed there was found to be black alkali with an absence of gypsum at each depth that was sampled.

In the Tularosa Basin the chamiso is estimated to cover about 650 square miles, or more than 400,000 acres. According to evidence of several kinds, the rate of recharge of ground water in this basin is relatively not very great. More or less discharge of ground water obviously occurs over an area of 150 to 200 square miles in which the ground water rises by capillarity virtually to the surface. Moreover, the mesquite almost certainly disposes of considerable quantities of ground water. It seems probable, therefore, that if the chamiso feeds on ground water in this basin it draws very sparingly on this supply. Apparently it utilizes water from the zone of saturation in some localities but is not a reliable indicator of ground water.

The tall, shrubby saltbush (*Atriplex torreyi*), which occurs in Utah, Nevada, and California, was found in a few localities in the shallow-water areas of Big Smoky, Ione, and Clayton Valleys, Nev.,[95] but at no place is it the dominant plant. From the field observations in Big Smoky Valley the conclusion was reached that this species can endure considerable alkali and is generally found in low places having more than an ordinary supply of moisture, but that it is not a reliable indicator of shallow ground water. In Ione and Clayton Valleys, however, its relations seem to be those of a true ground-water plant. Its occurrence in Ione Valley is described as follows:[96]

> The area of ground-water discharge at the mouth of Ione Creek is obviously due to rock formations that hem in the outlet and bring a part of the underflow to the surface. Capillary discharge is taking place in the wide Pleistocene stream valley from Black Spring to a point about 2 miles farther up the valley. The position of the water table is shown by Black and Warm Springs, and more precisely by the small stream which in October, 1913, rose about one-half mile above Warm Spring in a recently cut gully and was supplied entirely by ground-water seepage. From Black Spring to about the point where the small stream rises the surface contains crusts of alkali and black stains of sodium carbonate, and the vegetation consists chiefly of salt grass, rabbit brush, big greasewood, and the tall saltbush (*Atriplex torreyi*). Near Warm Spring the gully is only about 5 feet deep, and in October, 1913, water was drawn to the surface by capillarity. Near the source of the stream the gully

[95] Meinzer, O. E., op. cit. (Water-Supply Paper 423), pp. 96, 99, 100, 145.
[96] Idem, pp. 99, 100.

was about 9 feet deep, and the capillary water rose only to a level 3 feet below the surface, but some salt grass was growing in this place. Up the valley from this point the evidences of shallow water gradually disappear. Five miles above Warm Spring the ground in the stream valley was dry, but the vegetation consisted of big greasewood, the tall saltbush (*Atriplex torreyi*), and a small amount of rabbit brush. These plants are somewhat ambiguous as indicators. They probably draw on the ground-water supply, but may owe their presence to floods, the evidences of which were very distinct in the stream valley. A few miles farther upstream these species give way to *Atriplex confertifolia*, which predominates also on the dry bench lands.

Since the investigation in Ione Valley was made, much has been learned in regard to the behavior of ground-water plants, and it now seems altogether probable that the greasewood and rabbit brush at the locality 5 miles above Warm Spring feed on ground water and that the saltbush does likewise.

The occurence of *Atriplex torreyi* in Clayton Valley is described as follows:[97]

Outside of this zone in the part of the valley south of the playa there is a zone in which iodine weed, big greasewood (*Sarcobatus vermiculatus*), the tall shrubby saltbush (*Atriplex torreyi*), and the common spiny saltbush (*Atriplex confertifolia*) are associated. * * * Outward from this area, in the direction of the mountains, first the iodine weed and then the big greasewood and *Atriplex torreyi* disappear or become scarce, while the common saltbush (*Atriplex confertifolia*), often called shadscale, becomes dominant. Over the extensive gravelly and arid tracts of the middle and upper parts of the alluvial slopes this saltbush maintains its supremacy.

GREASEWOOD

The shrub known as big greasewood (*Sarcobatus vermiculatus*) is one of the most conspicuous and widely distributed of the desert bushes in Nevada and Utah and in adjacent States, especially to the north. According to Coulter[98] it is "common in the Great Basin, and to the upper Missouri, headwaters of the Platte, and southward." It should not be confused with the creosote bush (*Covillea tridentata*), which is commonly though incorrectly called greasewood in southern California and in Arizona, nor with the seepweed (*Dondia*), which is also sometimes called greasewood. It is an erect scraggy, leafy bush, 1 to 8 feet high, and has a vivid green color that contrasts strongly with the gray hues of shadscale and sagebrush. (See fig. 8.)

Greasewood was not at first regarded as an indicator of ground water, because to a large extent it grows on land that lies some distance above the water table. The information now at hand, however, makes it practically certain that greasewood habitually

[97] Meinzer, O. E., op. cit. (Water-Supply Paper 423), p. 145.

[98] Coulter, J. M., op. cit., p. 312.

sends its well-developed taproot to considerable depths to reach the water table or the overlying capillary fringe, and that it is a true

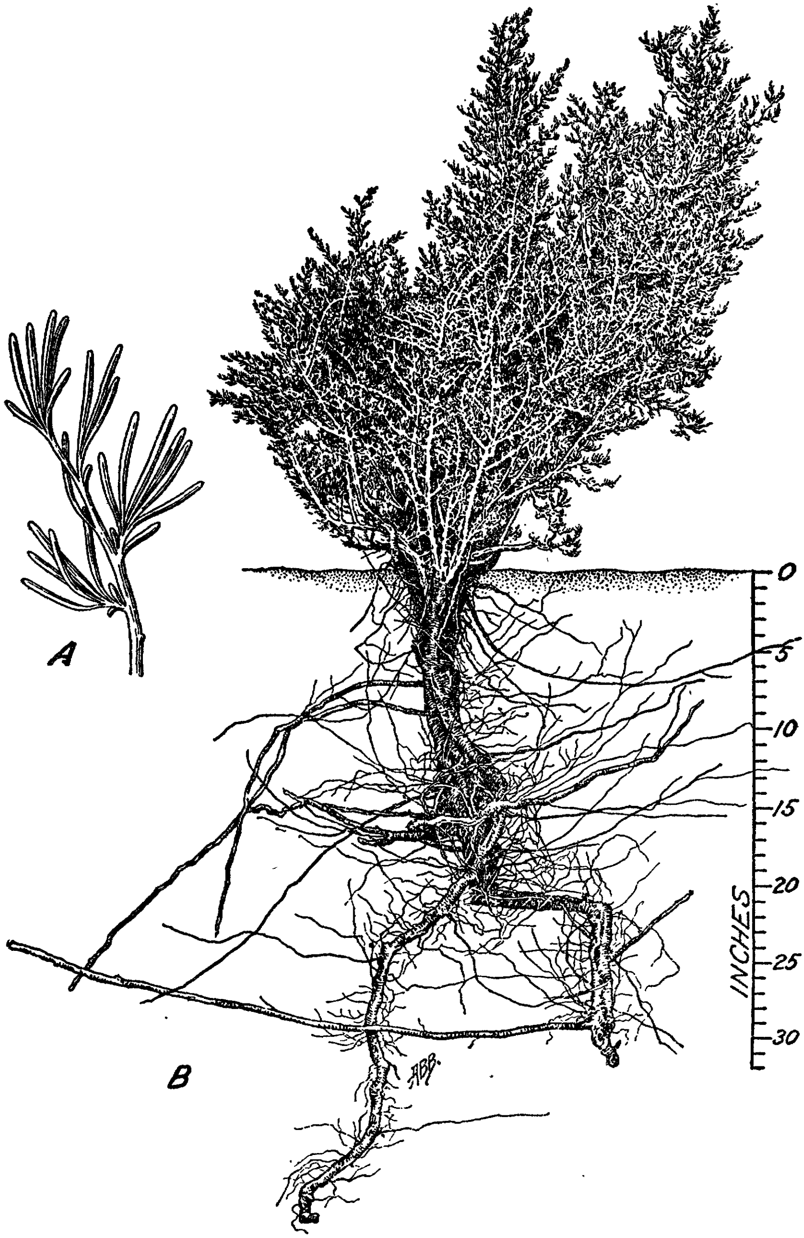


FIGURE 8.—Big greasewood (*Sarcobatus vermiculatus*). *A*, Detail showing the narrow, rather fleshy leaves; *B*, a plant, showing the excellent root development. The large, deeply penetrating taproot is characteristic of the species. (After Kearney, T. H., and others, op. cit., fig. 10)

ground-water plant not only where the water table is very near the surface but also in its favorite position surrounding a shallow-water tract. It is, thus, one of the most trustworthy of all ground-water indicators. It has been recognized as such an indicator in many western valleys, especially in Nevada and Utah. In their recent publication Aldous and Shantz [99] state that the species is limited to subirrigated alkali lands throughout the West.

In some places the big greasewood spreads meagerly to upland tracts that are wetted by storm waters, but it should not be confused with the little greasewood (*Sarcobatus baileyi*), which is not at all a ground-water plant. The little greasewood is commonly associated with shadscale (*Atriplex confertifolia*) on arid slopes and plains that lie too high above the water table to be influenced by ground water. Its appearance is extremely dry and lifeless, especially during the long autumn drought.

In Big Smoky Valley, Nev., the big greasewood is abundant in the shallow-water areas, in great mounds on the barren playas (pl. 4, *C*), in the sand hills in or near the shallow-water areas, and in a belt between the shallow-water areas and the extensive upland areas of shadscale and little greasewood, generally where the depth to the water table is less than 50 feet. (See fig. 9.) An interesting occurrence is on the mounds in the flat, barren, clayey, alkaline, and periodically submerged playa. These mounds have a sandy soil that was captured by the greasewood from the wind-borne materials. They have been gradually built to their present large dimensions by this process of wind deposition. The development of the mounds has produced favorable conditions for the greasewood, and the growth of the greasewood has tended to preserve and further develop the mounds.

In 19 localities of big greasewood that were studied in Big Smoky Valley the greasewood occurred alone in 3 localities and was associated with rabbit brush in 9, with salt grass in 7, with shadscale in 6, with sagebrush in 4, with *Atriplex torreyi* and iodine weed in 2 each, and with willow in 1. It was, of course, associated with the salt grass in the localities of shallowest ground water and with the shadscale chiefly in the upper part of the greasewood zone or somewhat above the zone of dominant greasewood.

The conditions as described for Big Smoky Valley agree closely with those found in Tooele Valley, Utah, which are set forth as follows: [1]

> The area occupied by the greasewood-shadscale association forms an interrupted belt across the valley between the areas occupied by the shadscale association and by the grass flats, respectively. It also covers the low ridges and hummocks which alternate with the basinlike depressions and flats near the shore

[99] Aldous, A. E., and Shantz, H. L., op. cit., p. 110.
[1] Kearney, T. H., and others, op. cit., pp. 400–405.

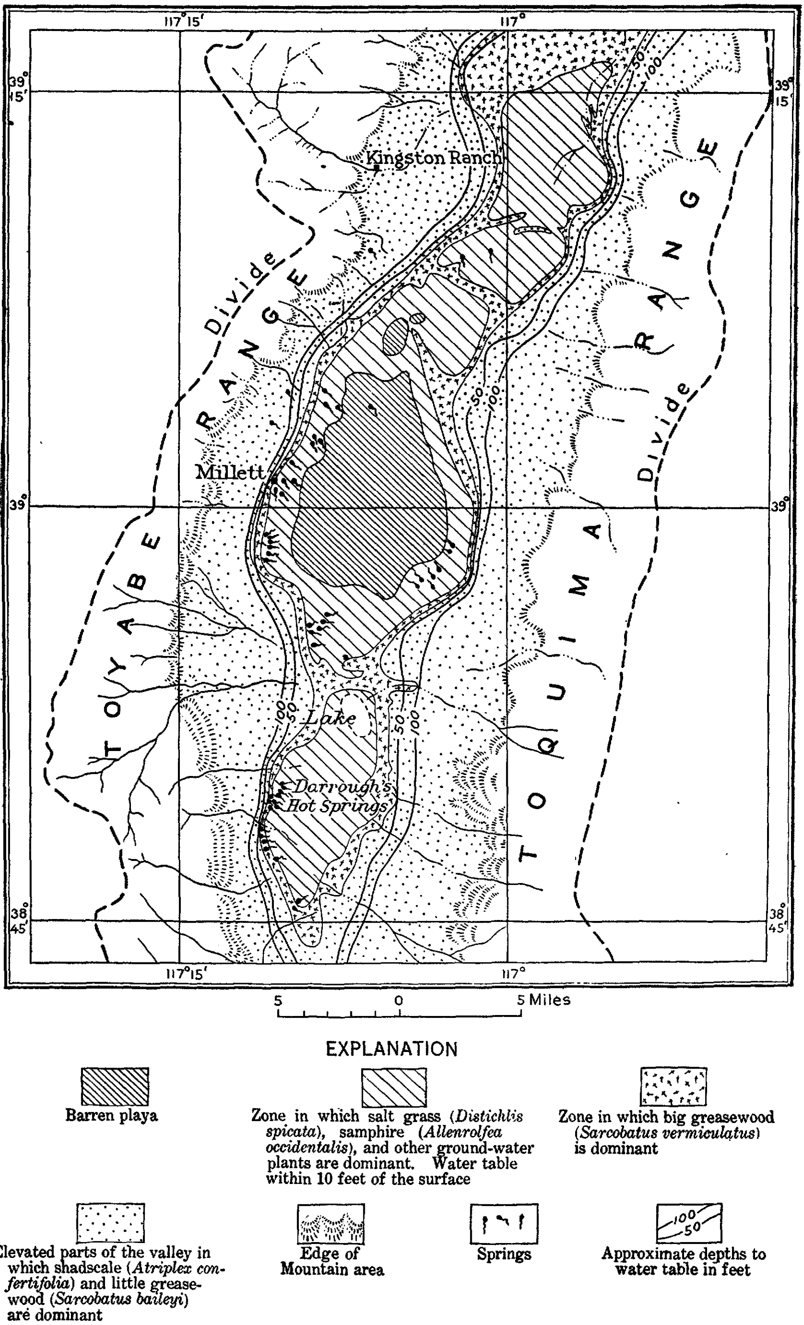


Figure 9.—Map of a part of Big Smoky Valley, Nev., showing zones of vegetation

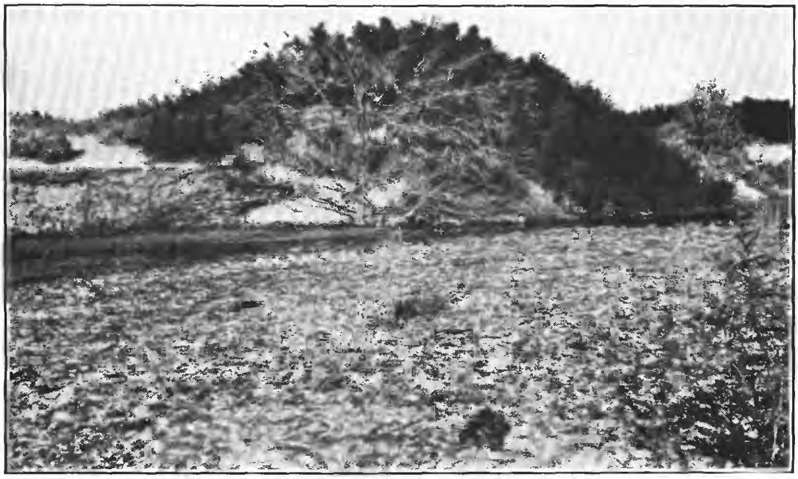
of Great Salt Lake. In general it occupies all areas where the water table is sufficiently high to make moist soil accessible to the deep-rooting greasewood and where at the same time 1 or 2 feet of the surface soil are sufficiently dry

A. AREA OF SHALLOW GROUND WATER IN SOUTHEASTERN CALIFORNIA WITH GROWTH OF SALT GRASS AND SCATTERED MESQUITE

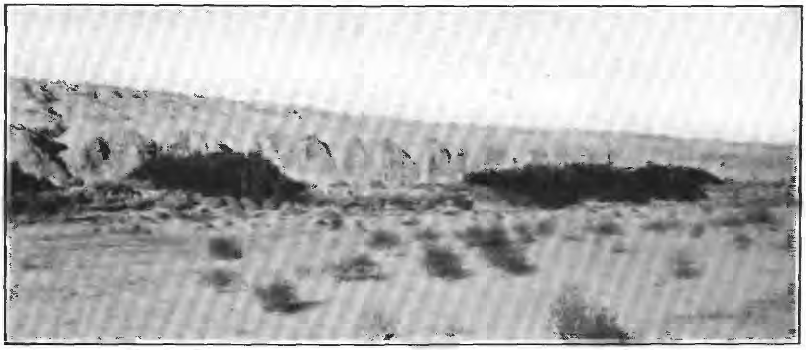
Photograph by John S. Brown

B. CUT BANK OF SANTA CRUZ RIVER NEAR TUCSON, ARIZ., SHOWING THE DEEP ROOTS OF MESQUITE

Photograph by V. M. Spalding (Carnegie Inst. Washington Pub. 113, pl. 3, 1909)

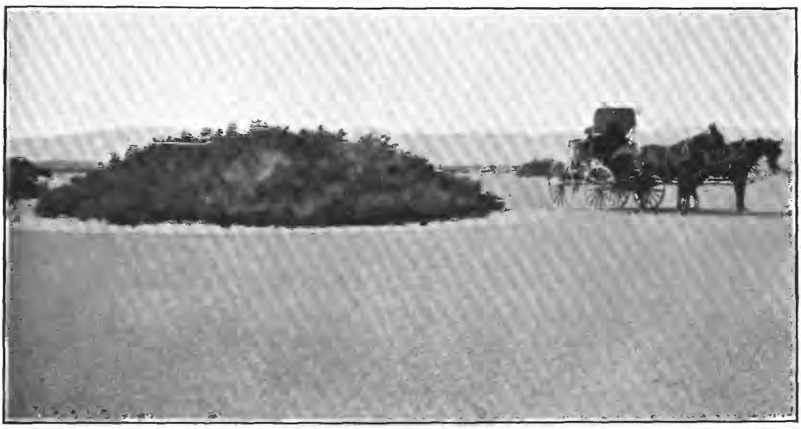


A. CLUMP OF MESQUITE, SHOWING ROOTS REACHING DOWN TOWARD WATER TABLE, WHICH IS JUST BELOW THE LOWLAND PLAIN

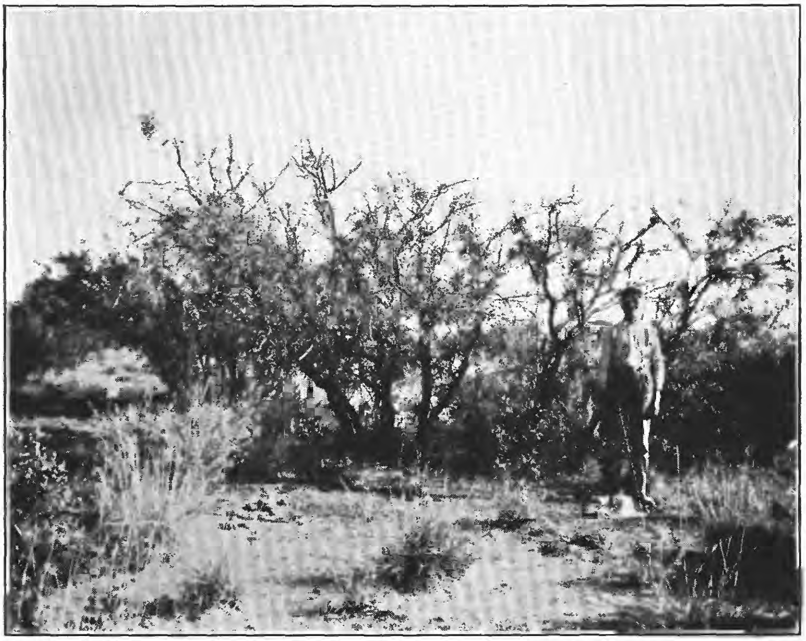


B. MESQUITE AT FOOT OF CLIFF, SHOWING CONTRAST WITH DESERT WHERE IT SUPPORTS ONLY SPARSE GROWTH OF VEGETATION THAT DOES NOT FEED ON GROUND WATER

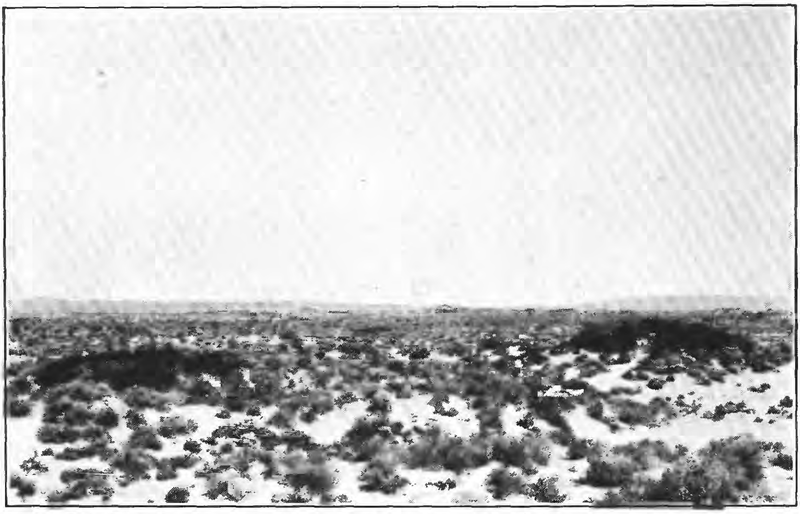
Photographs by D. G. Thompson



C. GREASEWOOD OCCUPYING WIND-BUILT MOUND ON THE OTHERWISE BARREN PLAYA OF BIG SMOKY VALLEY, NEV.



A. VEGETATION OF THE MESQUITE ZONE SURROUNDING THE AREA OF SHALLOW GROUND WATER IN SULPHUR SPRING VALLEY, ARIZ.

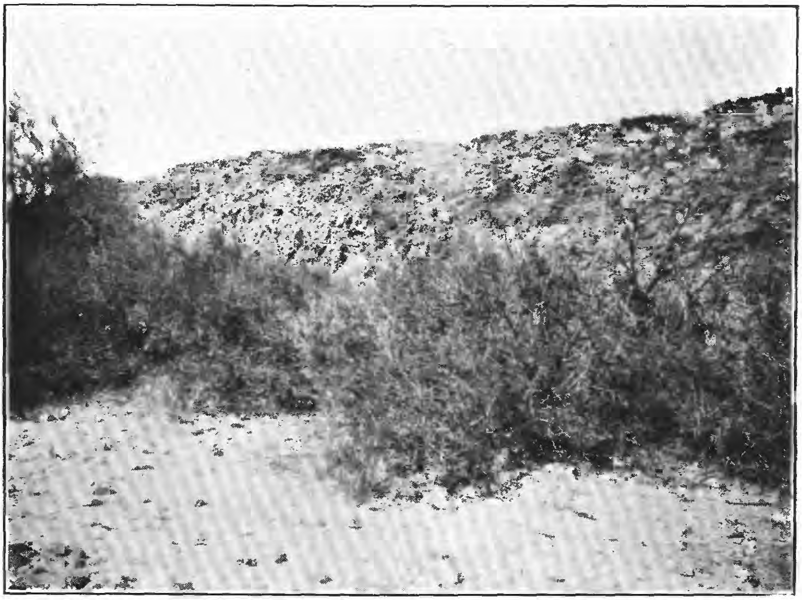


B. CLUMPS OF MESQUITE (LARGE DARK PATCHES) IN MOHAVE DESERT, NEAR DAGGETT, CALIF., INDICATING GROUND WATER WITHIN REACH OF THE MESQUITE ROOTS

Photograph by D. G. Thompson

A. MOHAVE RIVER VALLEY NEAR BARSTOW, CALIF., SHOWING MESQUITE AND POPLAR TREES SUPPORTED BY GROUND WATER

Treeless upland in background. Photograph by D. G. Thompson



B. RUNNING MESQUITE IN AREA OF SHALLOW GROUND WATER NEAR SHAVER WELL, IN THE DESERT REGION OF SOUTHEASTERN CALIFORNIA

Photograph by John S. Brown

to permit the growth of shadscale. Where the water table is too low this association gives place to the pure shadscale. On the other hand, as the soil becomes wet nearer and nearer the surface the shadscale gradually disappears, and at the edge of the grass flats greasewood associates with *Allenrolfea occidentalis* and *Suaeda moquinii* instead of with *Atriplex confertifolia.* * * *

Greasewood (*Sarcobatus vermiculatus*) grows in a greater variety of habitats than any other flowering plant of the Tooele Valley. It was found in one place or another in company with the dominant species of all of the leading associations. In much the greater part of its range in the valley greasewood is associated with shadscale, but there are exceptions to this rule. The largest and thriftiest-looking greasewood plants grew on the summits of dunes of pure sand, together with sagebrush, juniper, and other characteristic plants of the sand-hill mixed association. Shadscale is absent from this community. At the other extreme greasewood occurs in company with *Allenrolfea* in land which is too wet and saline for the growth of shadscale. * * *

The growth of greasewood on the sand hills makes it evident that this plant is not an infallible alkali indicator, although in the great majority of cases its occurrence is associated with an excess of salts in the soil, and in its ability to endure the presence of alkali it is surpassed by few other flowering plants. A condition which is almost always correlated with the presence of greasewood is a permanent supply of moisture available for growth within the depth of soil penetrated by its roots.

In Owens Valley, Calif., Lee [2] found greasewood and rabbit brush dominant in a belt in which the water table was from 8 to 12 feet below the surface and associated with salt grass where the depth to water was between 4 and 8 feet.

In Steptoe Valley, Nev., the data obtained indicate that in general greasewood occupies tracts where the depth to the water table is between 12 and 20 feet. (See fig. 10.) In 19 localities in Big Smoky Valley, Nev., in which greasewood was growing the measured or estimated depth to the water table ranged from 2.7 to 33 feet, except in one locality where the depth was estimated at 60 feet. The depth was less than 12 feet in 8 localities, between 12 and 20 feet in 7 localities, and between 20 and 33 feet in 3 localities. In prospecting for water in the early days in the gulches near Tonopah, Nev., the presence of greasewood was considered one of the most favorable indications of water. Its roots were found to go to depths of more than 20 feet, and, according to some reports, as much as 40 feet, to get ground water. Near Grandview, Idaho, H. T. Stearns observed roots of greasewood penetrating the roof of a tunnel 57 feet below the surface. Obviously a species which is able to endure desert conditions while it sends its roots so deep to find water will spread somewhat beyond its ground-water limits, and it may be expected that a scattered growth of stunted greasewood will be found in places where the water table is not within reach of this species.

[2] Lee, C. H., op. cit. (Water-Supply Paper 294), p. 77; Am. Soc. Civil Eng. Trans., vol. 78, pp. 232, 238, 250, 1915.

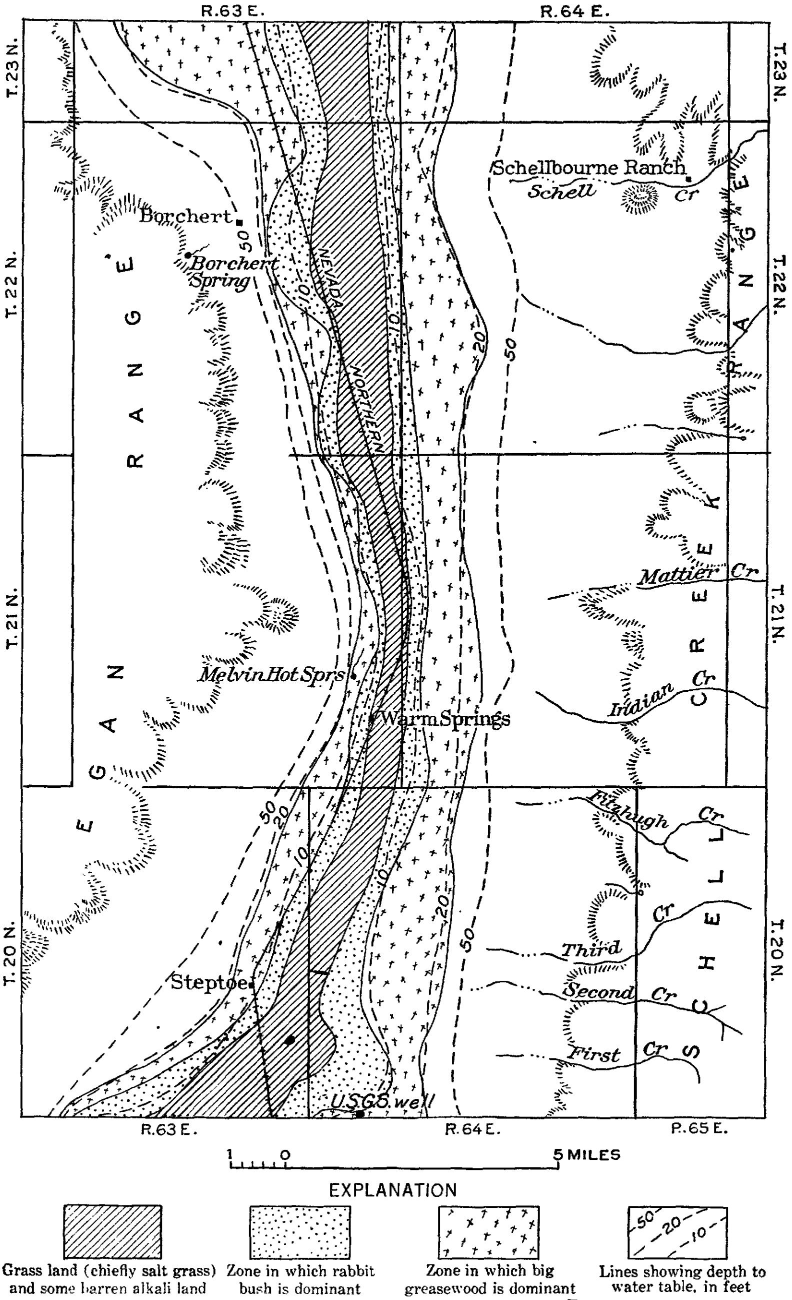


FIGURE 10.—Map of a part of Steptoe Valley, Nev., showing zones of vegetation and their relation to the water table. (After Clark, W. O., and Riddell, C. W., op. cit. (Water-Supply Paper 467), pl. 2)

MESQUITE AND ASSOCIATED PLANTS

Mesquite has been studied in a number of localities with more or less reference to its relation to ground water. These studies make it clear that mesquite is essentially a deep-rooting plant which, under favorable conditions, has a capacity for tapping the ground-water supply even where the water table is as much as 50 feet below the surface; also that it has excellent adaptations for obtaining water from other sources and for resisting drought, as is obviously necessary if individual seedlings are to survive while they are sending their roots to such great depths. On account of these characteristics the mesquite spreads to some extent to the uplands where the ground water lies too far below the surface to be reached even by these deep-rooting plants. In the upland areas, however, its growth is generally scattered and stunted, except in localities with unusual water supplies from other sources, and the experienced observer can distinguish these occurrences more or less successfully from the localities where it feeds on ground water. Localities where mesquite indicates ground water are shown in Plates 3, *B*, 4, *A*, *B*, and 5 to 7.

The common mesquite occurs in several closely related forms (*Prosopis juliflora*, *Prosopis velutina*, etc.). Distinct from these is the screw bean or screw-pod mesquite (*Prosopis odorata* or *Prosopis pubescens*, recently classified as *Strombocarpa odorata* or *pubescens*).[3] Brown[4] states that in the Salton Sea region of California the so-called "running mesquite" (*Prosopis juliflora*) is considered more reliable as an indicator of ground water than the screw bean. However, J. J. Thornber, writing from Tucson, Ariz., states that the screw bean is typically a ground-water plant, being found only in rich valley soils where the roots can reach water; in this respect it differs from *Prosopis velutina*.

Ball[5] states that water can usually be obtained at slight depths where mesquite is growing.

Mendenhall[6] states that mesquite may depend either on ground water or on the water from periodical flooding, and that where its growth is due to ground water the water may lie within a few feet of the surface or be as much as 50 feet below.

The description by Spalding[7] of the mesquite forest association on the flood plain of Santa Cruz River near Tucson, Ariz., contains so much valuable information and so much critical discussion that the following extensive quotation from it appears justified. The mesquite association includes two species of acacia besides several other plant species. The distribution of mesquite in an area that was investigated just west of Tucson is shown in Figure 11.

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[3] For a discussion of the different species of mesquite, see Sudworth, G. B., op. cit., pp. 362–367. See also Tidestrom, Ivar, op. cit., pp. 286, 287.

[4] Brown, J. S., op. cit., p. 114.

[5] Ball, S. H., op. cit. (Bull. 308), p. 22.

[6] Mendenhall, W. C., op. cit. (Water-Supply Paper 224), p. 20.

[7] Spalding, V. M., Distribution and movements of desert plants: Carnegie Inst. Washington Pub. 113, pp. 9–12, 1909.

The dominant species [on the flood plain of Santa Cruz River near Tucson, Ariz.] is the mesquite (*Prosopis*), here in the form of *velutina*. * * * It is by preference a plant of low flats, though it occurs far beyond these on the uplands, in situations where a sufficient water supply is obtainable. In the neighborhood of Tucson the mesquite ranges in size from a mere shrub a few feet high to a tree 2 feet or more in diameter and upward of 40 feet in height. Such trees grow thickly on the bottom land near the old mission of San Xavier, forming the fine forest that stretches for miles up the river, in the shade of which grows a rank vegetation similar to that of eastern mesophytic forests in luxuriance.

The habits of the mesquite are popularly well known, and its presence is taken to indicate a good water supply. Its roots extend widely to a distance of 50 or 60 feet, according to credible observers, and possibly to as great depth;

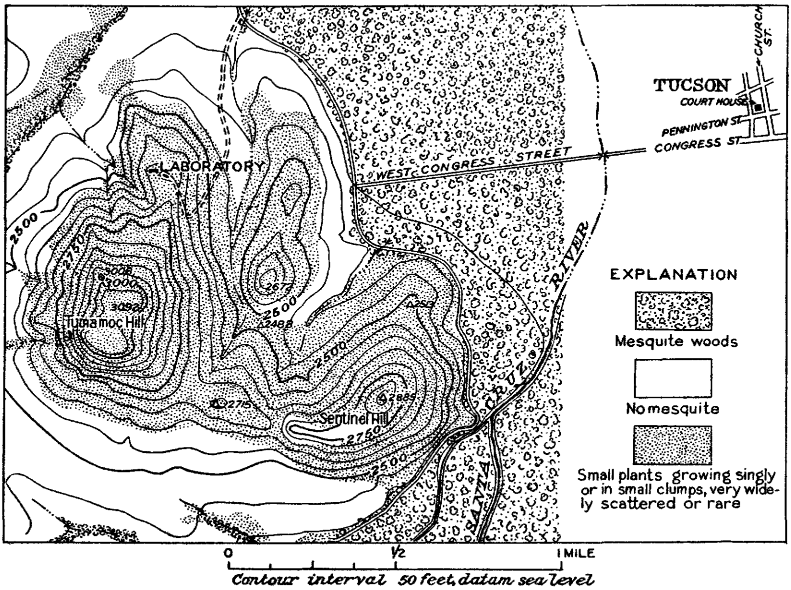

FIGURE 11.—Map of a locality near the Desert Laboratory, Tucson, Ariz., showing approximate distribution of mesquite (*Prosopis velutina*). Lines are contours of the land surface shown in feet above sea level. (After Spalding, V. M., Carnegie Inst. Washington Pub. 113, pl. 18, 1909)

and when cut green its wood tissue, which is hard and heavy, carries a large percentage of water, precisely as do the hardwoods of the eastern United States, and strikingly different from the creosote bush, its near neighbor on the slopes beyond the flood plain. At the same time the general structural peculiarities of the mesquite are xerophytic. It is commonly armed with spines, and its coriaceous leaves are well protected against excessive transpiration. It is a plant requiring a better supply of water 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, ranging as it does to the top of Tumamoc Hill, in spots where a soil retentive of moisture affords the conditions it needs, 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. * * *

Associated with the mesquite are a number of characteristic species, some of which are confined to the flood plain, while others extend with it beyond these limits. Of the latter *Acacia constricta* is a conspicuous representative. Its habits are essentially those of the mesquite as to water requirements, and it closely resembles this species in its xerophytic structure. The two grow side by side near the river and to the summit of Tumamoc Hill, in precisely the same situations, one being, apparently, the ecological equivalent of the other. Other species behave differently. *Acacia greggii* grows with the mesquite in its lower range but not on the hill above, and the same is true of *Condalia lycioides* [buckthorn]. Both of these exhibit distinctly xerophytic structures, but both are as yet adapted to a somewhat more restricted range of soil conditions than are the mesquite and *Acacia constricta*. *Sambucus mexicana* [elderberry] and *Fraxinus velutina* [leather-leaf ash], also of this association, are still more limited in their range, growing near irrigating ditches, hardly affecting even the edge of the mesa-like slopes, and structurally are to be thought of as essentially mesophytic. * * *

It appears, then, that the flood plain is the natural habitat of a number of species, many of which are incapable of successful growth elsewhere, while a few grow fairly well, but not at their best, under different conditions beyond these limits. Taken as a whole, the plants of the flood plain find there their real home, and they exhibit—such of them, at least, as have been carefully observed with reference to this—a striking conformity of the root system to the peculiarities of the soil in which they are growing. This, as already stated, is of fine texture, retentive of moisture, and of great depth, with the water table varying in level, but apparently never beyond the reach of the long taproots of the mesquite and *Acacia*.

The root system of these plants consists of a taproot which grows rapidly downward and when developed is always within reach of a permanent, deep water supply, and a system of widely spreading lateral roots which are in relation to more superficial layers of the soil. Thus the plant is admirably fitted to absorb water largely from the upper layers when these are moist, and at the same time, and also in times of drought, without any interval of precarious supply, to draw on the deeper sources below. The contrast between this and the shallow root system of many of the great trees of eastern mesophytic forests, familiar to everyone who has seen them uprooted by heavy winds, is highly instructive. There is little wonder that the mesquite and *Acacia constricta* have tenaciously held their places through all vicissitudes and promise to be dominant in their habitat until actually rooted out.

Cannon,[8] in a paper published two years later, confirms the observations of Spalding and states that mesquite forms stunted, irregular bushes in its scattered growth on the uplands near Tucson, but that on the flood plain of Santa Cruz River, its proper habitat, it may become a tree 50 feet high. He states that where the mesquite grows large the perennial supply of water or zone of saturation, is near the surface, and that away from the river, where the water table is nearest the surface, toward either side of the flood plain, in the direction of increasing depth to ground water, the mesquite becomes progressingly smaller, until at the edges of the flood plain, where the water table is deepest, it is little more than a large bush.

[8] Cannon, W. A., Root habits of desert plants: Carnegie Inst. Washington Pub. 131, pp. 80–81, 1911.

He observed roots of mesquite at a depth of 16 feet and obtained reliable evidence of roots that went to a depth of 26 feet. He also states that the ranchers of southern Arizona regard mesquite as an indication of the presence of ground water and sometimes follow its roots in digging wells. In another paper, published in 1913, Cannon shows that the root system of mesquite, as well as its form above the surface, is related to the depth to the water table, and reaches the conclusion that mesquite assumes the tree form where the soil is readily penetrated and the water table is not more than 50 feet below the surface.[9]

In Sulphur Spring Valley, Ariz.,[10] which was investigated in 1910, observations were made on the relation of mesquite to ground water. It was found that mesquite commonly ranging from 5 to 10 feet in height, but in some places reaching a height of 15 feet, was dominant in a zone that lies on the middle and lower parts of the alluvial slopes. The limits of this zone are as a rule well defined, although in some places, especially on the upper side, they are indefinite. Exclusive of the tracts of scattered mesquite on the upper slopes, this zone covers about 250 square miles, or nearly one-sixth of the valley surface. It is wide on the broad gentle slopes that descend from the large mountains, but narrower on the abrupt slopes bordering the smaller ranges, and in some localities it wedges out entirely. The inner boundary of the mesquite zone is in most places within the belt in which the depth to the water table ranges between 15 and 25 feet, the poorly drained alkaline clay soil of the shallow-water tract being uncongenial for the growth of mesquite. The outer boundary of the zone bears a general though indefinite relation to the depth to ground water and is in most places not very far on one side or the other of the line where the depth is 50 feet. (See fig. 12.)

Mesquite was found in 37 localities in Sulphur Spring Valley that were studied with respect to vegetation, soil, and ground-water conditions, in 21 of which the depth to the water table was ascertained and in the remaining 16 estimated. In the 37 localities the depth to the water table ranged from 11 to 50 feet. In 9 localities the depth was less than 15 feet, but in virtually all of these the mesquite was scattered or stunted; in 11 the depth was between 15 and 25 feet and the growth generally luxuriant; in 10 the depth was between 25 and 35 feet and the growth generally luxuriant; and in 7 the depth was between 35 and 50 feet, in 4 of which the growth was small or scattered. A little mesquite also occurs in localities not specifically investigated in which the depth is more than 50 feet. These data indicate that in this valley the most favorable conditions are found in the zone where the depth to the water table is

[9] Cannon, W. A., Some relations between root characters, ground water, and species distribution: Science, new ser., vol. 37, pp. 420–423, 1913.

[10] Meinzer, O. E., and Kelton, F. C., op. cit. (Water-Supply Paper 320), p. 183, pls. 1, 2.

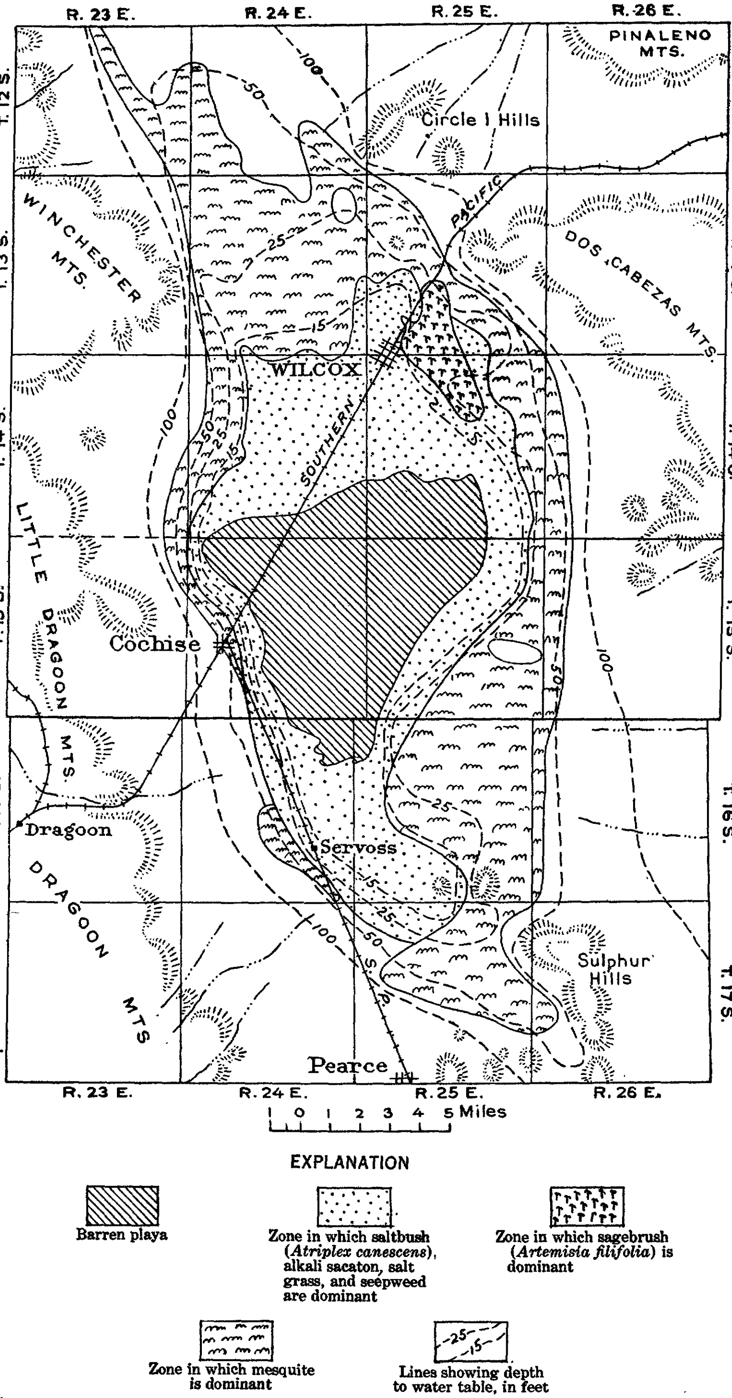

FIGURE 12.—Map of a part of Sulphur Spring Valley, Ariz., showing zones of vegetation and their relation to the water table. (After Meinzer, O. E., and Kelton, F. C., op. cit. (Water-Supply Paper 320), pls. 1, 2)

between 15 and 35 feet. Where the depth is less than 15 feet mesquite is associated chiefly with alkali sacaton; where the depth is greater than 15 feet it is associated with alkali sacaton and other grasses or occurs as the only prominent species.

In the Tularosa Basin, N. Mex.,[11] which was investigated in 1911, the mesquite zone occupies the intermediate parts of the alluvial slopes and forms an irregular belt on each side of the basin. Within the area that was mapped in detail it occupies about 180 square miles, five-sixths of which is on the east side, where the alluvial slopes are gentler and the water supply larger than on the west side. Its outer boundary is in most places formed by the creosote zone and is generally more definite than the inner boundary, adjacent to the chamiso zone. On the east side (fig. 6) the mesquite zone in most places extends up the slope to areas where the depth to water reaches 75 to 100 feet. Its lower boundary is obviously controlled not so much by the depth to water as by the occurrence of gypseous soil, which is not congenial to mesquite and in which it can not compete with chamiso.

On the west side (fig. 7) the relations are irregular. In the areas that are flooded by the principal ephemeral streams from the mountains the mesquite extends up the slope far above the 50-foot line of depth to water and even above the 100-foot line. These facts suggest that on both sides the mesquite at the highest levels maintains itself on flood water rather than on ground water.

Mesquite was found in 12 localities in the Tularosa Basin which were specifically investigated with respect to vegetation, soil, and water supply. In nine of these localities the depth to the water table was determined, and in the other three it was estimated. In these 12 localities the depth to water ranged from 11 to 62 feet. In one locality the depth was less than 15 feet, in eight it was between 15 and 35 feet, and in three it was more than 35 feet. In eight of these localities the mesquite was associated with chamiso.

In 1884 Havard[12] gave the habitat of mesquite as including parts of the United States south of the thirty-seventh parallel, particularly Texas and the Southwest, and South America to Brazil and Chile. He stated that the roots are of great horizontal and vertical extent, probably penetrating to depths of 30 or 40 or perhaps even 60 feet, and he expressed the belief that they usually reach the water table. He made the observation that the variation in the size of mesquite can be taken as an index of the depth to the water table, the largest mesquite indicating the shallowest depth.

In 1891 Coville,[13] in his botanical reconnaissance in the Mohave Desert and Death Valley regions of California, observed the root of

[11] Meinzer, O. E., and Hare, R. F., op. cit. (Water-Supply Paper 343), pp. 194, 306–311, pl. 2, fig. 46.

[12] Havard, V., The mesquit: Am. Naturalist, vol. 18, pp. 450–459, May, 1884.

[13] Coville, F. V., op. cit., pp. 35, 47.

a mesquite which had been washed out by a torrent and which was about 50 feet long but apparently had not extended to a depth of 50 feet. He states that in the Death Valley region, "where the hydrostatic water [ground water] is not intensely alkaline or [and] is situated only a few yards beneath the surface, its presence is indicated by a growth of mesquite."

In Playas Valley, N. Mex., investigated by Schwennesen and Hare[14] in 1913, the upper boundary of the zone of dominant mesquite is roughly determined by the 50-foot limits of the water table, but the lower boundary is less definitely related to the depth to water and is apparently determined by the occurrence of alkaline and clayey soil, which is poorly drained and difficultly penetrated by the taproots of the mesquite. (See fig. 13.) Mesquite was found in 27 localities in Playas and adjacent valleys, which were specially studied and for which the depth to water was determined or estimated by Schwennesen. In one of these localities the depth was only 10 feet, in fifteen it was between 15 and 50 feet, and in the remaining eleven it ranged from 54 to 300 feet. In general the mesquite between the 15 and 50 foot limits was luxuriant, and that above the 50-foot limit was small and scattered, but in several places good mesquite was found where the depth to water was between 50 and 100 feet.

Smith[15] describes the erosion of grassy bottom lands in Arizona that resulted from overgrazing. After the cutting of wide stream channels and the consequent lowering of the water table the sacaton disappeared, and trees, notably mesquite, took possession. Smith's statement continues as follows:

> Where the depth to ground water is within 25 or 30 feet the trees have become continuous forests covering the ground. That the trees send their roots down to the water table is easily proved, for the caving banks of rivers and arroyos reveal them. The mesquite, in particular, has deep, strong taproots, with a generous development of feeders.
>
> The hypothesis has been held by the writer for a long time that the water drawn up through trees and transpired constitutes the principal loss from the ground-water reservoir, and that, in some cases, this loss is the total loss, while in all cases evaporation is an agency of less import.

Later observations by Smith[16] indicate that mesquite will feed on ground water where the depth to the water table is somewhat greater than 30 feet.

In the lower Gila region of Arizona, which was surveyed for desert watering places by Ross[17] in 1917, it was found that mesquite grows in a number of valleys where the ground water is certainly

[14] Schwennesen, A. T., op. cit. (Water-Supply Paper 422), pp. 52, 144–149, pl. 2.
[15] Smith, G. E. P., Am. Soc. Civil Eng. Trans., vol. 78, p. 227, 1915.
[16] Personal communication.
[17] Ross, C. P., op. cit. (Water-Supply Paper 498), pp. 15, 16, 40.

too deep to be within reach of its roots. For example, in the Centennial Wash, beyond the stretch where there is a definite stream channel, mesquite bushes extend across the adobe plain, forming lines of green that join and part again in a pattern very similar to

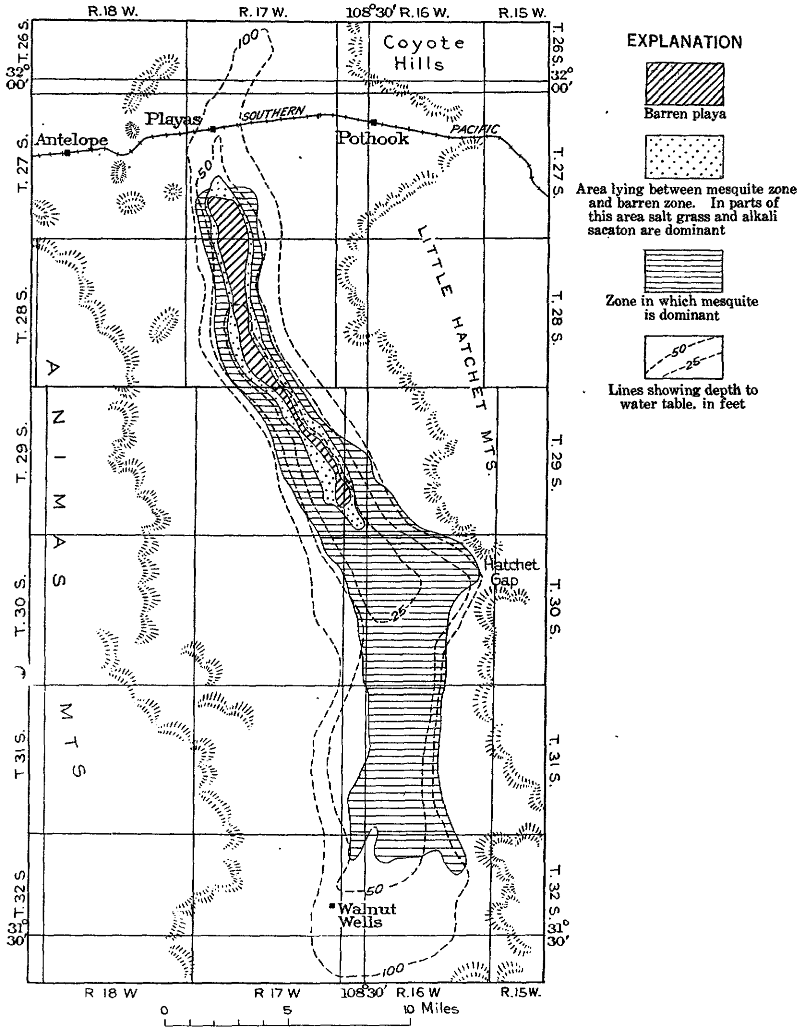

FIGURE 13.—Map of a part of Playas Valley, N. Mex., showing zones of vegetation and their relation to ground water. (After Schwennesen, A. T., op. cit., pl. 2)

that produced by the channels of a braided stream but following no visible channels. In the Lone Mountain well, in this vicinity, the depth to water is about 400 feet and careful inquiry of well drillers indicates that there is no perched ground water. In these localities of deep water table, however, the mesquite is always stunted and poor. On the other hand, where the ground water lies sufficiently near the surface to be reached by the roots of mesquite it forms dense thickets and forests of creeping and arboreal forms, in some places growing to heights of 20 and even 40 feet. The mesquite thicket on the adobe flats of Arlington Valley, with an optimum depth to the water table, is described by Ross as " so dense that the cow punchers can not penetrate it with their horses. If cattle get into it they are in a sanctuary safe from pursuit until they wander out again."

A study of the relation of mesquite to ground water was made by Brown,[18] in 1917, in connection with his survey of desert watering places in the Salton Sea region of southeastern California, including the Colorado Desert. The following table gives some of the data obtained by him:

Data showing relation of mesquite trees to water level

[By John S. Brown]

Locality	Depth to water (feet)	Character of mesquite growth	Nature of soil
Adams well, Palen Mountains	20	1 lone mesquite bush beside well; some others not far away in bed of dry wash.	Stream gravel.
Anshutz well, Eagle Mountains	8	Trench cut in side of canyon shows roots of mesquite penetrating crevices of rock to water; small clumps of mesquite in vicinity.	Granite, somewhat jointed and sheared.
Blair well, SE. ¼ sec. 24, T. 5 S., R. 6 E.	34	Abundant mesquite 10 to 12 feet high near by.	Very porous sand; forms dunes in neighborhood.
Chuckwalla well, sec. 33, T. 8 S., R. 17 E.	7½	Mesquite abundant locally in bed of dry arroyo.	Stream gravel and clay.
Clemens well, sec. 31 (?), T. 7 S., R. 13 E.	16	Stunted mesquite bushes locally in dry arroyo.	Gravel and clay.
Cook well, N. ½ sec. 22, T. 5 S., R. 6 E.	75	None	Porous sand.
Imperial new county well, sec. 1, T. 17 S., R. 18 E.	80	do	Porous sand and silt.
Frey well, SW. ¼ sec. 18, T. 5 S., R. 6 E.	70	do	Porous sand.
Harper well, sec. 26, T. 12 S., R. 10 E.	([a])	Thick forest of trees 10 to 20 feet high in neighborhood.	Sandy silt.
Indian Wells post office, sec. 24, T. 5 S., R. 6 E.	34	Abundant forests of mesquite 10 to 15 feet high in neighborhood.	Porous sand; forms large dunes in vicinity.
Packard well, Palen Mountains	18	Large patch of mesquite locally in bed of dry arroyo.	Gravel and rock; well ends in limestone.
San Felipe town site, sec. 5, T. 13 S., R. 10 E.	27½	Scattering growth 5 to 6 feet high near by.	Sandy silt.
Shaver well, sec. 27 (?), T. 6 S., R. 10 E.	21	Plentiful clumps 10 feet high in vicinity.	Stream gravel.
Sternberg well, SW. ¼ sec. 10, T. 13 S., R. 10 E.	45	Scattering growth 2 to 3 feet high all around.	Sandy silt.
Sec. 34 (?), T. 12 S., R. 10 E.	15	Heavy timber of mesquite 10 to 12 feet high.	Do.
Sec. 33 (?), T. 12 S., R. 10 E.	16	do	Do.
Sec. 4 (?), T. 13 S., R. 10 E.	20	Somewhat lighter than 2 above.	Do.
Palo Verde Valley	0-12	Heavy timber over large areas	Porous sandy silt.
Yuma Valley	8-15	do	Do.
Desert east of Imperial Valley	20-30	Scattering but persistent growth over large strip east of old beach.	Sand and silt.

[a] Flowing well; water stands in arroyo 8 feet below well.

[18] Brown, J. S., op. cit. (Water-Supply Paper 497), pp. 17, 114-117.

Brown states that in every extensive tract that is covered with mesquite there is a gradual dwarfing of the trees away from some district in which the water table is near the surface, suggesting that the size of the trees is a function of the depth to water, modified, however, by the character of the soil. This relation is shown for certain localities in Figure 14. Section A shows conditions in the Indian Wells region of Coachella Valley, where the soil is an exceedingly loose sand. It indicates a maximum depth to the water table of 50 or 60 feet where mesquite grows freely. Sections B and C show conditions in the Harper Well district, where the soil is generally porous sandy silt but in places is rather compact clay. These sections indicate that the maximum depth to the water table at which mesquite can reach ground water in this district is 40 to 50 feet. Section D shows the conditions between Alamo School and the new county well, on the east side of Imperial Valley. There is a strong flowing well at Alamo School. Water does not stand at the surface anywhere but is under artesian pressure for some distance east of the schoolhouse. Mesquite grows abundantly to heights of 10 or 12 feet west of the old beach, and it covers thinly a strip 2 to 3 miles wide above the beach to the east but is rather stunted. The depth to water at the line of disappearance is probably 30 to 40 feet. The soil is mixed sand and clay. The subject is summarized by Brown as follows:

> From the isolated occurrences tabulated it appears that healthy mesquite clumps in canyons and arroyos generally indicate water at a depth of less than 25 feet, although stunted specimens in small numbers may not be reliable indicators of water. Where mesquite covers large districts water is certainly present at depths probably less than 50 feet in any soil and less than 30 feet in very compact soil. Where healthy mesquite appears in isolated localities there is almost certainly water within at least 30 or 40 feet, usually less than 20 feet, of the surface. In examining carefully these isolated clumps of mesquite some good reason is nearly always discovered for the presence of water near the surface, and the mesquite is especially valuable in seeking water because it appears to have overlooked but few of the possible places where it might get a foothold.

In the survey of desert watering places in the Papago country of southwestern Arizona, Bryan [19] found that along Gila and Santa Cruz Rivers the mesquite groves undoubtedly draw a large part of their supply of water through the roots from the underlying water table, but that in the interior valleys mesquite trees and even large groves of mesquite exist where the ground water is from 60 to several hundred feet below the surface and seem to be dependent wholly on rain and flood water. He made the observation that the mesquite trees in the areas of deep ground water are more erect and more treelike than the mesquite of the areas of shallow ground water.

[19] Bryan, Kirk, op. cit. (Water-Supply Paper 499), p. 156.

This observation appears to conflict with the observations of some of the other authorities that have been cited, but it agrees with what

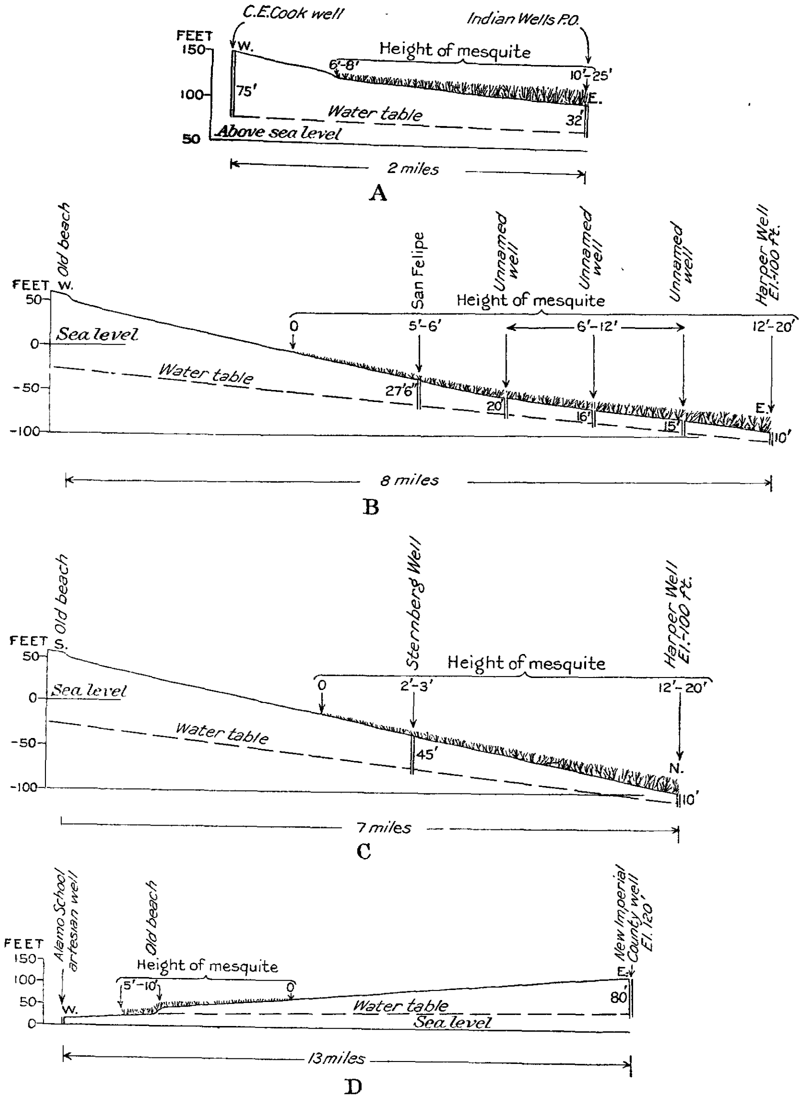

FIGURE 14.—Sections showing relation of mesquite to the water table in the Salton Sea region, California. A, Coachella Valley; B, C, Harper Well and San Felipe district; D, Imperial Valley. (After Brown, J. S., op. cit. (Water-Supply Paper 497), fig. 10)

the writer of this paper has seen in some localities. The following statements by Sudworth and Smith also bear contrary evidence:

> As a rule, the larger the stem above ground the smaller the root development; low, shrubby stems commonly have huge taproots descending to water at a depth of 50 or 60 feet or more.[20]

[20] Sudworth, G. B., op. cit., p. 365.

There seems to be a lack of relationship between the size of mesquite trunks and the depth to water. At Redington our experimental work is done in a mature mesquite forest. I say mature because the forest is so thick that the decay and drying up is as great as the new growth, and yet the trunks of the trees in no case are of very great size. It is a thick stand of small trees. On the other hand, on the Canoa land grant, between Tucson and Nogales, are the largest mesquites I have ever seen. One of them originally must have been at least 3½ feet in diameter. The depth to ground water at that place is as much or more than the depth at Redington.[21]

In the survey of desert watering places in the Mohave Desert region Thompson [22] found both the screw bean and the ordinary mesquite (*Prosopis juliflora*). He describes their distribution in the region as follows:

The screw bean and ordinary mesquite occur together in many places. They are abundant in stretches along Mohave River where ground water is close to the surface but are absent in other stretches where the depth to water is considerable. They are also found in the lower parts of some of the closed basins and in other places where the geologic conditions hold the water table close to the surface. They are present in the lower parts of the basins near playas in Antelope Valley, in Indian Wells Valley, and in Crucero Valley along Soda Lake and elsewhere. They grow also in a belt that stretches northwestward from the vicinity of Newberry Spring, where a buried geologic structural feature brings the water to the surface.

In many places where the mesquite grows in open expanses of land windblown sand accumulates around the plants. As the plant grows the sand accumulates more and more, and dunes, sometimes 15 or 20 feet high, are formed. The mesquite spreads out, and the different branches, being covered by sand, appear to be a number of individual plants. The roots generally penetrate some distance below the original ground surface in search of water, although the plants may appear to be perched on top of the dunes.

On the basis of numerous observations Thompson concludes that, whatever may be the uncertainties of mesquite as an indicator of ground water in adjacent areas, in the Mohave Desert region wherever mesquite was observed the depth to water is not more than 25 or 30 feet and the mesquite is generally considered to indicate that ground water is within that distance of the surface.

ALFALFA

Alfalfa requires a large supply of water to grow luxuriantly but does not generally thrive on poorly drained soil where the zone of saturation is at or very near the surface. It will send its roots to great depths to find water. According to Clarke,[23] of the California Experiment Station, it has been known to penetrate to the depth of 12 feet in a single season and the roots of older plants have been traced to a depth of 65 feet. Piper,[24] of the United States Department of

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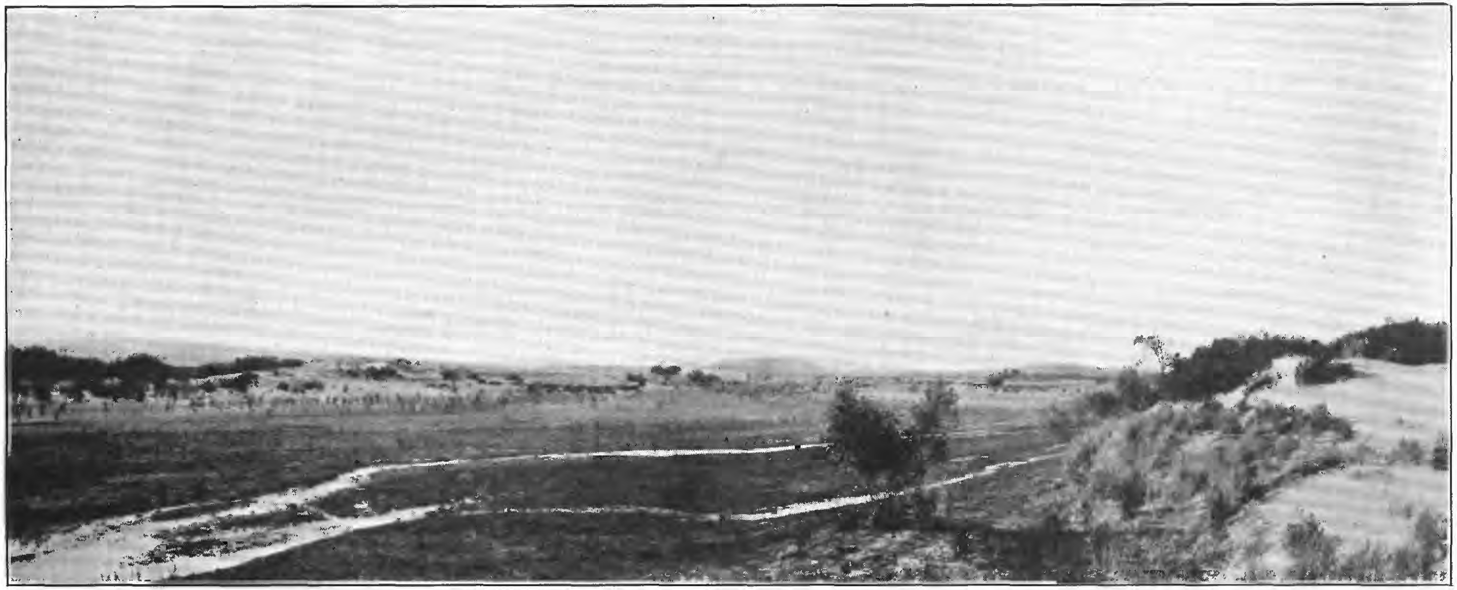
[21] Smith, G. E. P., personal communication.

[22] Thompson, D. G., op. cit.

[23] Clarke, W. T., Alfalfa: California Univ. Agr. Exper. Sta. Circ. 87, p. 1 (no date).

[24] Piper, C. V., Forage plants and their culture, revised ed., p. 362, New York, Macmillan Co., 1924.



MOHAVE RIVER VALLEY NEAR YERMO, CALIF., SHOWING DUNES ON BOTH SIDES, DUE LARGELY TO MESQUITE THAT FEEDS ON GROUND WATER

Photograph by D. G. Thompson

A. ALFALFA RAISED ON SEC. 31, T. 28 S., R. 10 W., NEAR MILFORD, UTAH, WITHOUT IRRIGATION

The water supply was drawn from the zone of saturation by the roots. Photograph by Walter N. White

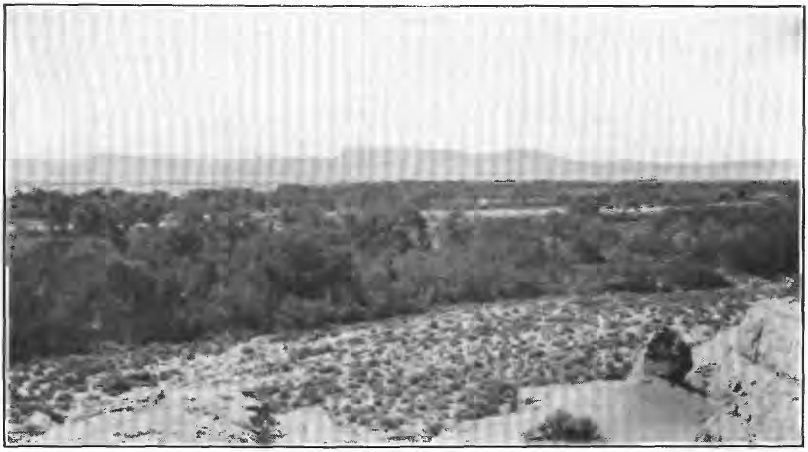
B. THICKET OF BIRCH TREES THAT FEED ON GROUND WATER AT THE MOUTH OF SANTA FE CANYON, BIG SMOKY VALLEY, NEV.

A. WILLOW TREES AT HIDDEN SPRINGS IN THE DESERT REGION OF SOUTHEASTERN CALIFORNIA

The springs issue from porphyritic rock on a hillside. Photograph by D. G. Thompson

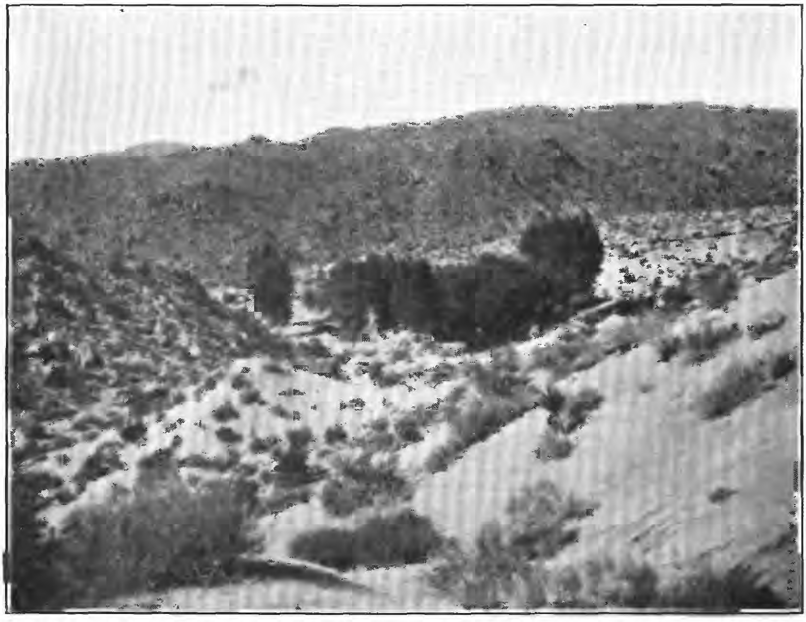
B. WILLOW TREE AT LEACH SPRING, IN THE DESERT REGION OF SOUTHEASTERN CALIFORNIA

Photograph by H. S. Gale



A. ZONE OF TREES THAT FEED ON GROUND WATER IN MOHAVE VALLEY, CALIF., IN CONTRAST WITH THE DESERT AREA THAT DOES NOT SUPPORT GROUND-WATER PLANTS

Photograph by D. G. Thompson



B. GROVE OF COTTONWOOD TREES THAT INDICATE AN AREA OF SHALLOW GROUND WATER IN THE SALTON SEA REGION, CALIFORNIA

Photograph by John S. Brown

A. SEVEN PALMS, A SPRING LOCALITY IN THE DESERT REGION OF SOUTHEASTERN CALIFORNIA

B. PALM, COTTONWOOD, AND MESQUITE TREES IN AREA OF SHALLOW GROUND WATER AT CORN SPRINGS, IN THE DESERT REGION OF SOUTHEASTERN CALIFORNIA

Photographs by John S. Brown

A. LARGE PALM TREES IN AREA OF SHALLOW GROUND WATER IN THE ARID REGION NEAR GUANTANAMO NAVAL STATION, CUBA

B. GROVE OF PALM TREES THAT INDICATE SHALLOW GROUND WATER IN AN ARID PART OF SOUTHERN CUBA

Agriculture, states that the roots of alfalfa will under ordinary conditions descend to a depth of 6 feet and are known to have reached depths of 15 feet. He also states that there are less well-authenticated reports of roots 25 to 45 feet in length and one record of a taproot 66 feet long. S. H. McCrory,[25] of the Department of Agriculture, states that at the Cheyenne Experiment Farm alfalfa roots were traced to a depth of 20 feet. C. W. Irish, also of the Department of Agriculture, observed the roots of alfalfa in a mine tunnel in Nevada at a depth of 129 feet. The tunnel was in "rotten porphyry" with crevices from which water was dripping. Through the crevices came also the roots, which were found to be those of alfalfa from a field above the tunnel.[26]

Recently alfalfa has been grown as a ground-water plant in various parts of the arid West, where the water table is within about 15 feet of the surface and has succeeded in recovering enough water from the zone of saturation to produce some hay as well as to make profitable crops of seed, although the growth is not nearly so good as under adequate irrigation.

In Estancia, N. Mex., in the immediate vicinity of which the climate is too arid for successful agriculture without irrigation, a small plat of alfalfa was observed where the water table stood about 14 feet below the surface. It was planted in June, 1921, and, though never irrigated, made a good stand and produced three crops of hay in 1922 and four crops in 1923. The third crop in 1923, according to weighings made by the owner, was equivalent to two-thirds of a ton to the acre. Favorable rains in 1921 started the alfalfa, but the good growth in the dry summers of 1922 and 1923 can not be attributed to rain and was undoubtedly due chiefly to the water obtained from the zone of saturation.

In the Escalante Desert, Utah, where the precipitation averages scarcely 10 inches a year, valuable crops of alfalfa seed have been successfully raised on a fairly large scale, as described by W. N. White on pages 89–91, in localities where the depth to the water table ranges between 6 and 15 feet. The young alfalfa is irrigated with water pumped from wells, but after it has established itself it grows and produces seed crops without irrigation. (See pl. 8, *A*.) Alfalfa is also raised without irrigation in shallow-water tracts in Sacramento Valley, Calif., but much difficulty is there experienced with gophers, which are not very troublesome in fields that are irrigated.

Evidently alfalfa has some of the properties of greasewood and mesquite in that it does not thrive where the water table is very near the surface but, on the other hand, will send its roots to considerable

[25] McCrory, S. H. (chief Division of Agricultural Engineering, U. S. Dept. Agr.), personal communication.

[26] See Coburn, F. D., Alfalfa, p. 14, New York, 1901.

depths in search for ground water. Much interest attaches to these properties of alfalfa for two reasons: First, they suggest the possibility of utilizing the great quantities of ground water that now virtually go to waste each year because of the prohibitive cost of pumping, by developing profitable ground-water plants in place of the worthless native species which at present consume so much of the ground water (p. 88); second, they suggest a new approach to the study of ground-water plants, especially as to the quantity of water consumed in relation to the dry material produced, and as to the quantity of the dry material produced in relation to the depth of the water table below the surface (p. 87).

A study of the history of alfalfa with special reference to its existence under conditions where it had to utilize ground water would be very instructive. It seems probable that its properties of feeding on ground water are not newly acquired but are rather inherited traits that were established long before man learned the art of irrigation. This is suggested by the facts that, so far as known, alfalfa was first cultivated in Persia and that it grows wild in parts of central and western Asia and in northern Africa.

WILLOW

The water-loving character of willows is recognized throughout humid as well as arid regions. Although the distinction between plants that feed on ground water and other plants can not be so sharp in humid as in arid regions because of the relative abundance of moisture in the soil above the capillary fringe in the humid regions, yet it is common knowledge that at least some species of willow prefer to live in low, moist tracts. There can be no reasonable doubt that even in the humid regions these willows feed largely on water from the zone of saturation and can therefore properly be called ground-water plants.

Willows also occur as ground-water plants in many desert valleys and have been described as such in the Mohave Desert[27] and Salton Sea[28] regions of southeastern California, the lower Gila region[29] of Arizona, several of the valleys of central and southern Nevada,[30] Pahsimeroi Valley, Idaho,[31] and Goose Creek Basin, Idaho.[32]

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[27] Thompson, D. G., op. cit. (Water-Supply Paper 490–B), p. 98.

[28] Brown, J. S., op. cit. (Water-Supply Paper 497), p. 17.

[29] Ross, C. P., op. cit. (Water-Supply Paper 498), p. 15.

[30] Ball, S. H., op. cit. (Bull. 308), pp. 22, 24. Carpenter, Everett, op. cit. (Water-Supply Paper 365), pp. 13, 36, 59. Meinzer, O. E., op. cit. (Water-Supply Paper 423), pp. 96, 100.

[31] Meinzer, O. E., Ground water in Pahsimeroi Valley, Idaho: Idaho Bur. Mines and Geology Pamphlet 9, p. 27, 1924.

[32] Piper, A. M., Geology and water resources of the Goose Creek Basin, Cassia County, Idaho: Idaho Bur. Mines and Geol. Bull. 6, p. 50, 1923.

Willows are described by Parish[33] as occurring throughout the Salton Sink, California, along river banks, near springs, and in damp soil, and by Spalding[34] as lining the banks of Santa Cruz River near Tucson, Ariz., in association with cottonwood trees. Two species of willow, *Salix gooddingii* and *Salix fluviatilis*, are especially mentioned by J. J. Thornber as ground-water plants. He states that in the Gila Valley, Ariz., both at Phoenix and at Yuma, *Salix gooddingii*, a large tree, is the common valley willow. In Big Smoke Valley, Nev., willows are found in localities where ground water can be obtained near the surface but where the soil has some drainage and is not very alkaline. Their presence was recorded in two localities—one where the depth to the water table was 6 feet and they were associated with salt grass; the other where the depth was 11.4 feet and they were associated with sagebrush and greasewood It is possible that these plants were wrongly identified and that they are desert willow instead of true willow. In Plate 9 are shown two springs in the desert region of southeastern California that are marked by willows.

DESERT WILLOW

The desert willow (*Chilopsis linearis*) generally indicates ground water, but there is evidence that in some localities it feeds on ground water where the water table is as much as 50 feet below the surface and that in others it has no relation to the water table. Coville[35] observed the species in a number of shallow-water localities and lists it with true willows, under "desert plants of humid habitat." He is, however, somewhat ambiguous in his summary statement that "this plant grows near streams or springs or in their dried beds." Brown,[36] in describing the vegetation of the Salton Sea region, California, states that the desert willow is a common tree in the dry washes of the desert and unfortunately ruins the reputation of true willows as indicators of ground water, for it apparently has no connection with permanent ground water. Thompson[37] considers that in the Mohave Desert region it is generally, though perhaps not always, found where ground water is near the surface. He states that although it grows in channels along Mohave River where the depth to water is probably not more than 25 or 30 feet it is not a certain indicator that the water table is close to the surface.

Bryan[38] states that in the Papago country, Arizona, the virtues of the desert willows, as also of the batamote (*Baccharis glutinosa*)

[33] Parish, S. B., op. cit., p. 107.
[34] Spalding, V. M., op. cit., p. 8.
[35] Coville, F. V., op. cit., pp. 39, 174.
[36] Brown, J. S., op. cit., p. 18.
[37] Thompson, D. G., op. cit. (Water-Supply Paper 490-B), p. 98.
[38] Bryan, Kirk, op. cit., pp. 156–157.

and the cherioni or wild china tree (*Sapindus marginatus*), as indicators of water are extolled by the old settlers of the region, largely on the basis of supposed Papago wisdom in regard to water. He concludes, however, that the moisture required by these plants can be supplied by water stored in joints and fractures in the rocks or by small amounts of water held above a clay or other compact bed in alluvium, which is too inconsiderable to supply a well.

COTTONWOOD AND OTHER POPLARS

Cottonwood trees form one of the most familiar and grateful features of the arid West, where they are extensively grown as shade trees in villages and on ranches. The cottonwoods of the desert region (*Populus fremontii*, *Populus wizlizeni*, etc.) are commonly found in areas where ground water is near the surface and are true ground-water indicators. (See pl. 10.) They are mentioned by Brown, Ross, Bryan, and Thompson in their desert reports, as trees that live on ground water. For example, Bryan states that the cottonwood is a reliable indicator of shallow ground water but requires so much moisture that it does not grow in doubtful localities. Gregory[39] states that in the Navajo country of northwestern Arizona and adjacent States cottonwood usually indicates a depth to water not exceeding 20 feet. He observed these trees growing in a wash where the water table is at least 50 feet below the surface, however, and he explained their presence in this locality as apparently due to perched ground water lying nearer the surface during at least a part of the year. Not all species of poplars should be regarded as indicators of ground water. For example, the aspen, or quaking asp, though it prefers moist localities, is not known to depend on the water from the zone of saturation. It is frequently found on mountain summits and slopes but is not a feature of mountain canyons that contain ground water.

In Pahsimeroi Valley, Idaho, cottonwoods line the principal stream channels for miles down the alluvial slopes. In 1921, however, these trees had in large part died in the middle portions of the slopes, probably because of the diversions for irrigation, which were especially felt in the preceding dry years. Most of the trees near the mouths of the canyons, where the stream waters are most abundant, and in the lower parts of the slopes, where the ground water is within reach of their roots, are still alive.

The tall, slender, and graceful Lombardy poplars, which are so distinctive of the villages and ranches of many parts of the West,

[39] Gregory, H. E., The Navajo country—a geographic and hydrographic reconnaissance of parts of Arizona, New Mexico, and Utah: U. S. Geol. Survey Water-Supply Paper 380, p. 131, 1916.

especially in Utah, frequently receive irrigation water but apparently can also live by means of ground water. At the abandoned San Antonio ranch, in Big Smoky Valley, Nev., two healthy Lombary poplars and three box elders were found growing where the water table was about 4 feet below the surface and where a test showed the presence of alkali at the surface. The ranch had apparently been abandoned for a considerable time, and these trees were growing without attention, obviously utilizing the supply of ground water.

BUFFALO BERRY, ELDERBERRY, BLACKBERRY, GOOSEBERRY, AND HACKBERRY BUSHES, SHRUBBY CINQUEFOIL, AND WILD ROSES

The buffalo berry bush (*Shepherdia*) is a tall woody and spiny bush that produces edible berries. It grows widely throughout the northern and middle parts of the arid West, probably not everywhere as a ground-water plant. One species was found growing abundantly in the shallow-water areas of the north basin of Big Smoky Valley, Nev., and also in the adjacent mountains in some of the canyons that carry underflow. Wherever it was observed it was growing strictly as a ground-water plant. Cannon,[40] quoting Merrill, states that in Nebraska the roots of *Shepherdia* attain a depth of 50 feet. The *Shepherdia* in Big Smoky Valley, however, grows where the water table is nearer the surface.

A shrub called "quail brush" was found by Carpenter[41] in several valleys of southern Nevada, where it grows along streams and in localities in which ground water is found at shallow depths. The technical name of this shrub is not given by Carpenter, but as it occurs in the warm valleys of southern Nevada it is presumably not *Shepherdia*.

Elderberry and gooseberry bushes are mentioned by Ball[42] as indicators of water in the deserts of southwestern Nevada and adjacent parts of California. He states that they are unknown in that region except in the vicinity of water. Elderberry and a species of buckthorn are mentioned by Spalding as confined to the habitat where the water table is within reach, at least of mesquite (p. 45). Thornber states that in Arizona the two common species of elderberry (*Sambucus caerulea* and *Sambucus neomexicana*) are invariably ground-water plants, as is also the small native blackberry (*Rubus oligispermus*).

[40] Cannon, W. A., Carnegie Inst. Washington Pub. 131, op. cit., p. 9.
[41] Carpenter, Everett, op. cit. (Water-Supply Paper 365), pp. 13, 36, 59.
[42] Ball, S. H., op. cit. (Bull. 308), pp. 22, 24.

Cumaru, or hackberry, especially the large species, which grows to a height of 50 feet, was observed by Bryan [43] along mountain borders in the Papago country, where it is an indicator of ground water.

Shrubby cinquefoil (*Dasiphora fruticosa*) occurs abundantly as a ground-water plant in the shallow-water area of Pahsimeroi Valley, Idaho,[44] and was not observed where the water table is too deep to be reached by its roots.

It is well known that roses thrive best where they enjoy an abundant supply of water, although they are also abundant as weeds in cultivated fields with only moderate supplies of soil moisture. The wild roses of the humid regions are, of course, found in a great variety of situations, but they grow most luxuriantly in low places, in many of which they doubtless obtain water from the zone of saturation. In the strictly arid regions they are found only near springs and streams or in other localities where the water table is near the surface.[45] As they can not endure much alkali they are not common in the lowlands except where there is enough drainage to prevent accumulation of alkali. A good example is afforded by a spring mound in the midst of a salt-grass tract in the shallow-water area at the San Antonio ranch, in Big Smoky Valley, Nev., on which roses were found growing luxuriantly.

WASHINGTON PALM AND OTHER PALMS

The oases of the deserts of the Old World are notable for their palm trees. In the western part of the United States wild palms are found in the hot and dry region of southeastern California, chiefly along the margins of the Salton Basin. This tree (*Washingtonia filamentosa*) is called by Brown [46] the premier of all the water indicators in the Salton Sea region. It is an unfailing sign of a spring or of water that can be found by digging a few feet. Moreover, says Brown, the tree stands up so conspicuously, with its green head high in the air, perhaps 50 feet or more, that it is visible for long distances and makes an excellent natural signpost. (See pl. 11.) Dos Palmas, Seventeen Palms, Twenty-nine Palms, Thousand Palms, Burnt Palms, Palm Springs, Palm Wash, and Palm Canyon are all

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[43] Bryan, Kirk, op. cit., pp. 45, 46, 157. In Bryan's paper the large species is called *Celtis occidentalis*, and a small species, which is more widely distributed and less of a ground-water indicator, is called *Celtis reticulata*. These designations are based on Mearns, E. A., Mammals of the Mexican boundary of the United States: U. S. Nat. Mus. Bull. 56, pp. 54, 55, 1907. According to Thornber, however, the principal species of hackberry in Arizona is *Celtis reticulata*, and *Celtis occidentalis* is not found in that State.

[44] Idaho Bur. Mines and Geology Pamphlet 9, p. 27.

[45] Ball, S. H., op. cit. (Bull. 308), pp. 22, 24; Meinzer, O. E., op. cit. (Water-Supply Paper 423), pp. 96, 99.

[46] Brown, J. S., op. cit. (Water-Supply Paper 497), pp. 112, 113, 246, 247, 271, 278.

names of watering places in this region. The shallow-water tracts where the palm trees grow support various familiar ground-water plants, such as salt grass, arrow weed, mesquite, and willow, which help in locating the springs or the localities of shallowest water but which do not attract attention from a distance, like the palms. The distribution and relations of the wild palm are further described by Brown as follows:

> It is found in most of the canyons or arroyos, particularly around the borders of the Salton Basin, in which water rises near the surface. It is also found at nearly all the artesian springs of Coachella Valley. Unfortunately, it does not always indicate good water; sometimes, indeed, it is found at springs of very bad water. But usually a healthy clump of palms means a spring of drinkable water. The palm does not extend to high altitudes. In the Peninsular Mountains it is seldom found more than 1,000 feet above sea level. In the eastern desert ranges it may extend as high as 2,000 feet. So far as known, however, it is absent from all the ranges near Colorado River in this region, probably because the water supply is too scant.

In the semiarid parts of Cuba the writer observed that large palm trees are growing in many of the areas of shallow ground water and appear to be reliable indicators of ground water (pl. 12), whereas the small yuraguano, or fan palm, grows on the dry limestone hills high above the water table. In many places banana trees evidently feed on ground water.

FOREST TREES

It is, of course, impossible to distinguish definitely among the forest trees of the humid parts of the United States and of the relatively humid mountain regions in the arid parts of the country those which habitually use water from the zone of saturation and those which do not, but it is certain that some species depend much more on ground water than others. Several species of birch, sycamore, alder, and live oak are examples of trees which in the forests of the East or South show obvious preferences for lowland tracts where they can utilize water from the zone of saturation, although they may not be confined to such tracts. Moreover, it should not be assumed that all species of these kinds of trees depend equally on ground-water supplies. For example, some species of birch seem to show more preference for shallow-water areas than others, and the different species of oak range from those that depend almost wholly on ground water to those that are markedly independent of the water table.

Trees of water-loving types show their true dependence on ground water at their frontiers, as it were—that is, in localities of shallow ground water within the arid regions. For example, birch trees are numerous in the canyons of certain mountainous regions of central Nevada, and there is evidence that their occurrence indicates in large measure the distribution of shallow ground water in these regions. (See pl. 8, *B*.) Sycamore trees indicate the presence of ground water in many localities in the arid regions. In the Papago country of southwestern Arizona the Arizona sycamore (*Platanus wrightii*) and the leather-leaf ash (*Fraxinus velutina*) may be taken as reliable indicators of ground water.[47] Alders and walnuts feed on ground water in many places in the arid West. The alder *Alnus oblongifolia* and the walnut *Juglans major* are mentioned by Thornber among the ground-water species in Arizona.

Many of the trees such as are found in the forests of humid regions will not, however, grow in the tight alkaline soils of the shallow-water areas in the desert lowlands. Thus the birch in Big Smoky Valley, Nev., and the sycamores and live oaks in Sulphur Spring Valley, Ariz., are confined to the well-drained upland tracts of ground water and are not found in the shallow-water areas in the low parts of the valleys. In Sulphur Spring Valley ribbons of timber, consisting of sycamore, live oak, and cottonwood, extend along the principal stream courses from the mouths of the canyons far down the alluvial slopes. Their occurrence here is obviously related to the relatively abundant water supplies along the stream courses. The forested stretches of these draws or watercourses do not, as a rule, have perennial streams. In most places they carry water only during certain seasons or at times of heavy rain and are dry for months at a time. In many places, however, springs and shallow wells indicate that they are underlain by perennial supplies of perched ground water. The intimate relation that exists between the forested portions of the draws and the areas of high-level ground water suggests that the trees are supported by these relatively permanent supplies rather than by those obtained directly from the uncertain floods. Along Turkey Creek, for example, the lower limit of trees corresponds rather closely to the lower limit of high-level ground water. This relation has been observed in enough places to warrant prospecting for shallow ground water in the forested draws in which wells have not yet been sunk.[48]

A study made by Cannon [49] of three species of oak that are characteristic of the valleys of central California showed that these species differ greatly in their relation to the water table. The blue oak (*Quercus douglasii*) occurs where the water table is lacking, or so deep as to be quite beyond the possible reach of the roots, so that

[47] Bryan, Kirk, op. cit., p. 157.

[48] Meinzer, O. E., and Kelton, F. C., op. cit. (Water-Supply Paper 320), pp. 102–111, 182, 187.

[49] Cannon, W. A., Pop. Sci. Monthly, vol. 85, pp. 417–424, 1914.

the species is wholly dependent on soil moisture near the surface for its water supply. The live oak (*Quercus agrifolia*) occurs where the water table is usually 35 feet or more beneath the surface. This species sends out some deep roots, but has a well-developed system of roots within 3 feet of the surface. The roble oak (*Quercus lobata*) differs greatly from the two other species in respect to water supply. It is best developed where perennial ground water lies within 10 to 20 feet of the surface or where the soil is practically homogeneous, so that the ascent of capillary water is great and the roots can penetrate to great depths. If not strictly confined to moist soils, it at least attains its best development where the soil is moist and the ground water is not so deep as to be beyond the reach of its roots.

Among the conifers some of the species that depend more or less on the zone of saturation for their water supply are the Engelmann spruce (*Picea engelmanni*), tamarack (*Larix laricina*), redwood (*Sequoia sempervirens*), and big-tree sequoia (*Sequoia washingtoniana*). The Engelmann spruce requires a good water supply and depends on ground water in many localities. A. E. Douglass has observed that this species has very "complacent" rings. The following statement in regard to its moisture requirements is made by Sudworth:[50]

> Its presence is controlled to great extent by the supply of soil moisture, demands for which limit its occurrence to high elevations or to land moist from springs, seepage, or overflow. Its lower range is limited to moist canyons or to protected north slopes, while on other exposures it finds suitable soil moisture only at higher altitudes.

In Pahsimeroi Valley, Idaho, the limber pine (*Pinus flexilis*) covers a considerable tract in the lowland area of ground-water discharge and forms a striking feature in the otherwise monotonous plain. In the valley these pines are strictly confined to the area of shallow ground water, but in the adjacent mountains they are found in very different habitats. The following interesting statement is furnished by O. M. Mink, forest supervisor, who collected specimens for identification by the United States Forest Service:

> These trees occur in a spring area in the middle of the Pahsimeroi Valley. This area is a regular bog throughout the spring and summer. The trees all seem to be very thrifty, and a good many of them are very old. I have counted the growth rings on some of the old stumps cut about 25 years ago and found from 160 to 175. There is still a good stand, and the larger trees are still living. Contrary to the usual growth of limber pine in this country these trees are straight, not forked and twisted. There are other stands of the same species in this district at different places on the high ridges, but this particular stand is peculiar and exceptional to the locality.

The redwood is very exacting in its requirements as to soil moisture but avoids swampy land. The big-tree sequoia is evidently less

[50] Sudworth, G. B., op. cit., pp. 80, 81.

dependent on ground water but also prefers localities where the water table is within reach.[51] Douglass[52] states that, roughly speaking, the big-tree sequoia depends upon soil moisture more than the yellow pine, and that the redwood of Santa Cruz has access to so much moisture and hence has such "complacent" rings that he can not use it in any of his tests. In an unpublished report to the National Park Service on a water supply for the Mariposa grove of Yosemite National Park, Kirk Bryan advised against the development of an additional ground-water supply because of the damage that might be done to the big-tree sequoias by lowering the water table. He states:

> Any system of obtaining sufficient ground water would involve lowering of the water table by draft on the ground-water reservoir. It is noticeable that the sequoias are clustered at the damp and boggy places and along water courses. Only a few grow on hillsides and ridge tops. The trees evidently require larger amounts of water than many other forest trees.

The most thorough study of the relation of trees to ground water has been made by Cannon, who gives the following statement:[53]

> An extension of observations on tree distribution, as related to the depth of perennial water, to regions outside of southern Arizona, gives interesting, if not entirely conclusive, results. A comparison of the depth to ground water of the coastal plain of Texas as given by Taylor[54] with the distribution as given by Bray,[55] for example, offers important suggestions in the present connection. In general it may be said that the stream bottoms of the coastal plain support a hardwood forest, which also extends over such upland as has a fairly shallowly placed water table. Such of the deciduous trees as are marked xerophytes—for example, the post oak—occur on dry ridges where pines of various sorts are also to be found and where the depth to permanent water is considerable. Of these trees, the root habit of the long-leaf pine is known. This species has a long taproot which penetrates to a great depth and which renders the species in a measure independent of surface conditions of soil and moisture. In the more arid southern portions of the coastal plain, where the water table lies below 50 feet, chaparral is characteristic of the upland, and along the streams, where the water table is less deep, forests occur.
>
> Northward from Texas, as well as westward from the coastal plain of the State, are to be found conditions analogous to much already noted for southern Arizona and the coastal plain. That is, other things being equal, trees and forests, especially deciduous forests, are limited to areas where the depth to the water table is not great. Thus in Kansas and Nebraska the deciduous forests are mostly confined to the flood plains of streams, while the adjacent upland is treeless.
>
> As one examines other regions (reference is made more in particular to those that are semiarid) he finds forests confined to such areas as are underlain by ground water not beyond the attainment by the roots of trees.

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[51] Sudworth, G. B., op. cit., pp. 144, 147.

[52] Douglass, A. E., personal communication.

[53] Cannon, W. A., Science, new ser., vol. 37, pp. 422–423, 1923.

[54] Taylor, T. U., Underground waters of the Coastal Plain of Texas: U. S. Geol. Survey Water-Supply Paper 190, 1907.

[55] Bray, W. L., Forest resources of Texas: U. S. Dept. Agr. Forest Service Bull. 47, 1904.

PROMINENT DESERT PLANTS THAT DO NOT HABITUALLY FEED ON GROUND WATER

The significance of the ground-water plants will be better understood and appreciated if attention is called to a few of the prominent desert plants that do not indicate ground water and do not habitually depend on the zone of saturation for their water supply.

The common sagebrush (*Artemisia tridentata*) is not an indicator of shallow ground water. It does not generally utilize water from the zone of saturation. It grows best in rather light soil, relatively free from alkali and with good drainage but with a fairly abundant supply of water, derived usually from rain or snow or from sheet floods and only exceptionally from the zone of saturation. In the Mud Lake Basin, Idaho, where the water table has been gradually rising during the last 25 years, presumably on account of irrigation in an adjacent area, the sagebrush has been killed by the ground water wherever the water table has risen near the surface. In these newly developed shallow-water tracts the ground-water plants have not yet gained much of a foothold, but a shallow water table is everywhere indicated by the presence of dead sagebrush. In Pahsimeroi Valley, Idaho, sagebrush was found growing to an unusual extent in association with greasewood and rabbit brush. The explanation of this association apparently lies in the fact that the subsoil of this valley is exceptionally gravelly and that therefore the fringe of capillary water above the water table is unusually shallow, thus leaving an aerated zone adequate for the sagebrush even in places where the water table comes within 5 feet of the surface and hence is within easy reach of the greasewood and rabbit brush. Doubtless sagebrush utilizes some ground water in this shallow-water tract, but its independence of the water table is shown by the fact that it forms the dominant vegetation over large areas in the valley where the ground water is certainly not within its reach.

Shadscale (*Atriplex confertifolia*) is the dominant plant over very extensive desert areas in Nevada and Utah. It apparently occupies the upland areas where the conditions of soil and water supply are too unfavorable for sagebrush. It will grow in tighter soil than sagebrush, in places where its roots are restricted to the top soil by an alkaline subsoil, and in places where the precipitation is scanty and the soil is not wetted by floods. As a rule it does not thrive in soil that is wet on account of the capillary rise of ground water, and its presence is usually an indication that at least the surface foot is dry during the greater part of the summer. Although it mingles with ground-water plants such as greasewood, it does not generally feed on ground water, and its greatest development is on the desert uplands where the water table is far beyond the reach of its roots. Over large parts of Nevada the little greasewood (*Sarcobatus baileyii*), also an abundant member of the group that do not depend on ground water, is associated with the shadscale.

Farther south, in the vast deserts of southern Nevada and of California, Arizona, and New Mexico, the familiar vivid-green creosote bush (*Covillea tridentata*) is dominant over the very arid and stony uplands, where the water table if present at all is far beyond the reach of its roots. Bur sage (*Franseria dumosa*) is associated with creosote bush in the extreme desert region of southeastern California and southwestern Arizona. Coleogyne (*Coleogyne ramosissima*) grows in similar habitats but extends farther north, into Nevada and Utah.

Among the other truly desert types of plants found in the Southwest are the giant cactus, barrel cactus, cholla, prickly pear, and many other kinds of cactus, and the Spanish bayonet, Joshua tree, ocotilla, and other kinds of yucca. All these depend on the moisture from the scanty rainfall, supplemented very rarely by moisture from an occasional flood. They have no relation to the water table and do not habitually utilize ground water.

Some of the desert trees of southwestern Arizona and adjacent regions, notably the palo verde and ironwood, commonly grow on land that is high above the water table and so far as known have no tendencies to utilize ground water. They do, however, attain their best growth in the dry washes where the soil is occasionally wetted by flood waters. Brown [56] furnishes the information that ironwood forms a thin but persistent forest over large areas in the Salton Basin and Chuckwalla Valley, Calif., and is also present in nearly all the dry washes; and that palo verde is confined largely to dry washes in the desert. He states that both of these trees grow to heights of 15 or 20 feet in favorable localities, and that one palo verde tree 50 feet high was seen. These large and substantial trees are the marvel of the Southwest, for they grow where the rainfall is very meager and they are not ground-water plants.

Although ironwood and palo verde are especially partial to draws where they receive some natural irrigation, it is true that sagebrush, shadscale, creosote bush, yucca, and in fact most of the prominent plants that have been mentioned above as not dependent on ground water have their most luxuriant growth, though perhaps an abnormal and unwholesome growth, where they receive flood water in addition to the direct rainfall. None of them are known to show affinity for the water table, although under certain conditions any of them may doubtless utilize water from the zone of saturation.

[56] Brown, J. S., op. cit., p. 18.

RELATION OF PLANTS THAT FEED ON GROUND WATER TO OTHER GROUPS

RELATION TO PLANTS THAT LIVE IN WATER

Water-loving plants might be divided into those which grow entirely under water, those which have their roots only under water, those which have their roots in saturated soil, and those which grow where there is a zone of aerated soil between the land surface and the water table but where the water of the zone of saturation or of the overlying capillary fringe is within reach of their roots. The plants discussed in this paper consist of the last two of these groups. If the term hydrophyte were used in a very inclusive sense to comprise all four groups, then the ground-water plants would, of course, become a subdivision of the hydrophytes. A superficially logical distinction might be made between hydrophytes and ground-water plants if the former were regarded as plants that grow in surface water (groups 1 and 2) and the latter as plants that grow on land where ground water is available (groups 3 and 4). According to this distinction the rushes, sedges, and cat-tails are on the border line, being hydrophytes where they grow at the edges of pools and streams and ground-water plants where they grow on land.

However, the distinction as to whether the body of water that feeds the plant is surface water or ground water is perhaps less important than the relation of the roots to the body of water—a question on which there is still great lack of information. Many ground-water plants probably develop a root system in the capillary fringe and avoid, so far as possible, sending their roots into the zone of saturation, thus differing in an important respect from true hydrophytes, whose roots are normally under water. However, the ground-water plants which are closely allied to the hydrophytes and which grow where the water table is very near the surface doubtless have functional roots in the zone of saturation. Moreover, G. E. P. Smith found both cottonwood and mesquite roots highly developed below the water table, and W. N. White found the roots of alfalfa extending somewhat below the water table.

The water table everywhere fluctuates. In most places within the areas occupied by ground-water plants the seasonal fluctuation amounts to 2 or 3 feet and in some places it is as much as 25 to 50 feet. This fluctuation is probably beneficial because on the whole it produces a thicker belt of aerated soil that is moistened by ground water, but it raises interesting and important questions as to how the root system is adjusted to the fluctuations of the water table.

An example of the problem is afforded by the well of the late F. J. Jones, near Millett, Nev., which was measured monthly by him for the Geological Survey during a period of more than three years.

In this well the water table fluctuated between a low stage of 10.9 feet and a high stage of 7.3 feet below the surface, the annual fluctuation being 2.5 feet in 1914, 3.5 feet in 1915, and 3.6 feet in 1916. The capillary fringe is about twice the thickness of this belt of fluctuation, but it is altogether probable that in the summer, when the water level is low, the salt grass and rabbit brush, which grow in the vicinity of the well, send feeders into the lower and wetter portion of the capillary fringe, close to the water table. By spring, however, this lower portion is submerged, and the plants must either draw their water supply from the zone below the water table or from another set of roots at a higher level or from both sources.[57]

An example of the problem where the fluctuation is unusually great is afforded by Pahsimeroi Valley, Idaho, in which seasonal fluctuations of more than 10 feet are common. The water table is usually lowest early in the spring, rises rapidly later in the spring, reaches its highest levels between June and September, and then subsides slowly but persistently until the next spring. Thus, most of the fluctuation occurs during the growing season. In the well of Dr. C. J. Gilman, in this valley, a total fluctuation of 38 feet has been recorded, the water level ranging from 2 to 40 feet below the surface.[58] In low stages of the water table the greasewood and rabbit brush in the vicinity of this well have an unusual range of moist aerated soil in which to develop their roots, but in the high stages this root system becomes submerged.

In salt-grass areas in which there is a great fluctuation in the water table the salt grass may be dormant during the low stages. This condition prevails in places around Great Salt Lake, where the low stage occurs in the fall.[59]

RELATION TO SALT-RESISTANT PLANTS

The salt-resistant plants, or halophytes, in the arid regions virtually form a subdivision of the ground-water plants, because the alkaline soils in which they grow are almost wholly confined to the areas that have ground-water discharge. Nevertheless, these plants, or at least the succulent species, such as pickleweed and samphire, which are found in the most alkaline soils, resemble the drought-resistant plants, or xerophytes, in that they have to subsist on very small quantities of water. The economy in the use of water may be required even of plants that grow in saturated soils. The explanation of this paradoxical condition is found in the well-known fact that a plant in order to absorb soil water must have a tissue fluid

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[57] Meinzer, O. E., op. cit. (Water-Supply Paper 423), pp. 100–102.
[58] Idaho Bur. Mines and Geology Pamphlet 9, pp. 24, 25, 1923.
[59] Aldous, A. E., personal communication.

of higher osmotic pressure and therefore of higher salt content than the soil water. For this reason the highly concentrated soil water is relatively unavailable to the plants, and the soil that contains such highly concentrated water is said to be physiologically dry even if it is saturated. Because of the slow rate at which these salt-resistant plants absorb water, they require adaptations for controlling transpiration similar to those of the drought-resistant plants. The high concentration of the tissue fluid itself retards transpiration.

The soils and subsoils underlying many of the playas and adjacent belts of succulent salt-resistant plants are, moreover, very clayey and tight and therefore have only small supplies of available water, in spite of the high water table and abundant water supply of the surrounding belt of more permeable soil. Thus the supply available to plants may be meager because of the fine texture and impermeability of the soil and subsoil as well as the high concentration of the soil water. It has been shown that the clay cores underlying many of the playas are virtually impermeable and have only very sluggish capillary movement of water. Thus their barrenness is due, at least in large part, to their deficiency of an available water supply.

It is known, however, that in the more permeable belts surrounding the clay cores a very alkaline soil may be underlain by ground water that is not excessively mineralized and that may indeed be very pure. Grasses that flourish on alkaline soil, such as salt grass and alkali sacaton, apparently have considerable transpiration. This fact leads to the suggestion that they may obtain most of their water supply not from the physiologically dry soil but from the relatively pure water of the zone of saturation. The leaves of tamarix are known to have glands for excreting salt,[60] and the leaves of salt grass apparently have a similar adaptation. This may enable the salt grass to function as a true salt-resistant plant at times when only highly concentrated soil water is available but to reduce its sap concentration and to transpire more freely when there is an adequate supply of better water. Deep-rooting plants that are found in alkaline soils may also be relatively independent of the alkali in the top soil and may feed on the relatively pure ground water. The young plants of such species must, however, have the ability to endure the alkaline soil until they are able to send their roots to the required depth, and this property is known to be possessed by the seedlings of greasewood.[61]

[60] Coulter, J. M., Barnes, C. R., and Cowles, H. C., A textbook of botany for colleges and universities, vol. 2, Ecology, p. 621, New York, 1911.
[61] Kearney, T. H., op. cit., p. 405.

The recent work of Harris [62] and others on sap concentration bears on this subject. Work of this kind could be applied more directly to the questions of the relation of the salt-resistant plants to the water in the zone of saturation and the significance of these plants as indicators of quantity and quality of ground water. The investigations of the native plants in Tooele Valley by Harris and his colleagues showed that the concentration of sap in greasewood, salt grass, and alkali sacaton was low as compared with that in pickleweed, samphire, and shadscale; furthermore, that the minimum concentration in greasewood, salt grass, and alkali sacaton was only moderately in excess of the concentration in sagebrush and dry-farm grains. These relations are shown by the following summary table:

Chloride concentration in the tissue fluids of native plants in Tooele Valley, Utah

[As shown by work of J. A. Harris and others]

Plant associations and species	Number of tests	Chlorides (grams per liter)		
		Minimum	Maximum	Average
Sagebrush association of alluvial fans:				
Artemisia tridentata [a]	4	2.1	3.6	2.7
Greasewood-shadscale association:				
Sarcobatus vermiculatus	7	4.8	14.3	8.7
Atriplex confertifolia	6	19.5	64.4	39.8
Allenrolfea occidentalis	5	14.9	23.5	17.5
Grass-flat communities:				
Allenrolfea occidentalis	5	14.6	25.0	19.6
Sporobolus airoides	3	7.0	15.2	11.4
Distichlis spicata	3	7.9	20.0	13.8
Salt-flat communities:				
Allenrolfea occidentalis	4	14.7	26.1	22.9
Salicornia utahensis	8	25.5	37.1	30.0

[a] The concentrations in sagebrush (*Artemisia tridentata*) are of the same order as those found near the end of the season in small grains as grown under dry-farm agriculture at Nephi, Utah.

RELATION TO DROUGHT-RESISTANT PLANTS

The desert ground-water plants may have a humid environment for their roots, but they resemble the drought-resistant plants, or xerophytes, in having a dry environment for their transpiratory organs. Moreover, some ground-water plants, chiefly those which send their roots to great depths to reach the water table, have considerable ability to endure adverse soil-moisture conditions when they are not in contact with an adequate ground-water supply. The young plants of these species, if they have grown from seeds, must be able to withstand drought until their roots reach the ground water; moreover, if they find ground water only at great depth the rate at which they can lift the water to their stems and leaves may be too slow to allow rapid transpiration.

[62] Harris, J. A., and others, The osmotic concentration, specific electrical conductivity, and chlorid content of the tissue fluids of the indicator plants of Tooele Valley, Utah; Jour. Agr. Research, vol. 27, pp. 893–924, 1924. See also the bibliography in this paper.

Seeds of deep-rooting plants may, of course, germinate wherever they happen to be dropped, and the young plants will live and grow as long as they can, regardless of whether the water table is 15, 50, or 200 feet below the surface. Thus some plants may send roots to great depths and yet fail to find ground water because the water table is still lower. These plants will obviously not give up the struggle for existence because they do not find ground water; they will struggle on as long as they can, even under adverse conditions. Evidently, therefore, these deep-rooting plants tend to break away from the strict control of the water table and to spread to areas where they do not draw on the ground-water supply. There is evidence that the deep roots are not sent downward through dry soil but make their deep growth when or where they can do so in moist soil. Nevertheless the water supply of such species must be precarious over large areas except as ground water is reached, and hence these species have need for adaptations to resist drought until they have tapped the ground-water supply.

However, the individuals that reach the water table are likely to survive and to reproduce their kind in preference to those that are less successful in developing deep roots. Moreover, as a rule, among the individuals that reach the water table those will reproduce most which are the most capable in utilizing the ground water. Hence, natural selection should produce a species which can exist drought but which nevertheless has great capacity to send strong roots to great depths rapidly and to pump ground water effectively up through these roots.

It was found by W. N. White,[63] in his work in Escalante Valley, Utah, that the small plants of greasewood which he dug up to transplant into soil tanks were all connected by roots or runners with larger and older greasewood plants. This would seem to be the most effective means of propagation by deep-rooting ground-water plants.

RELATION TO NORMAL PLANTS OF HUMID REGIONS

A number of species that are widely distributed through the humid regions also grow as ground-water plants in arid regions. These plants are chiefly forest trees, such as birch and sycamore. They are generally regarded as mesophytes rather than as hydrophytes. They are mesophytes in the sense that they can not tolerate much alkali and apparently have no special adaptations for resisting drought. In the arid regions they are found in the mountain canyons and large arroyos that have an underflow and in other places that have shallow ground water but fairly good drainage. They are commonly not associated with salt grass and greasewood on the

[63] Personal communication.

alkaline soils, nor with mesquite in areas of good soil where the water table is at considerable depth.

Even casual observation of the forests in humid regions will show that the trees of this type have an affinity for the water table in such regions as well as in arid regions. It is this affinity that enables trees such as birch and sycamore, which are recognized as especially water-loving genera in humid regions, to flourish in areas of ground water in arid regions; and it is the lack of this property in many other forest trees of smaller water requirement in the humid regions that accounts for their absence from such ground-water areas in arid regions. If it were not for the ability of the trees of the water-loving group to utilize water from the zone of saturation and the poor development of this ability in other trees it could reasonably be expected that the other trees would be the most successful and the water-loving trees the least successful in establishing themselves in the arid regions.

The distribution of the native vegetation throughout the eastern part of the United States is influenced by the water table to a much greater extent than is realized by most persons who have not given much attention to the occurrence of ground water. In some places in the woodlands near Washington, D. C., ferns have been observed adhering about as closely to tracts of shallow ground water as the well-recognized ground-water plants in the West, and many similar examples of the relation of plants of a particular species to the water table can readily be found almost anywhere in the East.

VALUE OF PLANTS AS INDICATORS OF GROUND-WATER CONDITIONS

OCCURRENCE OF GROUND WATER

The plants described in this paper are without question of great practical value as indicators of the occurrence of ground water in arid regions. They give evidence which supplements that furnished by the topography and geology and which is more specific as to the precise localities where the water occurs near the surface. They can not properly be ignored or relegated to casual consideration in any ground-water survey of a desert region. Many inhabitants of desert regions have a keen appreciation of the value of plants as indicators of ground water and an almost intuitive sense of the significance of particular native species. Doubtless some of this practical knowledge was possessed by primitive man long before the dawn of human history, and indeed as long ago as men first essayed to dwell in the deserts or to cross the vast expanses of these dread regions.

The value of a plant species as an indicator of ground water depends chiefly on the extent to which it is absent from areas where it can not feed on ground water. No species can be relied upon as an infallible indicator, for even the most consistent ground-water plants will grow in some areas where ground water is not available but under conditions that closely resemble those in the areas of shallow ground water. However, in the desert regions water supplies are so scarce that these simulating conditions can usually be detected without much difficulty. Much uncertainty may, however, exist as to the interpretation in particular localities of species that feed on ground water wherever they have an opportunity and yet have enough capacity to resist drought to succeed in maintaining themselves in relatively moist places far above the water table. For this reason more information is needed as to the distribution of the leading ground-water species and the extent to which they grow outside of the areas of shallow ground water. It is important to know how the different species rank in regard to the ground-water habit, and, so far as possible, to base forecasts concerning the occurrence of ground water on the most reliable species only. Obviously, however, this rule can not always be applied, for in some localities only species of doubtful significance are found.

In addition to their value as indicators of localities where water supplies may be developed by digging or drilling, the ground-water plants are of great value to travelers in the desert in directing them to existing watering places. How valuable they are in this respect can hardly be appreciated by anyone who has not traveled in such regions, and on the other hand, the habitual desert traveler uses the clues they afford without considering the service they render him. In an uninhabited region in which the distances between watering places may be 10, 20, or 50 miles it is sometimes difficult for a stranger to locate the precise spot where water occurs. It may be difficult even with detailed maps and directions such as are given in the desert guidebooks that have been published by the Geological Survey; it is likely to be still more difficult when only indefinite, hearsay directions are available. Roads and animal trails generally converge toward watering places, and signposts may be found that indicate the direction to water. At many watering places, however, the vegetation helps greatly in finding the water. The most valuable type of vegetation, of course, consists of trees, such as clumps of cottonwoods or of tall, stately palms, which may be visible from a great distance, but much help and comfort may also be afforded by so humble a ground-water indicator as salt grass, either by being visible at a distance as a green patch, or by giving at closer range definite assurance of the proximity of ground water and a virtual indication that the watering place is not far away.

DEPTH TO THE WATER TABLE

As has already been shown, the ground-water plants indicate not only the occurrence of ground water but also to some extent the depth to ground water; that is, the different species have different general limits of depths. Some species will grow where the water table is virtually at the surface but have maximum limits of depth to the water table beyond which they do not grow or at least do not grow luxuriantly, others have both minimum and maximum limits of luxuriant growth. With a few exceptions, the greatest depth from which ground water is known to be lifted by plants is about 50 feet.

The limits of depth for all species are somewhat indefinite, and the lower limits are more indefinite than the upper. The depth to which the roots of a given species will penetrate is affected by the texture of the soil. In general the maximum limit is deeper for loose, easily penetrated soil than for tight soil that is difficult to penetrate. Hardpan near the surface and impervious materials at the depth where the water table would normally occur, of course, disturb the relations greatly. For some species the minimum limit is less in coarse soil that has a thin capillary fringe than in soil of finer texture that has a thick fringe.

The clues that can be obtained from the different ground-water plants as to the approximate depth to water are of considerable practical value. For persons in distress they may be a matter of life or death. Thus a person without tools and in a weakened condition might be unable to dig down to the water that supplies a mesquite, although he would have a good chance of finding water where salt grass and palm trees are growing. Also, in estimating for a given area the acreage of irrigable land within certain feasible limits of lift, excellent use can be made of the clues furnished by the successive belts of ground-water plants.

In the investigations of Sulphur Spring Valley, Ariz., the Tularosa Basin, N. Mex., and Big Smoky Valley, Nev., the writer selected specific localities for intensive study bearing especially on the problem of irrigability with ground-water supplies. In these localities samples of soil were usually taken for determination of the alkali content, the depths to the water table were determined or estimated, the dominant species of native vegetation were observed, samples of water were usually taken for analysis, and various other observations were made. In the discussion of the principal ground-water plants on pages 16–64 much use has been made of the specific data obtained from these locality studies. Below are given most of the base data on the relation of the leading plants of this class to the water table.

Relation of ground-water plants to depth of water table below surface at specific localities

Sulphur Spring Valley, Ariz.

Locality	Depth to water table (feet)	Seepweed (*Dondia*)	Mexican salt grass (*Eragrostis obtusiflora*)	Alkali sacaton (*Sporobolus airoides*)	Chamiso (*Atriplex canescens*?)	Mesquite (*Prosopis glandulosa*)
1	4	×				
2	4	×				
3	4		×	×		
4	4			×		
5	5		×	×		
6	[a]5			×		
7	6		×	×		
8	[a]7	×	×	×		
9	7	×	×	×		
10	7		×	×		
11	7			×		
12	[a]8		×	×	×	
13	[a]10		×			
14	[a]10		×	×		
15	10		×	×		
16	10		×	×		
17	10			×		
18	10			×	×	
19	[a]10			×		×
20	11		×	×		
21	11		×	×	×	
22	[a]11		×	×		×
23	[a]11			×		
24	11			×		×
25	12		×			×
26	12			×		×
27	[a]13			×		×
28	13			×		×
29	14		×			
30	14		×	×		
31	[a]14			×		×
32	[a]15	×	×	×		
33	15		×	×		
34	[a]15			×		
35	[a]15			×		
36	16		×	×		
37	[a]17			×		×
38	17					×
39	18			×		×
40	[a]18			×		×
41	[a]18					×
42	19					×
43	20			×	×	×
44	22			×		×
45	22					×
46	[a]24		×	×		×
47	24			×		×
48	[a]25			×	×	×
49	[a]25					×
50	[a]27			×		×
51	27			×		×
52	29					×
53	[a]30					×
54	30					×
55	[a]30					×
56	31					×
57	32					×
58	[a]35			×		×
59	[a]35			×		×
60	[a]35			×		×
61	40					×
62	42					×
63	[a]45			×		
64	50					×
65	50					×

[a]Estimated.

54386—27——6

Relation of ground-water plants to depth of water table—Continued

Tularosa Basin, N. Mex.

Locality	Depth to water table (feet)	Barren	Pickleweed (*Allenrolfea occidentalis*)	Salt grass (*Distichlis spicata*)	Chamiso (*Atriplex canescens?*)	Mesquite
1	1		X			
2	[a] 2	X				
3	2	X				
4	[a] 2		X			
5	3	X				
6	3		X			
7	4		X	X		
8	6		X			
9	[a] 8		X		X	
10	[a] 10				X	
11	11		X			X
12	13				X	
13	[a] 15				X	
14	[a] 15				X	X
15	17					X
16	20		X		X	
17	20					X
18	22					X
19	[a] 23		X			
20	[a] 23				X	
21	[a] 25		X			
22	[a] 25		X		X	
23	[a] 25				X	
24	[a] 25				X	
25	[a] 25				X	X
26	[a] 25				X	X
27	28				X	
28	30				X	X
29	31				X	X
30	39				X	X
31	45				X	X
32	[a] 60				X	
33	62				X	X

Big Smoky Valley, Nev.

Locality	Depth to water table (feet)	Barren	Pickleweed (*Allenrolfea occidentalis*)	Salt grass (*Distichlis spicata*)	Rabbit brush (*Chrysothamnus graveolens*)	Big greasewood (*Sarcobatus vermiculatus*)	Willow (*Salix?*)	Salt bush (*Atriplex torreyi*)
1	0	X						
2	0	X						
3	2	X						
4	2		X	X				
5	2			X	X			
6	3			X				
7	3			X	X	X		
8	3			X	X	X		
9	4			X				
10	4			X				
11	6			X				
12	6			X			X	
13	6			X	X	X		
14	7			X				
15	7			X	X	X		
16	[a] 8					X		X
17	9			X	X			
18	9			X	X	X		X
19	10			X				
20	11					X		
21	11					X	X	
22	12			X	X	X		
23	12				X	X		
24	[a] 13					X		
25	[a] 13					X		
26	14			X	X	X		
27	[a] 14					X		
28	[a] 17					X		
29	[a] 23					X		
30	23					X		
31	[a] 25							X
32	[a] 33				X	X		
33	[a] 60					X		

[a] Estimated.

The propriety of making concise generalizations of depths to the water table indicated by the several species of ground-water plants may well be questioned in view of the inadequate data now available. However, in order to give a somewhat tangible basis for future work on this subject such generalizations are attempted in the following outline:

Rushes and sedges: Water at surface or water table within a few feet.

Giant reed grass (*Phragmites communis*): Water at surface or water table within a few feet, probably as much as 8 feet.

Giant wild rye (*Elymus condensatus*): From very near surface to 12 feet or more. In subhumid regions giant wild rye may grow without relation to the water table.

Salt grass (*Distichlis spicata*): From very near surface to a maximum of 12 feet, or rarely more.

Mexican salt grass (*Eragrostis obtusiflora*): From very near surface to about 15 feet.

Pickleweed (*Allenrolfea occidentalis*): Water table generally within a few feet, but this species may occur where the water table is as much as 20 feet or more below the surface.

Arrow weed (*Pluchea sericea*): Water at surface or water table at depths ranging to 10 feet or more, possibly as much as 25 feet.

Palm trees (*Washingtonia filamentosa*): Water table within a few feet.

Willow: From surface to 12 feet or more below surface (?).

Alkali sacaton (*Sporobolus airoides*): From less than 5 feet to 25 feet, and in some places much more. Most luxuriant growth where depth is between 5 and 15 feet. Alkali sacaton that occurs where depth is much more than 25 feet probably does not send roots to ground water.

Rabbit brush (*Chrysothamnus graveolens*): About 2 to 15 feet. More than about 8 feet for most luxuriant growth. This species also probably grows where it does not utilize ground water.

Big greasewood (*Sarcobatus vermiculatus*): From 3 feet or less probably to 40 feet or more. Abundant and luxuriant growth where water table is between 10 feet (or less) and 20 feet. Greasewood that occurs where depth is more than 40 or 50 feet probably does not send roots to ground water.

Mesquite (*Prosopis*): From less than 10 feet to 50 feet or more. Mesquite that grows where depth is much more than 50 feet probably does not send roots to ground water.

QUALITY OF GROUND WATER

That certain plants indicate the quality as well as the occurrence of ground water is widely believed by people in arid regions, and there is doubtless some basis for this belief. However, the indications of quality are not so definite as those of occurrence and should be regarded merely as general probabilities.

In general, the rushes, sedges, and reeds indicate fairly good water, but there are probably many exceptions to this rule. The Rye Patch, in Ralston Valley, Nev., in which giant reed grass and wild rye are prominent, is underlain to a depth of 50 feet with water of excellent quality, but in lower Big Smoky Valley the reed grass grows where the water is probably more mineralized. The succulent alkali-resistant plants, such as pickleweed and samphire, are likely to indicate highly mineralized water immediately under the water table, but the water a little deeper may be much better. Where salt grass or alkali sacaton is growing the water may be good or it may be very bad. Palm trees and greasewood also indicate water of doubtful quality, but potable water can generally be obtained in the vicinity of healthy palms. Mesquite generally though not invariably indicates good water. Shrubs and trees that normally grow in humid regions, such as roses, birch, and sycamore, commonly indicate good water.

The principal data available on the relation of ground-water plants to the mineral character of the ground water in three of the regions that were most carefully studied by the writer are given in the following tables. As a rule, the samples of water for which analytical data are given were obtained from dug or bored wells that extended only a few feet below the water table or from springs that discharge shallow ground water. Thus, the data represent the upper layer of ground water—that is, the ground water that occurs immediately below the water table, or at most not many feet below it. Obviously the water that occurs far enough below the water table to be beyond the reach of plant roots can not influence the character of the vegetation and should therefore be eliminated from such a study.

Total solids and certain mineral constituents of water from springs and shallow wells where specified ground-water plants are growing

Sulphur Spring Valley, Ariz.

[Analytical results in parts per million]

Designation	Depth of well (feet)	Depth to water level (feet)	Total solids	Sulphate radicle (SO_4)	Chloride radicle (Cl)	Black alkali as Na_2CO_3	Ground-water plants
1	(?)	49	186	7	10	0	Mesquite.
2	25	11	230	13	10	42	Mesquite, Mexican salt grass, alkali sacaton.
3	([a])	[b] 8	234	29	8	30	Alkali sacaton.
4	([a])	14	268	11	7	42	Mexican salt grass.
5	25	17	270	19	12	6	Mesquite.
6	33	31	284	8	29	0	Do.
7	([a])	22	294	8	21	17	Do.
8	([a])	13	298	16	10	110	Mesquite, alkali sacaton.
9	35	10	300	--------	10	127	Alkali sacaton.
10	(?)	24	304	21	7	42	Mesquite, alkali sacaton.
11	Spring.	--------	336	84	16	72	Mexican salt grass, alkali sacaton.
12	19	10	336	--------	7	199	Do.
13	23	20	340	33	20	21	Mesquite, alkali sacaton, saltbush.
14	40	35	372	60	36	8	Do.
15	15	7	410	34	47	38	Alkali sacaton.
16	20	11	424	29	41	203	Mexican salt grass, alkali sacaton.
17	([a])	22	526	53	63	136	Mesquite, alkali sacaton.
18	20	17	620	99	47	318	Mesquite.
19	[c] 47	6	708	99	48	356	Mexican salt grass, alkali sacaton.
20	([a])	6	1,268	98	80	670	Do.
21	([a])	7	1,912	279	53	1,153	Do.
22	40	31	2,008	184	784	0	Mesquite.
23	14	10	7,154	[d] 1,157	2,941	0	Alkali sacaton, saltbush.

[a] Shallow dug well.
[b] 10 feet where alkali sacaton was observed.
[c] Cased nearly to bottom.
[d] Permanent hardness as $CaSO_4$ is 881.

Total solids and certain mineral constituents of water from springs and shallow wells where specified ground-water plants are growing—Continued

Tularosa Basin, N. Mex.

Designation [e]	Depth of well (feet)	Depth to water level (feet)	Total solids	Sodium and potassium (Na+K)	Sulphate radicle (SO_4)	Chloride radicle (Cl)	Ground-water plants
1610	17	12	1,670	158	702	244	Mesquite, pickleweed.
1424	35	[f] 29	2,250	157	1,039	239	Mesquite, chamiso.
1106	85	62	2,407	567	699	700	Do.
1710	65	24	2,533	339	1,111	288	Mesquite, chamiso, pickleweed.
1626	60	39	4,241	495	1,250	1,072	Mesquite, chamiso.
S26	Spring.	4	4,576	453	2,100	576	Salt grass, pickleweed.
1304	([g])	17	4,856	442	2,370	616	Mesquite.
1407	40	28	4,870	526	2,590	523	Chamiso.
S17	Spring.	1	5,500	748	2,367	1,130	Pickleweed.
1721	62	31	11,640	1,482	3,786	2,841	Mesquite, chamiso.

[e] The designations are those used in Water-Supply Paper 343.
[f] Estimated 45 feet at short distance from well where vegetation was observed.
[g] Extends short distance below water table.

Big Smoky Valley, Nev.

Designation [h]	Depth of well (feet)	Depth to water level (feet)	Total solids	Sodium and potassium (Na+K)	Sulphate radicle (SO_4)	Chloride radicle (Cl)	Ground-water plants
S 11	Spring.	([i])	120	6	13	4	Barren playa with alkali crust
W 8	10	7	180		34	13	Salt grass.
W 10	12	6	224	33	31	34	Do.
W 14	14	4	313	31	69	18	Salt grass, tules, roses, Lombardy poplars, and boxelders.
W 6	15	9	329	6	48	11	Salt grass, rabbit brush.
W 18	50	[j] 37	363	55	50	21	Rabbit brush, greasewood.
W 17	63	[j] 38	490	114	93	74	Do.
W 2	22	17	494	70	Trace.	68	Salt grass.
W 1	15	12	764	98	90	171	Salt grass, rabbit brush, greasewood.
W 20	3	3	2,405	765	781	501	Do.
W 4	5	2	369,985	143,616	18,624	168,812	Barren playa.
S 8	Spring.		137		16	4	Salt grass, rabbit brush, greasewood, roses, buffaloberry bushes.
S 15	Spring.	5	267	38	53	21	Salt grass, rabbit brush, greasewood *Atriplex torreyi*.
S 7	Spring.		353	7	62	19	Greasewood.[k]
W 9	16	12	439	70	58	34	Rabbit brush, greasewood.
W 22	12	10	569	134	79	66	Salt grass.
W 19	6	4	869	190	169	69	Salt grass, alkali sacaton.
W 21	4	2	4,038	1,218	917	1,361	Pickleweed, salt grass.

Ralston Valley, Nev.

W 30	50±	5	273		38	16	Giant reed grass, giant wild rye, salt grass, rabbit brush, greasewood.

Clayton Valley, Nev.

W 26	28	23	3,611	997	227	1,665	Greasewood, seepweed.

[h] The designations are those used in Water-Supply Paper 423.
[i] Water table very near surface.
[j] Estimated 33 feet at short distance from well where vegetation was observed.
[k] Observed ⅛ mile west of spring.

Range of total solids, chloride radicle, and black alkali in ground water at points where specified ground-water plants are growing

Sulphur Spring Valley, Ariz.

Plant	Number of analyses	Substances dissolved in ground water, in parts per million		
		Total solids	Chloride radicle (Cl)	Black alkali as Na_2CO_3
Mexican salt grass	8	230–1,912	7–80	42–1,153
Alkali sacaton	16	230–7,154	7–2,941	0–1,153
Mesquite	12	186–2,008	7–784	0–318
Chamiso (*Atriplex canescens*?)	2	340–7,154	20–2,941	0–21

Tularosa Basin, N. Mex.

Plant	Number of analyses	Total solids	Chloride radicle (Cl)	Black alkali as Na_2CO_3
Pickleweed	4	1,670–5,500	244–1,130	------------
Mesquite	7	1,670–[a]4,856	239–[a]616	------------
Chamiso (*Atriplex canescens*?)	6	2,250–11,640	239–2,841	------------

Big Smoky Valley, Nev.

Plant	Number of analyses	Total solids	Chloride radicle (Cl)	Black alkali as Na_2CO_3
Pickleweed	1	4,038	1,361	------------
Salt grass	13	137–4,038	4–1,361	------------
Rabbit brush	9	137–2,405	4–501	------------
Greasewood	10	137–2,405	4–501	------------

[a] Exclusive of sample from well 1721, which came from a considerable depth below the water table.

The data in the foregoing tables show that all the species listed, with the possible exception of pickleweed (*Allenrolfea occidentalis*), may grow where the upper layer of ground water contains only small amounts of mineral matter and is of good quality. Thus, of 13 samples of ground water obtained in Big Smoky and Ralston Valleys at points where salt grass was growing, 11 contained less than 1,000 parts per million of total solids, 8 contained less than 500 parts, and 5 contained less than 300 parts, the minimum being only 137 parts. Of these same 13 samples more than half contained less than 35 parts per million of chloride, the minimum being only 4 parts. Likewise, of 8 samples in Sulphur Spring Valley at points where Mexican salt grass was growing, 5 contained less that 500 parts of total solids and 6 contained less than 50 parts of chloride. Greasewood and rabbit brush, in Big Smoky Valley, and alkali sacaton and mesquite, in Sulphur Spring Valley, have equally good records. For example, out of 10 samples of water taken where greasewood was growing, 7 contained less than 500 parts of total solids and 6 contained less than 35 parts of chloride. The record for pickleweed is not so good, though the number of samples is too small to be conclusive, especially as all except one came from Tularosa Basin, where most waters are highly mineralized. The best of these waters contains 1,670 parts of total solids and 244 parts of chloride—a poor water, but one that can be used for drinking if necessary.

On the other hand, the data show that all these species may be found growing where the ground water is highly mineralized, even mesquite not being an exception. This is not surprising in view of the usual high concentration of soil moisture in comparison to that of ground water. The alkali in the soil where the species under consideration are growing is shown in the following table. To make clear the significance of the data in this table it should be stated that if a soil with a specific gravity of 1.6, a porosity of 40 per cent, and an alkali content of 1 per cent is saturated and all of the alkali passes into solution, the soil moisture will contain about 40,000 parts per million of total dissolved solids, which is about five times the concentration that cattle can endure and about ten times the concentration that human beings can endure. If the alkali is not all in solution the concentration may be less, whereas if the soil is not saturated the concentration may be even greater. It is evident from the table that the plants under consideration must be able to tolerate water with much larger amounts of mineral matter than man or other animals can tolerate, for instead of using the ground water in its unmodified condition they must to a large extent use the soil moisture, which is essentially a concentration product of the underlying water. Even though the ground-water plants may to some extent avoid the soil alkali by getting their feeding roots close to the water table they can not wholly avoid it, especially at times when a part of the alkali is washed down to the water table. For this reason it is perhaps futile to expect that any definite relations can be found between the occurrence of ground-water plants and the quality of the ground water or that any species of such plants that can grow in even moderately alkaline soil will invariably indicate potable water.

Alkali in soils analyzed in which specified ground-water plants are growing

[In percentage of total dry soil by weight. Depth to which the soil was sampled ranged from 1 to 6 feet and was generally 4, 5, or 6 feet]

	Number of analyses	Total soluble solids			Sodium chloride (NaCl)			Black alkali (Na_2CO_3)		
		Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
Pickleweed:										
Tularosa Basin	10	1.75	4.20	--	0.40	1.55	--	--	--	--
Seepweed:										
Sulphur Spring Valley	2	.86	1.27	1.06	--	--	--	0.14	0.34	0.24
Salt grass:										
Big Smoky Valley	4	.79	1.32	1.06	--	--	--	--	--	--
Mexican salt grass:										
Sulphur Spring Valley	8	.33	1.24	.79	--	--	--	.01	.58	.28
Alkali sacaton:										
Sulphur Spring Valley	17	.21	1.93	.82	--	--	--	0	.48	.19
Greasewood:										
Big Smoky Valley	11	.81	2.19	1.39	--	--	--	--	--	--
Chamiso:										
Tularosa Basin	19	1.20	2.80	--	Trace.	.90	--	--	--	--
Mesquite:										
Sulphur Spring Valley	11	.14	1.93	.62	--	--	--	0	.48	.11
Tularosa Basin	12	1.10	2.25	--	Trace.	.60	--	--	--	--

QUANTITY OF GROUND WATER

Relation of transpiration of ground-water plants to water-supply projects.—In many of the arid valleys of the West projects for pumping large quantities of water from wells for irrigation or public supplies have been carried out or are under consideration. For these projects it is necessary to know as nearly as possible how much ground water can be recovered year after year without seriously depleting the supply stored in the underground reservoirs. As a rule the pumpage should not exceed the natural discharge, but should merely salvage the ground water that would otherwise be disposed of by natural processes. In these valleys the ground water is naturally discharged largely by transpiration from the vegetation, and hence information as to the amount of transpiration bears directly on the very important practical question of the supplies available for economic uses such as those of irrigation and city water works.

Analysis of the problem of quantity of water transpired.—To estimate the quantity of ground water that is annually discharged by the plants of a given valley it is necessary to determine the areas occupied by these plants and the rate at which they discharge water by transpiration. The rate of transpiration is generally expressed in inches or feet of depth of a layer of water covering the entire area and is comparable to the rainfall and the evaporation from a free water surface as usually expressed. If the area occupied by a certain association of ground-water plants is expressed in acres and the rate of transpiration from them in feet a year, the product of these two quantities represents the total annual discharge by transpiration from this association in acre-feet.

The area factor.—The areas occupied in a given valley by the different associations of ground-water plants can readily be determined by a survey of the valley. The information thus obtained, even without any definite data as to the rate of transpiration, is of great practical value in estimating the probable safe yield of the valley and in determining the magnitude of pumping projects to be undertaken. For example, in Steptoe Valley, Nev., in which exploratory drilling was done several years ago by the United States Geological Survey,[64] it was found that ground water is being discharged, through evaporation from soil or through the growth of native plants such as salt grass, rabbit brush, and greasewood, over an area of about 115,000 acres. (See fig. 10.) In most places the plants mentioned have a good stand and a luxuriant growth, indicating that they enjoy an ample water supply. The discharge per acre is probably much less than the quantity of water required

[64] Clark, W. O., and Riddell, C. W., op. cit. (Water-Supply Paper 467), p. 13.

per acre to irrigate useful crops, such as alfalfa, grain, or vegetables, and, moreover, not all of this water can be salvaged by pumping from wells. Nevertheless, the great extent of the area of discharge and the luxuriant character of its vegetation give reliable evidence that a substantial supply of ground water is available.

The value of information of this kind for furnishing reliable clues as to the presence or absence of a substantial supply of ground water in a given valley was impressed upon the writer in 1917, when he made a reconnaissance of Steptoe Valley and several other relatively well-watered valleys of east-central Nevada and then proceeded immediately to southeastern California for a reconnaissance of a number of most arid valleys of the Mohave Desert and Salton Sea regions. The difference was truly impressive. In the Nevada valleys he rode for miles through areas of discharge with moist soil and luxuriant ground-water plants; in the desert valleys of California, on the other hand, he found either no areas of ground-water discharge or else surprisingly small areas covered with a meager ground-water vegetation that showed the stress of unfavorable conditions.

The rate factor.—Although a survey of the areas of discharge of a certain valley gives information on which rough estimates of its ground-water supply can be based, much more accurate estimates can be made if data are also obtained on the rate of discharge. Until recently very little work was done on the rate of discharge by ground-water plants. A large amount of work has, indeed, been done by botanists on transpiration and by students of agriculture on the water requirements of useful plants, but the great volume of data that has accumulated from these investigations is not directly applicable to the hydrologist's problem of ground-water discharge. However, good use can doubtless be made of some of the methods of investigation already developed for these other purposes and, moreover, much of the large mass of data that has been obtained can be interpreted and applied to the ground-water plants.

In 1910 and 1911 a very valuable investigation was made by Charles H. Lee [65] of the rate of discharge from land covered with salt grass in Owens Valley, Calif. The salt grass was grown in a series of tanks filled with soil in which the water table was held at different depths below the surface. The records showed the total discharge of ground water, including both transpiration from the salt grass and evaporation from the soil to which the water rose by capillarity. Because of the lack of other data the results obtained in this investigation have been used in making estimates of ground-water supplies in other areas, in some of which the conditions are

[65] Lee, C. H., op. cit.

very different from those in Owens Valley. In the survey of the Mud Lake Basin, Idaho, tules were grown in a tank, and data were obtained on the aggregate discharge by evaporation and transpiration from this tank. In the same locality a record was obtained of the evaporation from a free water surface. For several years the discharge of ground water by mesquite and cottonwood trees and by sacaton and Mexican salt grass in San Pedro Valley, Ariz., has been studied by G. E. P. Smith, who has obtained, with water-stage recorders installed over dug wells, records of the daily fluctuation of the water table where these plants are feeding on ground water. Much work of the same kind has recently been done with good results in Escalante Valley, Utah, by W. N. White, of the United States Geological Survey, chiefly on alfalfa, salt grass, and greasewood.

The rate at which ground water is discharged by plants may reasonably be expected to vary with the plant species, the depth to the water table, the texture and alkali content of the soil, and the weather conditions. Each of these factors is somewhat complex, especially the last two. As it is hardly practicable to make tests for each of the great variety of conditions found in nature, it will be desirable to determine, so far as possible, what are the laws of transpiration by ground-water plants under the varying conditions.

Relation of rate of transpiration to kind of plant.—As a rule the plants that grow in water and the ground-water plants that are most closely related to them probably discharge water freely. In the tank experiments at Mud Lake the aggregate discharge by transpiration from the tules and by evaporation from the water in which they were grown was much greater than the evaporation from a free water surface during the season of active growth. From June 13 to September 23, 1921, the loss was 34.2 inches from a free water surface in a tank on the land and 51.4 inches from a tank in which tules were grown in a submerged soil.[66]

The alkali-resistant ground-water plants are generally assumed to be economical in their use of water, but definite information is lacking as to the rate of ground-water discharge of the different species. The succulent alkali-resistant plants, such as pickleweed and samphire, probably do not discharge ground water rapidly, but in most arid regions they do not cover extensive areas and are not of leading importance in quantitative studies. Greasewood, however, covers very large areas, and its rate of transpiration is of major importance in quantitative studies. The rate of discharge by this species is now under investigation by W. N. White. The results already obtained

[66] Stearns, H. T., and Bryan, L. L., Preliminary report on the geology and water resources of the Mud Lake Basin, Idaho: U. S. Geol. Survey Water-Supply Paper 560, pp. 97–102, 1925.

by him seem to indicate that greasewood is economical in its use of ground water, but in the aggregate discharges great quantities of ground water.

Salt grass is also of major importance in quantitative studies because of its very extensive occurrence in the areas of shallow ground water. The experiments by Lee in Owens Valley, Calif., and by White in Escalante Valley, Utah, indicate that salt grass discharges ground water freely, and the growth it makes under favorable conditions also indicates free transpiration. Alkali sacaton likewise makes a good growth and probably discharges considerable water.

Mesquite is another ground-water plant of great importance in quantitative studies, for it doubtless disposes of vast quantities of ground water in the areas in which it flourishes. Its large and luxuriant growth in tracts having favorable conditions of ground water and soil indicates that it has a high transpiration, and this indication is corroborated by the recent investigation by G. E. P. Smith. As mesquite can also effectively resist drought when necessary, it is believed to have an unusual capacity to adapt itself to varying conditions. Apparently it uses water lavishly when opportunity affords or sparingly when the supply is restricted.

The investigations by White indicate that alfalfa, when growing as a ground-water plant, uses water in large quantities.

Relation of rate to depth of water table.—A controlling factor in the water supply of ground-water plants is the depth to the water table. In this respect there is an analogy between the living plant that pumps up ground water for its use and the mechanical pumping apparatus that lifts ground water for the use of vegetation that is to be irrigated. In both cases the limiting condition is the lift required, the limitation in the first case being physical or biologic and in the second economic—that is, the cost of pumping. The individual plant or the individual pump draws upon a vast reservoir of water that is but little affected by its operation. In both cases, however, the aggregate withdrawal by all the plants or pumps will lower the water table and thereby regulate the rate of withdrawal.

As has been shown, for each ground-water species there is an approximate limit of depth from which it can lift ground water. As in every area the depth to the water table changes gradually from place to place, there is a zonal arrangement of the different species of ground-water plants according to their different depth limits. Within these limits the rate at which the plants can draw up ground water varies inversely with the depth to the water table beyond a certain optimum depth. Evidence of this relation between rate of discharge and depth to the water table is furnished especially by salt grass, mesquite, and alfalfa.

Lee found that in the salt-grass areas of Owens Valley the aggregate soil and vegetal discharge of ground water decreased in proportion as the depth to the water table increased, to a depth of about 8 feet, where the discharge became negligible. Application of this law to the figures obtained with the water table at several different depths gave a maximum discharge, with the water table virtually at the surface, of 48 inches from April 1 to September 30 and 11 inches from October 1 to March 31. This computed maximum discharge was about equal to the evaporation from a free water surface during the summer, but only a little more than one-half the evaporation from a free water surface during the winter, when there was little or no transpiration. This fact and the results from one tank without vegetation suggest that during the summmer about half of the loss may have been occasioned by transpiration of the salt grass.

The maximum discharge by mesquite occurs where the water table is some distance below the surface. This optimum depth varies with the character of the soil but is generally 10 feet or more. From the optimum depth, where the mesquite may have a heavy growth, it generally becomes more stunted and scattered as the depth increases, until at the limiting depth there is likely to be only a meager growth of small bushes. The range in size is doubtless due to a difference in the rate at which the mesquite can draw up water and serves as a rough measure of the relative rate of ground-water discharge.

Alfalfa will lift ground water from considerable depths and may produce crops of seed and some hay where it depends on a ground-water supply, but it will not make the growth on ground water that it would if it were well irrigated, doubtless because of its incapacity to lift water from the water table as rapidly as it could absorb water from a moist soil at the surface. Like mesquite, it has an optimum depth of water table. If the water table is nearer the surface than the optimum depth the alfalfa suffers for want of aeration; if it is farther below the surface the alfalfa is more severely handicapped by inadequate water supply. However, even at the optimum depth the growth is not as rapid as under ample irrigation, presumably because of the limitation in the available water supply.

The inverse relation between discharge of ground water and depth to ground water is doubtless applicable to most ground-water plants, but it is probably not generally a simple, inverse proportion such as was found for salt grass in Owens Valley.

Relation of rate to evaporativity.—In a cogent discussion of the rate of transpiration, G. E. P. Smith[67] showed that researches by

[67] Am. Soc. Civil Eng. Trans., vol. 78, pp. 226–230, 1915.

F. Shreve, B. E. Livingston, and Edith B. Shreve, of the Desert Botanical Laboratory,[68] and by G. F. Freeman, of the Arizona Agricultural Experiment Station, indicate that under similar conditions of soil moisture the ratio of transpiration to evaporation from a free water surface tends to be a constant. This principle of a constant ratio, or of equal "relative transpiration," leads to two important conclusions. To the extent that it is correct it eliminates from many discussions complex climatic factors such as light, air pressure, temperature, and humidity and bases estimates of transpiration on the more easily measured evaporativity, or evaporation from a free water surface. Moreover, it leads to the conclusion, as stated by Shreve, that "it is the desert plants in which the rate of transpiration is high and the rain-forest plants in which it is low, which is quite the reverse of the commonly accepted view." A well-known experiment in Austria indicated that in the growing season of six months a beechwood forest transpires the equivalent of a layer of water 22 inches deep. Applying the principle of equal relative transpiration to this experiment, Smith showed that to obtain the rate of transpiration in arid regions, where the evaporativity is about two and one-half times as great, this figure must be multiplied by about 2½, giving about 55 inches. He further expressed the opinion that 55 inches depth of water a year probably represents fairly well the loss by transpiration from the cottonwood trees and that the loss from the mesquite forest, on account of the smaller leaf expanse, is perhaps half as great as that from the cottonwood. He called attention to the power of desert plants to reduce transpiration when necessary, but concluded that there is no evidence that this power is exercised by trees growing on the bottom lands, where the roots are bountifully supplied from below the water table. Later experiments by Smith, already cited (p. 84), support his belief that the transpiration of desert plants that feed on ground water is relatively high.

Relation of rate to quantity of dry matter.—The water requirements of many crop plants and of some grasses and weeds have been determined, in various experiments, as the ratio of the weight of water absorbed by the plant during its growth to the weight of the dry matter produced, generally exclusive of the roots. In a large series of experiments made at Akron, Colo., by Briggs and Shantz,[69] rather wide differences were found in this ratio for different kinds of plants. Under the conditions of the experiments the average ratio for several varieties of alfalfa was found to be 831, which means that

[68] Shreve, F., The transpiration behavior of rain-forest plants: Carnegie Inst. Washington Yearbook 12, pp. 74–76, 1913.

[69] Briggs, L. J., and Shantz, H. L., Relative water requirements of plants: Jour. Agr. Research, vol. 3, pp. 1–65, 1914.

an average of 831 tons, or 0.637 acre-foot, of water was absorbed by the alfalfa plants for each ton of dry alfalfa hay that was produced.

If this method could be applied to ground-water plants it would furnish a convenient means of estimating their discharge of ground water. Whether it could be successfully used with woody perennials such as grease-wood and mesquite, however, is uncertain. In the areas of deep-rooting ground-water plants, where the water table is at considerable depth, all the ground-water discharge could be determined by this method, but in the areas of very shallow ground water the method would be inadequate in that it would fail to take account of the evaporation from the soil. On the other hand, deductions from the vegetal discharge would have to be made in some localities for soil moisture furnished by rain, snow, and flood water. This subject is under investigation by W. N. White in the Escalante Desert, Utah.

DEVELOPMENT OF GROUND-WATER PLANTS OF ECONOMIC VALUE

THE PROBLEM

The extensive investigations of the United States Geological Survey have shown that very large supplies of ground water occur in practically all the western States. In California about 1,000,000 acres is irrigated with ground water pumped from wells, but in the other arid States comparatively little irrigation has hitherto been accomplished with water from wells, because of the prohibitive cost of pumping, and most of the annual supply of ground water goes to waste or supports plants of very low value. The investigations in Big Smoky and Steptoe Valleys, Nev., indicate that not far from 10 per cent of the drainage basins of these valleys contain plants that feed on ground water. If these basins have anywhere near average conditions it follows that there are a few million acres of ground-water plants in Nevada alone. A part of this land is alkaline, but much of it has good soil.

Pumping water for irrigation is expensive, even where the lift is not great. The ground-water plants, however, lift the water without cost, and if plants of this kind that are of economic value can be developed, the means will be at hand for utilizing vast quantities of water that now virtually go to waste and of making hundreds of thousands of acres of desert land productive. There are two possible methods of achieving the desired result—(1) by developing more valuable varieties of certain established ground-water plants that already have some economic value, and (2) by developing ground-water varieties of certain valuable plants that already have some ground-water tendencies. With the first method it might, for example, be feasible to select and develop the best of the native grasses that feed on ground water; with the second it seems reasonable to expect that a variety of alfalfa can be developed that will lift ground water at a more rapid rate and from a greater depth than the varieties of alfalfa that are raised on irrigated land. Bermuda grass and pecan trees are also examples of promising ground-water plants of economic value. The following account of the successful use of ground water by alfalfa without pumping in the Escalante Valley, Utah, was kindly prepared for this paper by Walter N. White, of the United States Geological Survey. It is very suggestive of what may eventually be accomplished.

ALFALFA AS A GROUND-WATER PLANT

By Walter N. White

The fact that ground water is capable of maintaining deep-rooted plants in areas of deficient rainfall is illustrated by agricultural operations in Escalante Valley, near Milford, Utah. There the production of alfalfa seed with moisture derived from ground water has apparently passed the experimental stage and reached one where a reasonable degree of financial success is assured. The industry has been developed as the result of the experience of one rancher, and the story is rather romantic. The rancher was very poor, having lost practically all he had in a vain attempt at dry farming on a ranch about 5 miles south of Milford. A few head of mortgaged cattle remained, and in the spring of 1919 he was pasturing this stock on lands near his homestead, all of which had been abandoned and most of which had previously been settled by dry farmers. One of the tracts, the S. ½ sec. 31, T. 28 S., R. 10 W., owned by the Beaver County Irrigation Co., had been irrigated and planted to alfalfa during the season of 1917 and then abandoned as a result of loss by the company of its water right in Beaver River by an adverse court decision promulgated in the winter of 1917–18. The rancher noticed to his surprise that a scattering growth of alfalfa among the greasewood and weeds, with which this half section was now covered, was increasing in thickness and vigor, although not a drop of water had been applied to the land in nearly two years. He decided that the alfalfa would provide considerable pasturage for his stock, and accordingly in the spring of 1919 he leased the tract from the company for two years, the consideration being that he was to keep the fence in repair. During the summer of 1919 he partly removed the greasewood and weeds from the land and grazed it sparingly, and in the fall he cut the alfalfa and obtained a crop of seed which sold for $3,000. In the following year the seed crop brought about $5,000. All this was accomplished with comparatively little cash outlay or labor, and in the brief period of two years the rancher rose from poverty to a state of comparative prosperity. This experience created considerable excitement, and the reputation of sec. 31 was established throughout southwestern Utah, thereby creating a considerable boom for the Milford district. The prospect of obtaining a highly profitable crop without artificial irrigation or at least without irrigation after the crop was started was an attractive one. It was clear to all that the alfalfa in sec. 31 owed its life to the fact that the roots penetrated to the water table. However, it was also clear that if agricultural operations of this kind were to be extended, the alfalfa must be irrigated during the period while it was getting its start and its roots were penetrating to ground water. No surface water was available, and accordingly pumping from wells was resorted to.

During 1919 and 1920 six pumping plants were installed in the locality, and there has been a slow but steady pumping-plant development ever since. In 1923 there were 20 pumping plants in operation and about 900 acres in alfalfa which had been started by irrigation from these plants. In that year about 600 acres was irrigated from these plants, but the remaining 300 acres was not irrigated because the alfalfa had reached ground water and was able to subsist without artificial irrigation. This subirrigated acreage does not include the 240 acres of alfalfa seed land in sec. 31, in which the alfalfa got its start from one season of surface irrigation in 1917.

The reported yields of alfalfa seed from the S. ½ sec. 31 in the period 1920 to 1923 are: 272 bushels from 240 acres in 1920, 600 bushels from 240 acres in 1921, 701 bushels from 160 acres in 1922, and 700 bushels (estimated) from 160 acres in 1923. Comparable yields were reported from other nonirrigated alfalfa-seed lands in the vicinity.

In 1923 the lands devoted to this industry were located within an area about 3 miles long and 1 mile wide, the center of which is about 4 miles south of Milford, near the township corner common to Tps. 28 and 29 S., Rs. 10 and 11 W. The area lies on the lowermost slopes of the Beaver River delta, slightly to the east of the trough of Escalante Valley and 10 to 15 feet above the lowest lands in the valley. It ranges from 4,970 to 5,010 feet above sea level and slopes to the northwest with gradients ranging from 10 to 15 feet to the mile. Measurements of about 15 fairly evenly spaced wells in this area in the fall of 1923 showed depths to water ranging from 9 to 15 feet. The water table rises 1½ to 2½ feet in the late winter and early spring. On lands where natural subirrigation has proved feasible the soil and subsoil down to the water table is a dark-gray clay loam or sandy loam and a black loam derived largely from decomposed peat. Attempts to extend the cultivation of subirrigated alfalfa to adjoining areas where the subsoil is gravelly have not proved successful, although the depths to ground water in these areas are no greater than in the area where success has been attained.

Sagebrush forms the dominant vegetation, but unused lands cleared of sagebrush several years ago now carry a fairly vigorous growth of greasewood. A series of tests with the electrolytic bridge in the area shows that the soil does not contain excessive amounts of alkali, though the alkali content is near the danger line for young alfalfa, the average for 10 tests of soil to a depth of 5 feet being 0.39 per cent.

Figure 15 shows the root system of an alfalfa plant in a field near Milford that is naturally subirrigated. The soil penetrated by this root system to a depth of 8½ feet is gray clay loam and black peaty loam. Below this depth it consists of coarse sand and gravel. During a part of the growing season a considerable portion of the root system is below the water table. In the spring and early part of the summer, when the water table is at depths less than 8½ feet, the growth of alfalfa plants in the immediate vicinity of the excavation is rapid and vigorous. Later in the season, however, the water table drops into the gravel, and then the plants assume a withered appearance and do not make much more growth.

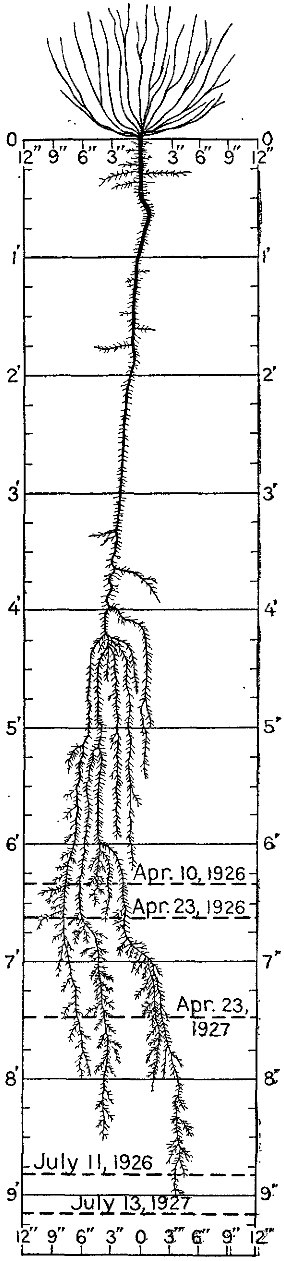

FIGURE 15.—Diagram of the root system of an alfalfa plant on the farm of W. H. Hendrickson, in the NE. ¼ sec. 36, T. 28 S., R. 11 W., Escalante Valley, Utah. The alfalfa was planted in 1922 and was irrigated the first season only. The capillary fringe is 3½ feet or a little more in thickness. The root system was excavated and the drawing made by O. E. Meinzer and W. N. White, July 13, 1927. Dates indicate levels of water table

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