Use of Water by Bottom-Land Vegetation in Lower Safford Valley Arizona

By J. S. GATEWOOD, T. W. ROBINSON, B. R. COLBY, J. D. HEM, *and* L. C. HALPENNY

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FOREWORD

By C. G. Paulsen [1]

The Safford Valley investigation was made in 1943-44 by the Geological Survey in an effort to determine how much water could be made available for an essential war industry by removing the saltcedar growth from the bottom lands of Gila River in Safford Valley, Ariz. However, before the investigation was completed, the water needed for the industry was obtained from another source, and so the investigation was not carried as far as was desired or to a conclusion that was satisfactory in all respects. The water and vegetal conditions under which the investigation was made, the observational data, the methods of analysis of these data, and the results obtained are presented in this report.

The investigation was an attempt to measure quantitatively the amount of water consumed, and therefore wasted, by vegetation of little or no known value that grows on the bottom lands of the valley. Saltcedar, which grows luxuriantly in the lowlands of Safford Valley, is a great consumer of water and has no present value for any purpose. Its removal would, in theory at least, save and make available for beneficial use the water consumed by it. Problems involved in its removal, and recovery of water that might be "saved" thereby, were outside the scope of this investigation, which related primarily to the quantity of water that was consumed in nonbeneficial use.

The methods used in the investigation, the analysis of the data collected, and the results obtained by the analysis are believed to be of general interest and value because of the need of conserving for more beneficial use the water consumed by vegetation that has little value in many arid and semiarid regions. In such regions the water thus consumed constitutes a definite economic loss which may presumably be avoided. This report indicates that in the 46-mile reach of Gila River in Safford Valley from Thatcher to Calva about 28,000 acre-feet of water is consumed annually by worthless vegetation in the bottom lands. If a substantial part of the water thus lost could be conserved and used for valuable crops, a distinct economic gain would be achieved.

This investigation, so far as is known, was the first attempt actually to measure the water consumed by a particular class of vegetation

[1] Chief hydraulic engineer of the Geological Survey, U. S. Department of the Interior.

under natural conditions on a scale large enough to be of economic significance. As a consequence, field methods of investigation of a somewhat complex character had to be used. Although laboratory studies were made in certain phases of the investigation, laboratory accuracy cannot be claimed for the over-all results. However, the general agreement obtained by the six largely independent methods utilized indicates that reasonable accuracy was probably achieved. Whatever the degree of accuracy obtained in this comprehensive undertaking, it is hoped that this recording of conditions, methods, and results of the investigation will be of value to those who may have need for the results or may conduct similar investigations in this or other river basins.

USE OF WATER BY BOTTOM-LAND VEGETATION IN LOWER SAFFORD VALLEY, ARIZONA

By J. S. Gatewood, T. W. Robinson, B. R. Colby, J. D. Hem, and L. C. Halpenny

ABSTRACT

Lower Safford Valley, Graham County, Ariz., is an alluvial lowland plain 1 to 3 miles wide along Gila River. The valley is underlain to an average depth of about 100 feet by silt and waterbearing sand and gravel deposited by the river. The plain is occupied by farmed lands, which are irrigated from wells and from the river, and by a belt of natural vegetation in the bottom land along the river. Most of the natural vegetation consists of phreatophytes, plants that send their roots to the capillary fringe or to the water table. The principal phreatophytes in lower Safford Valley are saltcedar, baccharis, cottonwood, and mesquite, all of which are nonbeneficial users of large quantities of ground water. In order to supply the basic data from which an estimate could be made of the quantity of water that might be saved if such bottom-land vegetation were destroyed, an investigation of the annual use of water by the vegetation was made in 1943 and 1944.

Six methods of determining use of water were applied during the investigation: Tank method, transpiration-well method, seepage-run method, inflow-outflow method, chloride-increase method, and slope-seepage method. The tank method was based on the measurement of the quantity of water used by native vegetation growing in tanks in which a water table was maintained, so that hydrologic conditions in the tanks resembled those in the field as nearly as possible. The transpiration-well method was based on the measurement of the diurnal water-table fluctuations caused by transpiration by phreatophytes; the daily rate of use of ground water, as shown by observation wells in the bottom-land area, was determined by multiplying the amount of daily decline of the water table by the coefficient of drainage (specific yield). The seepage-run method was based on sets of discharge measurements made at about monthly intervals along Gila River to determine the seepage inflow to the river; use of water by vegetation along the river was computed as the difference in the seepage inflow between the growing and nongrowing seasons. The inflow-outflow method was based on a water inventory for which, in a given area in a given time, the quantities of water entering and leaving and the changes in stored water were determined by measurements in the field; the use of water by vegetation, which could not be determined for this method by field measurements, was computed as the difference remaining after all other factors had been measured or accounted for. The chloride-increase method was based on the determination of the increase in the concentration of chloride in the ground water as it moved from the outer edge of the vegetation-covered bottom-land area to the river, and computation of the use of water by the vegetation was based on the fact that the quantity of water withdrawn by transpiration was proportional to this increase in chloride content. The slope-seepage method was based on the fact that the rate of use of water by vegetation in a reach of the bottom-land area represented the difference between the rates of ground-water inflow to the bottom-land area and to the river; the rate of ground-water inflow to the river was determined from the sets of seepage

measurements, and the rate of ground-water inflow to the bottom-land area was determined on the basis of the hydraulic gradient of the water table at the time of each set of seepage measurements, the transmissibility of the aquifer, and the length of the reach. Although the methods differed greatly, the figure for use of ground water computed by each method was within 20 percent of the mean determined by averaging the results of all six methods.

As a part of the investigation, the quality of the waters of lower Safford Valley was studied in detail. The quality-of-water studies included more than 5,000 analyses of surface and ground waters. These analyses showed that surface waters of the area contain 250 to about 6,000 parts per million of dissolved solids and that ground waters contain 200 to more than 10,000 parts per million. The waters of low dissolved-solids concentration contain mostly sodium or calcium and bicarbonate. Highly mineralized waters contain mostly sodium and chloride.

Based on the results obtained by the six methods, the total use of water by vegetation during the 12-month period ending September 30, 1944, was 28,000 acre-feet in a total of 9,303 acres in the 46-mile reach of Gila River from Thatcher to Calva. As precipitation and runoff were subnormal in most of the period of the investigation, it is possible that the total use of water in other years may exceed 28,000 acre-feet. Of the total water used, 23,000 acre-feet was derived from the ground-water reservoir, and the remainder was derived from precipitation on the area. Of the 23,000 acre-feet, more than 75 percent was used by saltcedar.

PART 1. GENERAL DESCRIPTION

INTRODUCTION

The primary objective of this investigation was to determine the use of water by natural bottom-land vegetation in the lower part of Safford Valley, Ariz. All the surface water in Gila River Basin above Coolidge Dam has been appropriated, and additional demands for water in the basin must be supplied without disturbing existing water rights. Consideration of the matter was begun late in 1942 as a result of a demand for more water to expand wartime copper production at the Morenci, Ariz., mines of the Phelps Dodge Corp. Because no water was available for appropriation, a plan was proposed whereby the additional water needed was to be taken from tributaries of Gila River. To replace this water, most of the nonbeneficial use of water by bottom-land vegetation along Gila River in lower Safford Valley was to be stopped by removing the vegetation. In 1941 a study of the water resources of Safford Valley,[2] made by the Geological Survey, had shown that large quantities of water were consumed by natural vegetation growing along the Gila River.

In March 1943 the Assistant Secretary of Commerce, Hon. W. L. Clayton, acting in behalf of Defense Plant Corp. and Phelps Dodge Corp., requested the Director of the Geological Survey to undertake a determination of the quantity of water that could be saved by removing vegetation and a study of other related problems, such as the effect of clearing on the quality of water in and downstream from the cleared area.

The investigation was begun in April 1943 as a project of the Water Resources Division by the late G. L. Parker, chief hydraulic engineer, who assigned the general supervision to a committee comprised of C. S. Howard, district chemist, Quality of Water Branch, John H. Gardiner, district engineer, Surface Water Branch, and S. F. Turner, district engineer, Ground Water Branch. Mr. Howard was named chairman of the committee.

In April 1943, when the Geological Survey began work, the Phelps Dodge Corp., through A. T. Barr, chief engineer of its New Cornelia Branch, Ajo, Ariz., was already actively engaged in surveying, mapping, and installing structures and equipment needed for the investigation. Under a general division of duties the corporation continued its work in cooperation with the Survey, and the Survey collected

[2] Turner, S. F., and others, Water resources of Safford and Duncan-Virden Valleys, Ariz. and N. Mex., 50 pp., U. S. Geol. Survey, 1941. (See list of studies p. 5.)

most of the data, conducted the experiments, and compiled and interpreted the results of the investigation. Most of the water-level measurements in observation wells were made by the corporation.

SCOPE AND PURPOSE OF THE INVESTIGATION

Under the plan proposed for supplying additional water to the copper mines and reduction works at Morenci, water was to be pumped from San Francisco River, which flows into Gila River and thence into San Carlos Reservoir. The pumped water was to be replaced with water to be saved by clearing the land upstream from the reservoir, thus removing bottom-land vegetation, which dissipates water by transpiration. The investigation was originally undertaken to determine the quantity of water used by bottom-land vegetation and the quantity of water that could be saved by clearing. After clearing, the investigation was to be continued to determine the quantity of water actually saved and the changes in quality of water resulting from clearing. In addition, the Phelps Dodge Corp. was to determine the quantity of sediment, if any, moved downstream as a result of the clearing.

In November 1943 the Defense Plant Corp. and Phelps Dodge Corp. adopted a plan to obtain the needed water for the Morenci plant from Black River, a tributary of Salt River, in exchange for flood waters to be stored on Verde River, in the Salt River Basin. The plan to save water by clearing bottom-land vegetation in lower Safford Valley was therefore abandoned. The investigation was continued, however, to determine: (1) Quantity of water used by bottom-land vegetation in 1943-44, and (2) chemical character of surface and ground water in 1943-44. The results of this research are discussed in this report, and computations of water use by six different methods are given for the 12-month period ending September 30, 1944.

ORGANIZATION OF REPORT

The investigation covered many fields and of necessity explored and developed several new ideas and methods. A tremendous volume of data was collected. As a result, the scope of the report is so broad and the content so voluminous that a discussion of the arrangement of the report is presented here.

The report consists of four parts. Part 1 gives a comprehensive view of the area and of the problem. Part 2 gives tabulations summarizing the data, the details of the methods of collecting them, and discussions of their significance. Basic computations in the various fields are given to simplify the more advanced computations and the final assembling of data. Part 3 contains descriptions of six different methods of computing water use and the results of the computations. Part 4 contains a comparison of the results and a discussion of their probable accuracy. Conclusions derived from the investigation follow part 4.

PREVIOUS INVESTIGATIONS

Results of a water inventory covering the entire Safford Valley, which was conducted during the years 1939-42 under the supervision of S. F. Turner, district engineer, Ground Water Branch, and results of the regular stream-gaging program, conducted for a number of years under the direction of J. H. Gardiner, district engineer, Surface Water Branch, were available. The data from this earlier work were utilized in the present investigation.

Studies by the Geological Survey relating to Safford Valley are described in the reports that follow.

Surface-water resources:

- U. S. Geol. Survey 21st Ann. Rept., pt. 4, pp. 339-349, 1900.
- Lippincott, J. P., Storage of water on Gila River, Ariz.: U. S. Geol. Survey Water-Supply Paper 33, 1900.
- Surface water supply of the United States, Colorado River Basin: U. S. Geol. Survey water-supply papers beginning with 1899. (Nos. 38, 50, 66, 75, 85, 100 133, 175, 289, 309, 389, 409, 439, 459, 479, 509, 529, 549, 569, 589, 609, 629, 649, 669, 689, 704, 719, 734, 749, 764, 789, 809, 829, 859, 879, 899, 929, 959, 979, 1009, 1039, 1059.)
- Quality of surface waters of the United States: U. S. Geol. Survey water-supply, papers beginning with 1941. (Nos. 942, 950, 970, 1022, 1030.)

Geology and ground-water resources:

- Schwennesen, A. T., Geology and ground-water resources of the Gila and San Carlos Valleys in the San Carlos Indian Reservation, Ariz.: U. S. Geol. Survey Water-Supply Paper 450-A, 1921.
- Knechtel, M. M., Hydrology, Indian Hot Springs, Graham County, Ariz.: Washington Acad. Sci. Jour., vol. 25, no. 9, Sept. 15, 1935.
- Knechtel, M. M., Geological relations of the Gila conglomerate in southeast Arizona: Am. Jour. Sci., 5th ser., vol. 31, pp. 80-92, Feb. 1936.
- Knechtel, M. M., Geology and ground-water resources of the valley of Gila River and San Simon Creek, Ariz.: U. S. Geol. Survey Water-Supply Paper 796-F, 1938.
- Turner, S. F., and others, Water resources of Safford and Duncan-Virden Valleys, Ariz. and N. Mex., 50 pp., U. S. Geol. Survey, 1941. [Mimeographed in small quantity, now exhausted. Copies on file in Geological Survey offices in Phoenix, Safford, and Tucson, Ariz., and Washington, D. C.]
- Water levels and artesian pressure in observation wells in the United States: U. S. Geol. Survey water-supply papers beginning with 1940. (Nos. 911, 941, 949, 991, 1021, 1028.)
- Morrison, R. B., McDonald, H. R., and Stuart, W. T., Records of wells and springs, well logs, water analyses, and map showing locations of wells and springs in Safford Valley, Ariz., Arizona State Water Commissioner, 1942. [Mimeographed in small quantity, now exhausted. Copies on file in Geological Survey offices in Phoenix, Safford, and Tucson, Ariz., and Washington, D. C.]
- Hem, J. D., Quality of water of the Gila River Basin above Coolidge Dam, Ariz.: U. S. Geol. Survey Water-Supply Paper 1104 (in preparation).

Turner, S. F., and others, Ground-water resources and problems of the Safford Basin, Ariz., U. S. Geol. Survey, 1946. [Mimeographed.]

Other reports that refer to water resources and related subjects in Safford Valley basin are listed below.

Olmstead, F. H., Gila River flood control, Report to Secretary of the Interior: 65th Cong., 3d sess., S. Doc. 436, 1919.

Poulson, E. N., and Young, F. O., Soil survey of the Upper Gila Valley area, Ariz.: U. S. Dept. Agr., Bur. Chem. and Soils [Soil Survey Repts.] ser. 1933, No. 15, 1938.

Technical Committee, Upper Gila River Basin report: National Resources Planning Board, Water Resources Committee, 1940.

Firth, C. A., Distribution of waters of the Gila River: Gila Water Commissioner, Annual reports for the years 1937-44.

PERSONNEL

The committee that had general supervision of the 1943-44 investigation appointed J. S. Gatewood project engineer, to be responsible for coordinating the technical work of the three branches. B. R. Colby was in charge of the surface-water studies, J. D. Hem of the quality-of-water studies, and T. W. Robinson of the ground-water studies. Preceding Mr. Robinson were: J. F. Hostetter, in charge of construction of the Glenbar experiment station from April 4 to June 7, 1943; W. T. Stuart, in charge from June 20 to August 13, 1943; and L. C. Halpenny, in charge from October 18, 1943, to January 7, 1944. Other technical personnel were: For the Ground Water Branch, R. L. Cushman, J. H. Brown, R. E. Mann, G. E. Hazen, J. Z. Thompson, Theda P. Shelley, and several others for short periods; for the Surface Water Branch, A. Dalcerro, A. B. Goodwin, and C. D. Bingham; and for the Quality of Water Branch, R. T. Kiser, R. L. White, and D. C. Lillywhite. The services of Dorothy G. Dungan were divided between surface-water and ground-water work. The Phelps Dodge Corp. assigned G. E. Greiner, hydrographer, and personnel engaged in measuring water levels in observation wells to work under direct supervision of the Geological Survey. The discussion of the geology of the basin is based on field work in 1940-41 by R. B. Morrison, Ground Water Branch.

A preliminary report was prepared during a 6-week period following the end of field work in the fall of 1944. The authors were J. S. Gatewood, T. W. Robinson, B. R. Colby, and J. D. Hem. In 1946, funds were allocated to prepare the final draft, and the work was done by J. S. Gatewood, L. C. Halpenny, and J. D. Hem. The final draft was reviewed by Robinson and Colby, who were engaged on work in other areas at the time of its preparation.

ACKNOWLEDGMENTS

The general plan of the investigation was laid out originally by R. A. Hill and W. W. Lane, consulting engineers for the Phelps Dodge Corp., and by S. F. Turner, district engineer, Ground Water Branch, for the Geological Survey. Previous work done by Turner and others [3] was of great importance in developing the plan of the investigation. Turner also worked with Robinson in developing the method whereby laboratory tests of specific yield could be translated to field conditions. A. T. Barr of the Phelps Dodge Corp. was especially helpful during the investigation. H. R. Brisley, also of the Phelps Dodge Corp., assisted appreciably by his careful work in mapping the bottom-land vegetation and identifying plant species. C. A. Firth, Gila Water Commissioner, permitted the use of two of his canal gaging stations and allowed access to his current records of diversions into canals. The officials of the canal companies and their engineer, Thomas Maddock, gave permission for the construction of gages on the canals and helped obtain permission for the installation of observation wells on privately owned land.

LOCATION, EXTENT, AND GENERAL FEATURES OF LOWER SAFFORD VALLEY

Safford Valley lies along Gila River in Graham County, Ariz., within a basin that is limited along the northeast side by the Gila Mountains and along the southwest side by the Graham, Santa Teresa, and Turnbull Mountains. In 1940 Graham County had a population of 12,113, mainly concentrated in Safford Valley. Safford, the county seat and largest town, is by highway 180 miles east of Phoenix, 134 miles northeast of Tucson, and 240 miles west of El Paso, Tex. The valley is served by U. S. Highway 70 and by a branch of the Southern Pacific Lines, both of which pass through Safford.

The area studied, which for the purpose of this report is designated as "lower Safford Valley," occupies the part of the valley from the town of Thatcher, 3 miles west of Safford, to the railroad bridge over the Gila River near Calva (see pl. 1). The area includes the cultivated and bottom lands between the mesas on both sides of Gila River. It is about 46 miles in length and ranges in width from 1 to 3 miles, covering about 38,000 acres, or slightly less than 60 square miles.

AGRICULTURAL DEVELOPMENT AND IRRIGATION

Agricultural development in Safford Valley began as early as 1872. Rainfall was insufficient for the growth of crops, and water was diverted from Gila River for irrigation. The water users depended on

[3] Turner, S. F., and others, op.cit., 1941

the natural flow of the river and diverted water into canals by small dams. The demand for irrigation water increased in proportion to the increase in the amount of land put into cultivation. The diversion rights for irrigation from Gila River in the entire Safford Valley, as shown in the report of the Gila Water Commissioner,[4] increased from 0.4 second-foot in 1872 to 406.4 second-feet in 1920, with no increase thereafter. The amount of land under irrigation, based on a diversion right of 1 second-foot for each 80 acres,[5] was about 32 acres in 1872, 498 in 1880, 16,224 in 1890, 21,664 in 1900, 29,232 in 1910, and 32,512 since 1920.

Development of ground water for irrigation in the valley began about 1930, when the first large irrigation well was drilled. At the end of 1940 there were approximately 150 irrigation wells, of which 120 were being pumped. The remaining 30 were inactive, either because pumping plants were not available or because the yields of the wells were too small. In the fall of 1944 there were about 260 irrigation wells in the valley, of which about 215 were being pumped. There is no record of the pumpage prior to 1940; however, it is believed not to have been large. The water pumped in the Safford Valley during the calendar years 1940, 1941, 1942, 1943, and 1944 was about 23,600, 8,700, 18,900, 35,000, and 52,000 acre-feet, respectively.[6] These figures do not include the small amounts of water pumped on the San Carlos Indian Reservation at Bylas and Calva. The lower pumpage in 1941 was the result of increased precipitation and river flow during that year.

The river water, which carries considerable silt, is generally used in preference to ground water for irrigation. Water from many of the irrigation wells in the valley has a rather high percentage of sodium,[7] which causes deflocculation of the soil; therefore, when feasible, ground water is diluted with river water in order to reduce the deleterious effect of the ground water.

The valley as a whole has a favorable relief for irrigation and has good natural drainage that facilitates the leaching of salts from the soil by the irrigation water. Although many fields lie near the river, waterlogging of irrigated fields has not occurred except in small areas.

Prior to 1920 agriculture in the valley was devoted principally to the growing of grain, hay, and sorghum, with some orchard crops. In 1944 cotton was the dominant crop, with hay (mostly alfalfa), grain, vegetables, and vegetable seed as lesser crops.

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[4] Firth, C. A., Distribution of waters of the Gila River: Gila Water Commissioner, 9th Ann. Rept., pl. 44, 1944.

[5] Idem.

[6] Meinzer, O. E., Wenzel, L. K., and others, Water levels and artesian pressures in observation wells in the United States, part 6, Southwestern States and Territory of Hawaii: U. S. Geol. Survey Water-Supply Papers 911, p. 10, 1941; 941, p. 9, 1943; 949, p. 9, 1944; 991, p. 9, 1945.

[7] Turner, S. F., and others, Ground-water resources and problems of the Safford Basin, Ariz., p. 12, U. S. Geol. Survey, 1946. (See list of studies, p. 6.)

NATURAL VEGETATION

The natural vegetation that grows in lower Safford Valley may be divided into two groups, the division depending on the relation of the root system to the water table. The two groups are known as xerophytes and phreatophytes.

Xerophytes are adapted for efficient use of the small quantity of soil moisture that is supplied by infrequent rains, and their roots do not extend below the belt of soil moisture. During prolonged periods of drought, these plants maintain themselves in a nearly dormant condition. They usually grow on upland slopes where the water table is at great depth. The most common xerophyte in lower Safford Valley is the creosote bush (*Covillea tridentata*), which grows on the uncultivated mesas and terrace fronts. As the investigation covered by this report was made to determine the use of water by bottom-land vegetation, no further consideration will be given to xerophytes.

FIGURE 1.—Roots of mesquite in Brawley Wash, Avra-Altar Valley, Ariz. Cliff is about 22 feet high. Photograph by S. F. Turner.

Phreatophytes, which depend almost entirely on the ground-water reservoir for their water supply, use much more water than xerophytes. The roots of phreatophytes extend either to the water table or to the capillary fringe lying immediately above the water table. The roots of tamarisk (saltcedar), a phreatophyte, have been known to penetrate more than 90 feet, as shown by excavations for the Suez Canal.[8] Figure 1 shows mesquite roots more than 22 feet long in the bank of a wash in the drainage basin of Santa Cruz River, Ariz.

The phreatophytes in lower Safford Valley grow principally on the bottom land, although they also occur along wash channels, in some instances upstream almost to the mountains. In addition, a few isolated phreatophytes, particularly cottonwoods, grow along roads and canals and in yards in the cultivated part of the valley, and a few groves of mesquite grow in uncleared parts of the valley.

BOTTOM-LAND VEGETATION

The bottom land, which in general constitutes the area subject to periodic inundation by floods in Gila River, ranges in width from a quarter to seven-eighths of a mile and is covered for the most part with a dense growth of natural vegetation (see fig. 2). The term bottom land as used in this report applies to these low-lying phreatophyte-covered lands along Gila River, as indicated by the boundary lines on plates 2 and 3. In a few places in the bottom land there has been some clearing for cultivation, but in 1944 this cultivated acreage was negligible. The lack of agricultural development in the bottom land is primarily due to the ever-present hazard of floods and the attendant damage or destruction of crops, although the cost of clearing and, in places, the undesirable character of the soil for tilling, are also factors.

FIGURE 2.—Gila River about half a mile above Colvin-Jones Canal heading, showing dense growth of saltcedar along river channel, June 17, 1943. River is at extreme low flow. Photograph furnished by Phelps Dodge Corp.

[8] Renner, O., Wasserversorgung der Pflanze: Handworterbuch der Natur wissenschaften, vol. 10, pp. 538-557, Jena, 1915.

Originally the bottom-land growth was composed of plant life indigenous to southeastern Arizona, the most common species being cottonwood (fig. 3), willow, baccharis (fig. 4), and mesquite (fig. 5). Sometime during the second decade of this century, saltcedar (fig. 11), a plant brought into Texas and New Mexico from the Mediterranean region, was introduced into the Gila River Valley. Conditions for the growth of this plant were ideal. and it spread rapidly throughout the

FIGURE 3.—Field of typical miscellaneous brush with cottonwood trees in background, bottom land, lower Safford Valley. Photograph by L. C. Halpenny.

bottom land wherever it could send its roots to the water table. The number of cottonwoods and willows in the meantime declined, both because of destruction by man and because these plants could not compete with the saltcedar, which thrived and spread at the expense of nearly all the native plant life.

Where conditions are favorable saltcedar grows as a dense junglelike thicket that is difficult to penetrate. Where conditions are less favorable and on the fringes of the thickets it grows in clumps. Saltcedar is a rapidly growing plant, particularly when young. During the course of the investigation shoots from an area cut over in 1943 were observed to have grown to a height of 6 to 8 feet in about 12

FIGURE 4.—Thicket of baccharis, lower Safford Valley. Photograph furnished by Phelps Dodge Corp.

FIGURE 5.—Grove of mesquite, near Fort Thomas, lower Safford Valley. Photograph by J. S. Gatewood

months. At the Fort Thomas test plot, cut over on the last day of July 1944, shoots had grown to an average height of 2½ feet in 3 months. (See fig. 6.)

CLIMATE

The climate of Safford Valley is mild and arid. The amount and distribution of precipitation are inadequate to assure the growth of crops. The three driest months—April, May, and June—are followed by the three wettest months—July, August, and September. Rainfall is about equally distributed during the other six months of the year. Snow

FIGURE 6.—Fort Thomas test plot, showing new growth of saltcedar 2½ feet high 3 months after cutting. Photograph by T. W. Robinson.

in the valley is an unusual occurrence, and none fell during the period of the investigation. However, snow may fall on the surrounding mountains during any month from October to April. Average annual rainfall at Thatcher for the 34-year period ending in 1937 was 9.50 inches.

Daily and seasonal temperatures in Safford Valley have a rather wide range. The highest recorded temperature at Thatcher for the 33-year period ending in 1930 was 116° F. and the lowest 7°. June, July, and August are the hottest months and December and January the coldest. Over a 26-year period the average length of the growing season, or frost-free period, at Thatcher was 203 days. On the average the latest killing frost in the spring occurs on April 11 and the earliest in the fall on October 31, but the latest and earliest on record occurred on May 7 and October 6, respectively. The relative humidity during daylight hours in Safford Valley is low, evaporation is rapid, and the percentage of sunshine is high. Wind movement is greatest during March and April and least during the fall. Over a 26-year period the prevailing wind direction at Thatcher was southeast.

METEOROLOGICAL DATA

Records of meteorological data in lower Safford Valley have been collected and published by the U. S. Weather Bureau[9] as shown in the following table.

TABLE 1.—*Meteorological records available for lower Safford Valley, Ariz.*

Station	Period of record
Fort Thomas	1880–91
Pima	1898–1903
Thatcher	1904–37
Safford	[1] 1937
Safford evaporation [2]	1940–47

[1] In operation in 1949.
[2] Operated by Geological Survey.

TABLE 3.—*Monthly evaporation and wind movement, Safford Valley, 1943-44*

Month	Safford evaporation station		Glenbar experiment station			
			Weather station		Shaded pan [1]	Field pan [2]
	Evaporation (inches)	Total wind movement (miles)	Evaporation (inches)	Total wind movement (miles)	Evaporation (inches)	Evaporation (inches)
1943						
July	8.721	129	10.143	....	3.836	14.331
Aug.	7.305	222	8.057	....	1.837	10.581
Sept.	6.280	175	7.459	....	2.050	10.178
Oct.	4.638	283	5.306	....	1.625	7.035
Nov.	3.315	....	3.704	....	1.707	4.628
Dec.	1.784	....	2.120	666	.991	2.669
1944						
Jan.	1.967	403	2.217	559	.929	2.675
Feb.	2.844	439	3.047	679	1.581	3.723
Mar.	5.366	616	6.190	1,038	3.348	7.504
Apr.	7.890	665	8.646	1,064	4.711	10.756
May	8.892	432	9.871	648	5.080	13.263
June	10.590	357	11.724	726	5.704	15.436
July	9.618	334	10.339	600	4.550	12.684
Aug.	8.894	280	10.289	699	3.697	13.073
Sept.	6.166	135	[3] 7.293	[4] 590	[5] 2.675	[5] 10.138
Oct.	3.525	142	4.504	710	....	[6] 6.525

[1] In circular open space about 5 feet in diameter in dense growth of saltcedar at experiment station.
[2] On dry sand bar in large clearing about 1,000 feet southeast of experiment station.
[3] Estimated for Sept. 25-28.
[4] Estimated for Sept. 25-26.
[5] Estimated for Sept. 26-Oct. 1.
[6] Estimated for Oct. 1-5.

NOTE.—All pans were Weather Bureau type class A.

[9] U. S. Weather Bureau, Climatological data, Arizona section, monthly reports.

TABLE 2.—*Monthly precipitation, in inches, at points in Safford Valley, 1943-44*

Month	San Jose	Safford evaporation station	Pima bridge[1]	Glenbar experiment station: Weather station	Glenbar experiment station: Shaded gage	Glenbar experiment station: Field gage	Fort Thomas	Black Rock Wash[2]	Geronimo gaging station[1]	Bylas	Calva
1943											
July	......	1.43	......	2.15	1.73	1.81	......	......	......	......	......
Aug.	......	1.57	3.96	3.56	2.04	3.60	2.15	......	......	2.98	1.94
Sept.	1.45	1.40	1.79	2.63	2.04	2.61	1.79	......	1.94	1.42	1.06
Oct.	.18	.23	0	.16	.12	.18	.03	......	.06	.17	.88
Nov.	0	0	0	0	0	0	0	......	0	.19	0
Dec.	.92	1.00	1.10	.89	.91	.88	1.22	......	.88	1.04	1.31
1944											
Jan.	.02	.40	.24	.32	.32	.34	.27	......	.25	.30	.69
Feb.	.12	.31	......	.50	.50	.47	.62	......	.44	.58	.70
Mar.	.60	.66	......	.64	.61	.62	.46	......	.47	.45	.91
Apr.	.20	.09	......	.15	.15	.15	.29	......	.56	.42	.62
May	.24	.13	......	.18	.16	.16	.18	......	.38	.38	.44
June	0	.15	0	0	0	0	0	......	0	.13	0
July	.67	2.48	1.30	1.62	1.30	1.33	1.28	1.76	1.88	1.47	2.38
Aug.	1.53	1.06	1.44	1.19	1.21	1.16	.90	1.28	2.06	.99	2.06
Sept.	2.37	6.07	2.47	2.76	2.62	2.70	......	2.48	2.98	2.46	1.06
Oct.	.70	1.16	.39	.66	.37	.62	.53	.50	.50	.60	1.19

[1] Gages are 6.5-inch metal containers; all others are standard-type Weather Bureau gages.
[2] Seven miles southwest of Fort Thomas.

Measurements of precipitation were made by the Geological Survey during the course of the investigation at San Jose, Safford evaporation station, Pima bridge, Glenbar experiment station, Fort Thomas, Black Rock Wash, Geronimo gaging station, Bylas, and Calva. The records of rainfall at these stations are contained in table 2. Evaporation was measured by the Geological Survey at San Jose, Safford evaporation station, Glenbar experiment station, and Fort Thomas. Table 3 contains records of evaporation from the pan at the Safford evaporation station and the three pans at the Glenbar experiment station. Measurements of evaporation at San Jose and Fort Thomas were made only once each week, and these records are not published in this report. Temperature and relative humidity records, collected at the Glenbar experiment station, are given in table 4.

TABLE 4.—*Temperature and mean relative humidity, Glenbar experiment station, 1943-44*

Date	Temperature (°F.)				Mean relative humidity (percent) [1]
	Maximum	Mean of daily maximums	Minimum	Mean of daily minimums	
1943					
July	109	101.0	49	62.2	55
Aug.	104	97.0	58	65.0	67
Sept.	105	94.0	44	53.0	60
Oct.	94	83.0	26	42.0	59
Nov.	82	74.3	13	23.8	51
Dec.	72	61.5	14	25.4	64
1944					
Jan.	73	60.0	8	20.8	58
Feb.	73	64.8	15	26.8	59
Mar.	84	71.4	16	30.3	47
Apr.	89	80.2	24	33.4	39
May	102	91.5	29	41.8	44
June	109	99.3	38	47.5	40
July	110	102.2	44	61.6	51
Aug.	114	101.7	48	62.8	52
Sept.	104	93.7	46	56.4	58
Oct.	92	83.0	40	49.7	62

[1] Monthly mean of daily mean relative humidity, as determined from recording hygrometer.

GEOLOGY AND ITS RELATION TO GROUND-WATER SUPPLIES

The following is quoted from a report by Turner and others:[10]

CHARACTER OF BASIN

The Safford Basin is a deep trough that lies between mountain blocks of older rocks. These rocks are mostly volcanic lava and ash deposits on the northeast side of the basin and gneiss on the southwest side of the basin. The older rocks that comprise the mountain blocks are hard and resistant and for the most part impermeable, although they carry some water that issues as springs from cracks, fissures, and weathered zones along the sides of the mountains. The mountain blocks perform two major func-

[10] Turner, S. F., and others, Ground-water resources and problems of the Safford Basin, Ariz., pp. 4, 5, U. S. Geol. Survey, 1946. [Mimeographed.]

tions with respect to ground water in the basin: (1) Because of their higher elevations they have greater annual rainfall and thus contribute a large share of the water that enters the basin; (2) because they are composed of relatively impermeable rocks they tend to confine the ground water within the basin.

The deep trough of the Safford Basin is partly filled with more or less unconsolidated deposits of gravel, sand, silt, and clay. The ground water occurs principally within these deposits.

Older Alluvial Fill

The larger part of the more or less unconsolidated deposits in the Safford Basin is termed "older alluvial fill" in this report. These deposits were derived from the hard rocks of the mountain blocks and were washed into the basin by streams and by sheet runoff. The alluvial fill was deposited in an enclosed basin, and a shallow lake of the playa or semiplaya type was formed along the axis of the basin. The thickness of the older alluvial fill is at least 3,767 feet at one place, based upon the log of the Mary S. Mack oil test [sec. 13, T. 6 S., R. 24 E.]. Several deep water-bearing beds were encountered in this well. A well drilled at Safford for the Southern Pacific Railroad did not reach bedrock at 1,820 feet. An oil test drilled near Ashurst (SW¼NE¼ sec. 30, T. 5 S., R. 24 E.) was abandoned in older alluvial fill at 2,645 feet.

Near the mountains on both sides of the basin the older alluvial fill consists of boulders, gravel, and conglomerate with small amounts of sand and silt, and is termed the "gravel zone" in this report. The width of the gravel zone is from 1 to 2 miles on each side of the basin. The gravel zone of the older alluvial fill is partly consolidated and moderately permeable. Layers of relatively impermeable caliche lie near the surface in most of the outcrop area of the gravel zone. Streams have cut channels through these layers, enabling water from rain and from stream flow to enter the fill along the stream channels.

The materials that comprise the older alluvial fill gradually become finer-grained toward the interior of the basin, grading first to interbedded sand and silt with some gravel, then to silt with some sand, and finally, along the axis of the basin in the playa or "lake-bed zone," to silt and clay with local stringers of sand. The silts and clays of the lake-bed zone are relatively impermeable and contain salt and gypsum.

Alluvial Fill of Inner Valley and Tributary Washes

The alluvial fill of the inner valley and tributary washes was deposited after the Gila River entered the Safford Basin. When the river first entered the basin it started a cycle of erosion that included development of gorges through the mountain barriers and rapid cutting of the fill in the interior of the basin. After the first rapid cutting the erosion slackened, and an erosion surface was developed on the softer areas of the older alluvial fill. This surface is about 50 to 100 feet below the original depositional level, and it slopes gently toward the Gila River. It is covered with a thin mantle of gravel and is the main "mesa" level above the river plain near Safford. Subsequently the rate of erosion by the river was accelerated, and an inner narrow valley, about 150 feet deep, was cut within the larger one. This valley is partly filled, to a depth of 50 to 100 feet, with silt, sand, and gravel deposited by the river and its tributary washes. The part of the basin underlain by these younger deposits is called the inner valley and includes nearly all the irrigated lands.

The alluvial fill of the inner valley and tributary washes consists of irregular and discontinuous beds, and adjacent wells may encounter water-bearing sand or gravel beds at entirely different depths. The layers of silt are not continuous, and water from the surface percolates downward, often by circuitous routes, to recharge the underlying ground-water reservoir.

WATER RESOURCES

SURFACE WATER

Gila River in Safford Valley is typical of streams in the Southwest. It has a rather steep slope, a shifting and changing channel, and numerous overflow channels that carry water during flood periods. The average slope is 7.1 feet per mile in the 45.8-mile reach of the river from the gaging station at Thatcher to the gaging station at Calva. Many small dams divert river water into canals for irrigation. Generally speaking, the river, as it moves through the valley, gains water from the ground-water reservoir.

Within the area there are no perennial streams tributary to the Gila River, but numerous washes, which normally have no flow, enter the river from both sides. These washes at times carry large flows of water for short periods as a result of heavy rainstorms on the mesas or in the mountains bordering the valley.

GROUND WATER

Ground water occurs at shallow depths in the sand and gravel beds of the alluvial fill of the inner valley of Gila River. These beds are the source of water for nearly all the irrigation wells in the valley; The water-bearing beds are not continuous, however, so that a given bed of gravel may be 10 feet thick at one point, and a few hundred feet away it may be only 2 feet thick or may have pinched out entirely. The depth to the water table in the bottom land ranges from about 1 to about 12 feet and in nearly all the farmed area from about 8 feet to about 50 feet. Locally there may be small areas in which the ground water in the alluvial fill of the inner valley is under a slight artesian head, but generally the ground water is not confined.

The ground water of the inner valley is derived primarily from four sources: (1) Spring flow and upward seepage from the older alluvial fill, (2) underflow of Gila River and tributary washes, (3) recharge from the Gila River when the water table is below the level of the river, and (4) infiltration from rainfall and from irrigation water in canals and on fields. The ground water is discharged by pumping and by natural means. Natural discharge occurs through transpiration and evaporation in the area occupied by phreatophytes, as evaporation from bare wet land surfaces in the bottom land, as underflow out of the valley along Gila River, and as seepage from the ground-water reservoir into the river.

QUALITY OF WATER

At low stages water of the Gila River in lower Safford Valley is in general rather highly mineralized. At high stages, the water of the river because of dilution contains only small to moderate amounts of dissolved mineral matter.

Most of the ground waters of lower Safford Valley are rather highly mineralized. In a few places, however, they are composed of wash underflow that contains only moderate amounts of dissolved matter. In general, the principal constituents of the highly mineralized waters in the valley are sodium and chloride; the principal constituents of the waters of low mineral content are bicarbonate and calcium or sodium.

METHODS OF DETERMINING USE OF WATER

Several different methods of measuring the use of water by bottom-land vegetation were proposed before the investigation was begun and during its course. Some of these methods involved clearing of large areas occupied by phreatophytes and measuring the difference between the amount of water available before clearing and the amount available after clearing. The methods dependent on clearing were of necessity abandoned in November 1943, when clearing of growth was no longer contemplated.

In making computations of water use by the several different methods it was desirable to express the results on a comparable basis. Particularly it was necessary that the figures for use of water computed by the different methods should include or exclude the same components. The term "use of water" was analyzed into its basic parts, therefore, and all the results by the methods applied are expressed according to the definition that follows.

DEFINITION OF USE OF WATER

Young and Blaney [11] define use of water as follows:

> "Use of water," * * * sometimes called "evapotranspiration," is the sum of the volumes of water used by the vegetative growth of a given area in transpiration or building of plant tissue and that evaporated from adjacent soil, snow, or intercepted precipitation on the area in any specified time.

That definition has been adopted for this report.

APPLICATION TO LOWER SAFFORD VALLEY

As the determination of use of water by bottom-land vegetation was the objective of the investigation, the use as computed in this report includes only transpiration and evaporation in the phreatophyte-covered part of the bottom-land area. Use of water was determined in terms of two components: use of ground water, sometimes called draft on ground water, and use of precipitation. Computations by each of the methods give results in terms of use of ground water. It was assumed that all precipitation in the phreatophyte-covered area was used by

[11] Young, A. A., and Blaney, H. F., Use of water by native vegetation: California Dept. Public Works, Div. Water Resources Bull. 50, p. 2, 1942.

transpiration and evaporation. Therefore, the total precipitation on the phreatophyte-covered area during the year was added to the use of ground water for the year as computed by each method. The sum of use of ground water and precipitation is termed "total use of water" in this report.

Water transpired by phreatophytes or evaporated from the bottom land of lower Safford Valley may come from any of three zones: zone of saturation, zone of soil moisture, and water at the land surface. Within the phreatophyte-covered area the main source of water at the land surface and of soil moisture above the capillary fringe was considered to be the precipitation on that area. Minor amounts of surface water and soil moisture supplied by irrigation wastes and floods in the Gila River were considered negligible, except for the period between the large flood of September 25, 1944, and the end of the 1944 growing season. As the soil-moisture changes were not determined during the investigation, and as soil moisture was high during the period from September 25, 1944, to the end of the 1944 growing season, the computed water use was unreasonably low for that period.

A relatively small amount of water is evaporated from the surface of Gila River and from wet sand bars bordering the river. Although these small losses have been computed, they have not been included in any of the figures for total use of water in this report, because they are not directly related to use of water by bottom-land vegetation.

DESCRIPTION OF METHODS USED

The six methods used during the investigation to determine use of water by bottom-land vegetation were:

1. Tank method.
2. Transpiration-well method.
3. Seepage-run method.
4. Inflow-outflow method.
5. Chloride-increase method.
6. Slope-seepage method.

Computations by these methods are discussed in detail in part 3.

Results by all the methods are expressed in terms of use of ground water for a year in acre-feet. Precipitation on the gross phreatophyte-covered bottom-land area (not including wet sand bars and river surface) was computed in acre-feet and added to the use of ground water obtained by each method to determine total use of water.

Part 2. COLLECTION AND ANALYSIS OF DATA

The basic data required for the six methods of determining water use covered almost the entire field of hydrology. All the data had to be assembled and analyzed before the six methods could be applied. Most of the basic data were needed for each of several different methods, although some were needed for only one method. In this part of the report the data are arranged so that the discussions under each heading are generally predicated on the discussions under the preceding headings. Thus the first subject in this part of the report covers a phase of the investigation for which information is needed for nearly all that follows, and the last subject discussed covers a phase that is based more or less on all that has been described previously.

AERIAL PHOTOGRAPHS, SURVEYING, MAPPING, AND LEVELING

As detailed maps were needed for both field work and the preparation of the report, one of the first steps in the investigation was to make a set of aerial photographs of lower Safford Valley from the Safford bridge to the railroad bridge at Calva, a distance by river of about 50 miles. A sufficient width of the valley was covered to show all of the phreatophyte-covered bottom lands and most of the farmed lands. At the suggestion of R. L. Cushman, the photographs were made at a time when the leaves and frondage were colored by frost, so that differentiation of species could be detected from the photographs. The photographs were made by Fairchild Aerial Surveys, Inc., on December 10, 1942, on a scale ranging from 650 to 740 feet to the inch. Figure 7 is a typical photograph.

The entire area from Thatcher to the San Carlos Indian Reservation line and between the farthest outlying canals on each side of the river was mapped on a scale of 1:7,200, or 600 feet to the inch, by the Phelps Dodge Corp. The location of each well was determined by a transit survey. The maps, plates 2, 3, 4, and 5, are based on this work. Lines across the bottom-land area approximately perpendicular to the course of the river were cleared, and monuments were established at the ends of each line. The lines were about 1,000 feet apart. Elevation profiles were made along these lines in order to have data with which to determine the possible effect of land-clearing on silt removal or deposition. Levels were run to all the observation wells, so that all water-level measurements could be referred to mean sea level. The datum of the gage at each river gaging station was also referred to mean sea level.

FIGURE 7.—Aerial photograph of typical part of lower Safford Valley, showing bottom land, cultivated lands of inner valley, and washes crossing older valley fill. Most of the dense growth between river and eroded older fill is saltcedar of 100-percent areal density. Photograph taken by Fairchild Aerial Surveys, Inc.; furnished by Phelps Dodge Corp.

DENSITY OF BOTTOM-LAND VEGETATION

DEVELOPMENT OF VOLUME-DENSITY METHOD

It was recognized that the total amount of water transpired from any area would be related to the density of vegetation in that area. Previous studies [12] have indicated that the amount of water transpired is proportional to the weight of the transpiring material. The problem for this investigation was to develop a method of estimating the relative weights of transpiring material in any given areas. This was done by means of the volume-density method—a method of estimating the volume and density of growth of a given species of plant in relation to a standard for that plant, which for convenience was taken as the assumed maximum possible density for that plant. The method was developed from a suggestion by H. R. Brisley, botanist for the Department of Agricultural Investigation, Phelps Dodge Corp. Two of the methods applied in the quantitative determination of use of water require for their application to field conditions a knowledge of the volume density of phreatophyte growth.

CLASSIFICATION OF BOTTOM-LAND VEGETATION

In the application of the volume-density method the first elements to be considered were the types of plants and the areal extent of each type. During the early spring of 1943, J. C. Dunne, engineer for the Phelps Dodge Corp., made a preliminary survey of the amount, kind, and density of the bottom-land vegetation from Thatcher to Calva. In the summer of 1943, H. R. Brisley made a detailed survey of the bottom-land vegetation from Thatcher to the boundary of the San Carlos Indian Reservation. This survey was independently checked by C. R. Davis, botanist, also of the Phelps Dodge Corp. The results of the surveys by Brisley and Davis and that part of the preliminary survey by Dunne from the boundary of the Indian reservation northwest to Calva were used in determining the area and density of bottom-land growth. In the summer of 1944 a small amount of supplemental work was done by the Geological Survey to complete the mapping of bottom-land vegetation.

During their investigations Brisley and Davis collected and identified specimens of most of the plant life growing in the bottom land. The identifications were confirmed by Dr. Lyman Benson of the Department of Botany, University of Arizona. Table 5 lists the plants found, giving both the common name and the scientific name. The plants listed have been divided into two groups, known phreatophytes and other

[12] Raber, Oran, Water utilization by trees, with special reference to the economic forest species of the North Temperate Zone: U. S. Dept. Agr. Misc. Pub. 257, pp. 75-83, 1937. Horton, R. E., Transpiration by forest trees: U. S. Weather Bureau, Monthly Weather Rev., vol. 51, No. 11, pp. 571-581, Nov. 1923.

TABLE 5.—*Plants identified in bottom land, lower Safford Valley*

[Identification by H. R. Brisley, botanist for Department of Agricultural Investigations, Phelps Dodge Corp.]

Known phreatophytes		Other plants	
Common name	Scientific name	Common name	Scientific name
Saltcedar	Tamarix gallica	Rattlesnake weed	Euphorbia albomarginata
Baccharis, or batamote,	Baccharis glutinosa	Chinese pusley or quailplant	Heliotropium curassavicum
or seepwillow,	Baccharis emoryi	Fremont goosefoot	Chenopodium fremontii
or watermotie	Baccharis sergilloides	Blazing-star	Mentzelia multiflora
Mesquite	Prosopis velutina		Ximenesia exauriculata
Fremont cottonwood	Populus fremontii		Bassia hyssopifolia
Black willow	Salix nigra	Curly-leaf dock	Rumex crispus
Sandbar or coyote willow	Salix exigua		Rumex conglomeratus
	Suaeda moquini	Canaigre	Rumex hymenosepalus
Arrowweed or marsh-fleabane	Pluchia sericea	Tree tobacco	Nicotiana glauca
Saltgrass	Distichilis spicata	Desert thorn	Lycium fremontii
Chamiso	Artiplex canescens	Horehound	Marrubium vulgare
	Artiplex elegans	Anglepod	Gonolobus productus
Burrobrush	Hymenoclea salsola	Doveweed	Croton texensis
Pickleweed	Allenrolfea occidentalis	Wheatgrass	Agropyron sp.
Catclaw	Acacia greggii	Barleygrass	Hordeum nodosum
Spiny aster	Aster spinosus	Perennial ryegrass	Lolium perenne
		Jackass clover	Wislizenia refracta
		Sandverbena	Abronia villosa
		Rabbitfoot grass	Polypogon monspeliensis
			Haplopappus pluriflorus
		Narrowleaf globemallow	Spheralcea angustifolia
		Fragrant bittersweet	Actaea odorata

plants. All but one of the plants listed in the first group have been classified by Meinzer [13] as phreatophytes; the spiny aster was not included in his list. The plants listed in the second group form only a small part of the bottom-land growth.

The most common phreatophytes in lower Safford Valley are saltcedar, baccharis, cottonwood, willow, and mesquite. In the field survey the areas of bottom-land vegetation were classified as follows: saltcedar, baccharis, cottonwood and willow, mesquite, brush, barren land, and sand bars. Plates 2 and 3 show the general areal distribution by predominant species.

MEASUREMENT OF VOLUME DENSITY

As the field of study of use of water by phreatophytes is relatively new, a method had to be evolved to allow for variations in density of growth of the plants. In some areas the plants were widely scattered, and in other areas they grew in dense thickets. Field studies indicated that there were two variables with respect to density of growth—areal density and vertical density—and their product was termed "volume density." Both of these variables, therefore, had to be evaluated in terms of the "maximum possible."

Areal density is a term used to describe the ratio of the area occupied by a given species of phreatophyte in a parcel of land to the total area of the parcel. The maximum possible (100 percent) areal density was chosen as an area in which the plants are growing as close together as nature will permit; thus the addition of one plant to the area would presumably cause the choking out of a plant of equal size. Vertical density is a term used to describe the ratio of vertical depth of fronds or leaves on the phreatophytes in a parcel of land to the maximum possible vertical depth of fronds or leaves permitted by nature on that particular species of plant. A thicket of optimum (100 percent) vertical density would be one in which the addition of new growth at the top of the thicket would result in a choking out of an equivalent amount of growth on the lower branches. The investigation showed that the depth of frondage was generally less than the over-all heights of the plants, as the lower parts of the plants were so well shaded that frondage growth did not occur. For saltcedar the average depth of frondage was 13 feet for plants 13 feet or more high, and equal to the height of the plant for plants less than 13 feet high. For baccharis the average depth of frondage was 5.5 feet for plants 5.5 feet or more high, and equal to the height of the plant for plants less than 5.5 feet high. The average depth of frondage for cottonwood was not determined accurately during the investigation, although preliminary data indicate that frondage

[13] Meinzer, O. E., Plants as indicators of ground water: U. S. Geol. Survey Water-Supply Paper 577, 95 pp., 1927.

TABLE 6.—*Summary of tests with saltcedar to determine relation between dry weight and volume density of frondage*

Test plot	Area (square feet)	Average height of trees (feet)	Average depth of frondage (feet)	Areal density (percent)	Vertical density (percent)	Volume density (percent)	Weight of fronds (pounds)		Oven-dried weight per unit area (pounds per square foot)	
							Green	Oven-dried at 170° F.	Actual	Adjusted to 100-percent volume density [1]
Pima	162.6	13.5	12.9	100	99	99	46.94	[2] 20.38	0.125	0.127
Bellman	421.3	27.0	13.5	85	104	88	128.50	[2] 45.16	.107	.122
Fort Thomas	371.7	6.0	6.0	85	46	39	58.84	17.89	.048	.123
Ashurst No. 1	408.8	8.3	[3] 5.7	100	44	44	66.75	[2] 21.97	.054	.122
Ashurst No. 2	570.6	9.7	8.7	55	67	37	67.50	24.98	.044	.118

[1] Actual divided by volume density.
[2] Based on representative portion of air-dried weight.
[3] Depth of frondage less than normal, owing to large amount of dead material caused by brush fire several years earlier.

occupies the volume between two concentric hemispheres with surfaces about 6 feet apart. The vertical density of willow, mesquite, and miscellaneous brush was not determined during the investigation.

ACCURACY OF VOLUME-DENSITY MEASUREMENTS

Field studies were made to determine the accuracy with which the investigators could estimate the volume density—and therefore the relative quantities of transpiring material per unit area—using the methods described. Five test plots of saltcedar were selected for the study. No two plots had the same volume density or trees of the same height. The plots were selected so that the surrounding plant growth was of about the same volume density as the plant growth within the plot. The area of each plot was measured, the height of the plants was measured, and the areal and vertical densities were estimated. The plants were then cut and the fronds stripped. The fronds were weighed green and then air-dried and reweighed. For two plots, Fort Thomas and Ashurst No. 2, the entire amount of fronds was oven-dried. Representative portions of the air-dried fronds from the other plots were oven-dried, so that the total weight of fronds for each plot could be expressed as oven-dried weight. The oven-dried weight of the fronds was found to average about 90 percent of the air-dried weight.

The results of the study are given in table 6. As was to be expected from the plots selected, the actual oven-dried weight per unit area varied greatly among the plots. Adjustment of these weights to 100 percent volume density on the basis of the observed volume density, it will be noted, brings them into satisfactory agreement. The range of variation (0.009 pound per square foot) is only 7 percent of the mean weight per unit area. It is thus shown that the volume of saltcedar growth in any area of that growth, as measured by the volume-density method, is an accurate measure of the weight of transpiring growth. The relationship was assumed to hold true for other species of growth. It was stated previously (p. 23) that other investigators have found that the amount of water transpired was proportional to the weight of the transpiring material.Whether the amount of water transpired is a function basically of the weight of transpiring material, the volume of growth, or some other directly related quantity such as area of fronds, is not known. On the basis of this study, however, it is considered that whatever the basic function is, the various factors are so related that the volume density is a measure of sufficient accuracy for estimating, for this investigation, the amount of water transpired. Therefore in later sections of the report the amount of water transpired will be related directly to the volume density.

FIELD APPLICATION OF VOLUME-DENSITY METHOD

The method finally developed for the field determination of acreages and densities of each type of plant was as follows: Four base plots of each type of vegetation were selected to guide in estimating density. In these base plots the areal density of growth was 25, 50, 75, and

FIGURE 8.—Saltcedar in base plot of 25-percent areal density. Photograph furnished by Phelps Dodge Corp.

FIGURE 9.—Saltcedar in base plot of 50-percent areal density. Photograph furnished by Phelps Dodge Corp.

FIGURE 10.—Saltcedar in base plot of 75-percent areal density. Photograph furnished by Phelps Dodge Corp.

FIGURE 11.—Saltcedar in base plot of 100-percent areal density. Photograph furnished by Phelps Dodge Corp.

100 percent, respectively. (See figs. 8-11.) The plots were studied periodically in order to keep the estimates of field density on a uniform basis. The aerial photographs were studied, and the entire bottom land was divided into parcels according to the apparent density of growth. Each of these parcels of land was numbered, and each was visited in the field. Photographs were made of the vegetation in each parcel, as a record for later reference, if and when clearing was done. During the field inspection the over-all areal density of growth in the parcel was recorded, expressed as a percentage of optimum growth. The proportion of each type of phreatophyte in each parcel was recorded. The average height of each type of phreatophyte was also recorded for each parcel. The parcels of land were plotted on a base map, and the area of each parcel was measured with a planimeter.

The net area of vegetation at optimum density in each parcel was calculated as shown in the following hypothetical example.

Base data:

	Percent	*Average height (feet)*
Parcel No. X:		
Areal density of parcel	85	...
Saltcedar in parcel	90	22
Baccharis in parcel	10	4.8

Calculations:

	Acres
Gross area of parcel	14.62
Gross area of saltcedar, 14.62 acres x 0.90	13.16
Area of saltcedar at 100-percent areal density, 13.16 acres x 0.85	11.19
Gross area of baccharis, 14.62 acres x 0.10	1.46
Area of baccharis at 100-percent areal density, 1.46 acres x 0.85	1.24

The vertical density of phreatophytes in the parcel was calculated as follows:

Saltcedar:

$$\frac{\text{Depth of frondage as measured (but not greater than 13 feet)}}{\text{Optimum depth of frondage}}=\frac{13}{13}=100 \text{ percent}$$

Baccharis:

$$\frac{\text{Depth of frondage as measured (but not greater than 5.5 feet)}}{\text{Optimum depth of frondage}}=\frac{4.8}{5.5}=87 \text{ percent}$$

The volume density of the phreatophytes in the parcel is the product of areal density and vertical density.

Area of saltcedar at 100-percent volume density $= 11.19$ acres $\times$ 100 percent $= 11.19$ acres

Area of baccharis at 100-percent volume density $= 1.24$ acres $\times$ 87 percent $= 1.08$ acres

TABLE 7.—*Density of bottom-land vegetation, in percent, 1944*

Reach	Saltcedar			Baccharis			Cottonwood and willow			Mesquite			Brush		
	Areal density	Vertical density	Volume density	Areal density	Vertical density	Volume density	Areal density	Vertical density	Volume density	Areal density	Vertical density	Volume density	Areal density	Vertical density	Volume density
Thatcher to Glenbar	72.2	100	72.2	46.2	100	46.2	55.7	100	55.7	50.3	100	50.3	37.8	100	37.8
Glenbar to Fort Thomas	63.7	100	63.7	26.3	92.7	24.4	39.8	100	39.8	57.6	100	57.6	43.5	100	43.5
Fort Thomas to Black Point	55.0	100	55.0	38.8	100	38.8	59.8	100	59.8	61.1	100	61.1	49.9	100	49.9
Black Point to Calva	54.3	86.2	46.8	27.9	92.7	25.9	35.4	100	35.4	40.9	100	40.9	50.9	100	50.9

TABLE 8.—*Areas of bottom-land vegetation, in acres, 1944*

Reach	Saltcedar		Baccharis		Cottonwood and willow		Mesquite		Brush		Barren	Total	
	Gross area	Area at 100-percent volume density	Gross area	Area at 100-percent volume density	Gross area	Area at 100-percent volume density	Gross area	Area at 100-percent volume density	Gross area	Area at 100-percent volume density	Gross area	Gross area	Area at 100-percent volume density
Thatcher to Glenbar	1,302	940	279	128	235	131	54	27	259	98	30	2,159	1,354
Glenbar to Fort Thomas	1,426	908	266	65	41	16	43	25	147	64	88	2,011	1,166
Fort Thomas to Black Point	852	469	202	78	100	60	263	161	378	189	23	1,818	980
Black Point to Calva	1,002	469	764	198	206	73	624	255	719	366	0	3,315	1,361
Thatcher to Calva	4,582	2,786	1,511	469	582	280	984	468	1,503	717	141	9,303	4,861

The net acreages at 100-percent volume density of all the parcels were then totaled to determine the area of each type of vegetation at 100-percent volume density.

Table 7 shows the average areal density, vertical density, and volume density of phreatophytes, by reaches. Table 8 shows the gross area of each type of plant and the area adjusted to 100-percent volume density, by reaches. The information given in table 8 shows that saltcedar is by far the most abundant phreatophyte in the bottom land. Although saltcedar occupies only about 50 percent of the gross area, it grows more luxuriantly than the other plants and represents about 60 percent of the total growth when converted to the area at 100-percent volume density.

GAGING-STATION RECORDS OF STREAM FLOW

Gaging-station records of stream flow were collected partly to determine the relations between the ground-water reservoir and the flow of the river, but in addition the quantitative data collected in these surface-water studies were used directly in the inflow-outflow method, and the gaging stations on the river provided control points, which aided immeasurably in obtaining accuracy in the seepage-run measurements.

Surface water enters lower Safford Valley by Gila River, by irrigation canals diverting from Gila River above Thatcher, and by washes that drain the bordering mountains. Sometimes the river has no flow in short reaches in the spring and summer. Most of the canals carry water all year except for short periods when they are shut down for cleaning or repairs and for periods when diversion is not permitted under the Gila River decree [14] or when the river is dry. The washes have no appreciable surface-water flow most of the time, but in their lowermost reaches some of the larger washes often carry low flows derived principally from ground-water seepage and from waste or return irrigation water. The washes usually carry flood flows for a few hours during or following rainstorms in their drainage areas. The area drained by the washes tributary to Gila River between Thatcher and Calva is about 1,000 square miles.

For convenience of study, lower Safford Valley was divided by gaging stations into four reaches, as follows: (1) From Thatcher to near Glenbar, 10.6 miles; (2) from near Glenbar to Fort Thomas, 11.1 miles; (3) from Fort Thomas to Black Point, 9.9 miles; and (4) from Black Point to Calva, 14.2 miles. The distances were measured along the river. Gaging stations were also established on the canals at the ends of each reach. The end of each reach was an irregular line across the valley passing through a river gaging station and its associated canal gaging

[14] The District Court of the United States, in and for the District of Arizona, No. E-59-Globe, 1935.

stations (see pls. 2 and 3). In addition, a gaging station was operated on the river within each reach. As a result of this arrangement, daily discharge records are available for the gaging stations and the periods listed below. The stations are listed in downstream order, first for the river, then for the canals.

Gila River near Thatcher, June 1943 to February 1944.
Gila River at Pima, June 1943 to February 1944.
Gila River near Glenbar, June 1943 to October 1944.
Gila River near Ashurst, June 1943 to September 1944.
Gila River at Fort Thomas, June 1943 to October 1944.
Gila River near Geronimo, June 1943 to October 1944.
Gila River at Black Point, near Geronimo, June 1943 to September 1945.
Gila River at Bylas, June 1943 to March 1944.
Gila River at Calva, October 1929 to —.[15]

- Graham Canal near Thatcher, July 1943 to February 1944.
- Smithville Canal near Thatcher, July 1943 to February 1944.
  - Smithville Canal waste near Thatcher, July 1943 to February 1944.
- Union Canal near Thatcher, July 1943 to February 1944.
  - Union Canal diversion along Ray Lane, near Thatcher, July 1943 to February 1944.
- Curtis Canal near Glenbar, July 1943 to September 1944.
- Fort Thomas Consolidated Canal near Glenbar, July 1943 to October 1944.
- Fort Thomas Consolidated Canal at Fort Thomas, July 1943 to December 1944.
- Dodge-Nevada Canal near Glenbar, July 1943 to September 1944.
- Colvin-Jones Canal near Fort Thomas, July 1943 to December 1944.

Except for the gaging station at Calva, which was equipped with a continuous water-stage recorder, each gaging station had a Stevens type F weekly water-stage recorder housed in a small shelter mounted on a gage well. Most of the wells consisted of 18-inch culvert pipe, but a few were of wood-frame construction. Most of the gage wells on Gila River were held in place by lengths of railroad rail driven into the stream bank, one length on the upstream side of the well and one on the downstream side.

For the purposes of the investigation, records of high discharge were not necessary. Therefore, daily discharge was not computed for those days on which the peak discharge exceeded 1,000 second-feet for stations on Gila River near Thatcher, near Glenbar, at Fort Thomas, at Black Point for the water year 1944, and at Bylas, nor for those days on which the peak discharge exceeded 200 second-feet for stations on the Gila River at Pima, near Ashurst, near Geronimo, and at Black Point prior to October 1, 1943.

No discharge records were computed for any wash, but gage-height records for the few medium and high flows were obtained from August 1943 to October 1944 on the five largest washes in lower Safford Valley

[15] Station was still being maintained in 1949.

—Cottonwood, Markham, Matthews, Black Rock, and Goodwin Washes.

The following daily discharge records collected for the investigation in 1943-44 have been published:[16] Combined flow of Gila River and canals across valley sections near Thatcher, near Glenbar, and at Fort Thomas; Gila River at Black Point; and, for the water year 1944 only, Gila River at Calva. Records for the Gila River at Calva for the water year 1943 were published in Water-Supply Paper 979. Records collected for the investigation which have not been published, but which are referred to and used in this report, are in the open files of the Geological Survey.

The relation between gage height and discharge at most of the gaging stations shifted frequently, sometimes by large amounts. At stations where this relation was unstable, discharge could not be computed accurately unless current-meter measurements were made frequently. Accordingly, the general practice was to make discharge measurements at each station twice a week. Additional measurements were made, especially during the summer of 1944, during periods of rapidly fluctuating discharge. Records of river discharge used in the investigation are based on more than 1,000 current-meter measurements. Records of canal discharge are based on more than 700 current-meter measurements.

The daily discharge records are, in general, accurate within 10 percent, except for short periods of missing gage-height record or periods when the discharge was less than 2 second-feet. Records of discharge of less than 2 second-feet may not be accurate within 10 percent and yet may be entirely satisfactory for practical application. The records for periods of a month or more are, in general, more accurate than those of daily discharge.

OBSERVATION WELLS

A comprehensive network of observation wells was constructed by the Phelps Dodge Corp. from Thatcher to the San Carlos reservation line in order to measure changes in storage in the ground-water reservoir of the bottom-land area, to determine the quantity and direction of movement of ground water, and to determine the chemical quality of the ground water. Each well was 1½ inches in diameter, with a 60-gage, 3-foot sand point at the bottom. The wells were driven between March and June 1943. All of them penetrated the water table about 10 feet. The wells were spaced approximately 600 feet apart in the bottom land and at somewhat greater distances on cultivated lands.

[16] Surface water supply of the United States, 1944, part 9, Colorado River Basin: U. S. Geol. Survey Water-Supply Paper 1009, pp. 297-302, 1945.

In the summer of 1943, shortly after the wells were driven, all of them were pumped with a hand-operated pump until the water became clear. This was done in order to insure free circulation of water into the wells and to obtain representative water samples for analysis. The process was repeated in April and May 1944 for the wells being observed at that time.

The wells were grouped in 22 zones and numbered within each zone. For zones 1-10, each zone was a mile wide and consisted of a tier of sections extending from south to north across the river. Zones 9 and 10 were terminated by the line between Tps. 5 and 6 N. For zones 11-22, each zone was a mile wide and consisted of a tier of sections north of the line between Tps. 5 and 6 N., extending from east to west across the river. Only a small corner of zone 10 lay within the bottom land, and there were only two wells in the zone. The numbers within each zone were assigned in the order in which the wells were driven. A typical well number, 3-8 for example, represents the eighth well put down in zone 3.

A total of 1,331 wells were driven for the investigation, and observations were made in 95 other wells, of which 10 were in the San Carlos reservation. Some of these other wells were installed by the Geological Survey in 1940,[17] and some were privately owned. Thus, 1,426 wells were available for measurement of water level during this investigation. However, not all the wells were in use for observation at any one time. Many of them had to be abandoned for one reason or another. Some did not function properly because they became filled up or the screen became clogged, and others were buried, destroyed, or removed because they interfered with farming operations or the clearing of new land.

The altitude of the measuring point of each well, which in nearly all cases was the top of the pipe, was determined by instrumental leveling. The distance of the measuring point above the land surface was also determined. Thus, for any well it was possible to compute the elevation of the water table above sea level or the depth to the water table below the land surface. The location and distribution of the observation wells are shown on plates 2-5. There were so many wells in the bottom land that numbers for all could not be shown on the maps, and the only wells so numbered are those discussed in the report or for which tables or graphs have been prepared.

FREQUENCY OF MEASUREMENTS

From March 1943 to about September of that year measurements of water levels in all observation wells were made at weekly intervals. During September a group of about 80 key wells, which were to be measured weekly, and another group of about 20 wells, which were to be

[17] Turner, S. F., and others, Water resources of Safford and Duncan-Virden Valleys, Ariz. and N. Mex., p. 13, U. S. Geol. Survey, 1941. (See list of studies, p. 5.)

measured twice a month, were selected. The remaining wells were measured once a month. This program of water-level measurements was continued until March 1944. After March 1944 measurements were discontinued in all wells in the reach from Thatcher to Glenbar except those observed weekly and semimonthly. Measurements of water levels in all observation wells were discontinued on October 28, 1944, except for monthly measurements in those observation wells which had been measured regularly since 1939-40. During the investigation about 41,200 measurements of water level were made in the observation wells.

TRANSPIRATION WELLS

Records of the daily fluctuations of the water table in the phreatophyte-covered parts of the bottom land were needed for computations by the transpiration-well method. For this purpose 29 shallow wells were bored in 1943 and 5 in 1944. Not all of them produced usable records. Some went dry and could not be deepened because of large rocks. Others were affected to such an extent by waste water from irrigation or by fluctuations in flow of the Gila River that the records were not representative of the daily fluctuations of the water table and therefore could not be used. The wells were designated with the prefix "T" (T-4, for example). Records from 18 of them were used in compiling this report; the location of these wells is shown on plates 2, 4, and 5, and their location, the range of water-level fluctuation, and the type and volume density of the vegetation surrounding each well are given in table 31.

The wells were bored by hand with an 8-inch auger and penetrated the water table about 2 feet. It was planned to bore the wells deep enough so that they would not go dry during the growing season. However, the water table declined below the expected level, and it became necessary to deepen some of them.

Samples of the materials encountered in each well were collected, one sample for each foot of depth. The physical properties of the samples from the zone of fluctuation of the water table were determined later in the laboratory.

Each well was cased with medium-weight galvanized-iron casing, which extended from the bottom of the well to about 1 foot above the land surface. The bottom 1½ feet of the casing was perforated with nail holes on 2½-inch centers. Heavy screen wire was stretched over the tops of the casings to prevent small animals from falling into the wells. A Stevens type F weekly recorder, protected with a metal cover, was installed over each well on a rectangular wooden stand about 2½ feet high, with sides and top enclosed. Each recorder was so geared that the water-level fluctuations on the recorder chart were reproduced on a natural scale (1:1 ratio).

GLENBAR EXPERIMENT STATION

To determine use of water by bottom-land vegetation by the tank method, an experiment station was installed in the spring of 1943 by the Phelps Dodge Corp. near Glenbar in the bottom land. (See pl. 2.) This experiment station was modeled after the smaller experiment station installed near Safford by the Geological Survey in the spring of 1940. The experience gained at the Safford station was of value in the design and operation of the Glenbar experiment station. The depth to the water table in the Glenbar area was about 8 feet. The site for the station was chosen by A. T. Barr, chief engineer, New Cornelia Branch of the Phelps Dodge Corp., R. A. Hill and W. W. Lane, consulting engineers, Phelps Dodge Corp., H. F. Blaney, senior irrigation engineer, Soil Conservation Service, and S. F. Turner, district engineer, Ground Water Branch of the Geological Survey. They sought to establish the station in the midst of representative phreatophyte growth near the center of the area under investigation, and where it would be readily accessible.

FIGURE 12.—Looking northeast along axis of natural clearing at Glenbar experiment station. Workmen are constructing weather station. Soil tanks in center; tanks containing vegetation in thicket to right. Photograph by S. F. Turner.

The axis of the station was a natural elongated clearing (see fig. 12) trending N. 57° E., in a dense thicket of saltcedar and baccharis near an area containing nearly every type of phreatophyte studied. The station was located in a rectangular plot 227 by 442 feet, surrounded by a

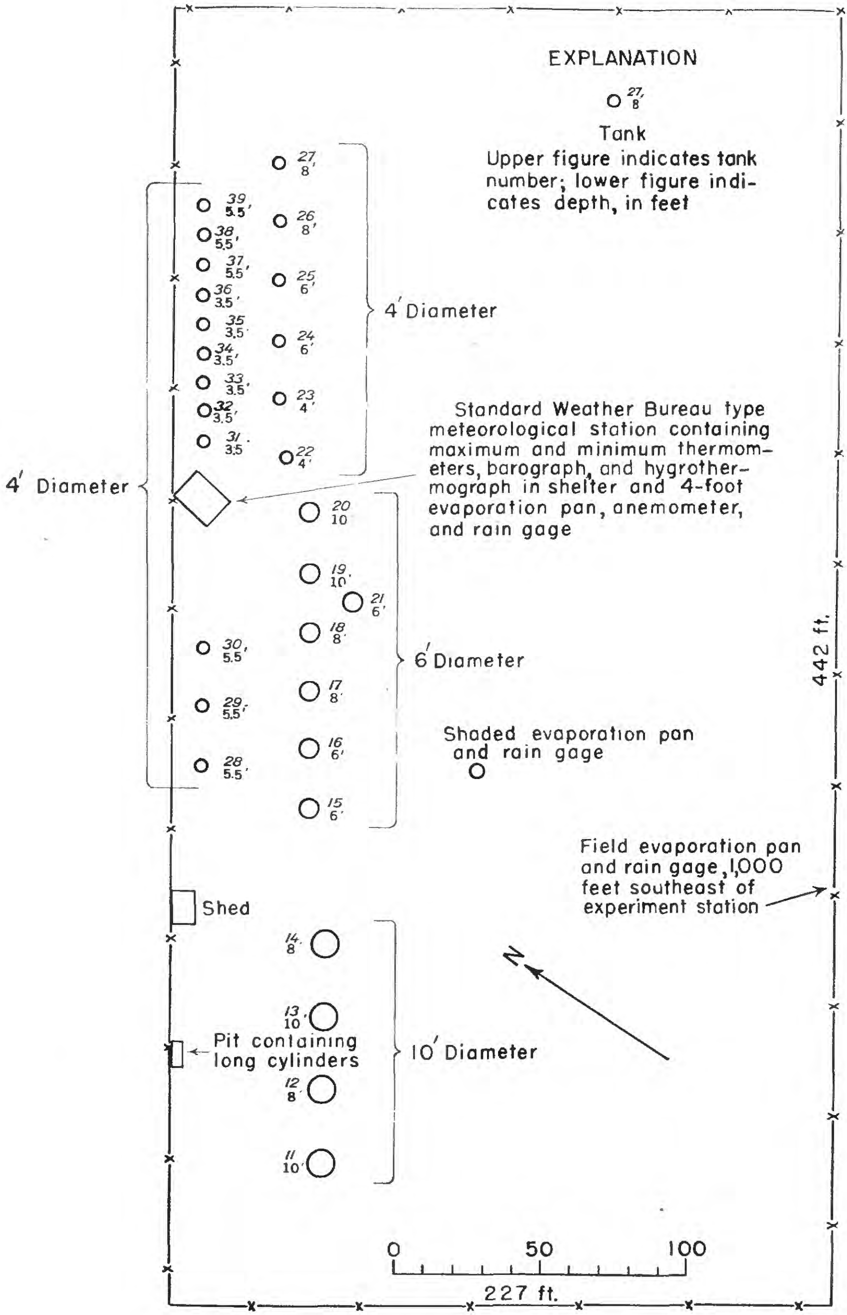

FIGURE 13.—Plan of Glenbar experiment station

wire fence 5 feet high with two large gates. At the station 29 sunken soil tanks (numbered 11 to 39), a United States Weather Bureau standard class A meteorological station, a water-distributing system, and a tool shed were installed (see fig. 13). Soil tank numbers began with 11 to avoid confusion with tanks 1-10 at the Safford experiment station, established by the Geological Survey in 1940 near Gila River bridge at Safford.

The meteorological station included a standard class A evaporation pan with hook gage, a three-cup anemometer, a standard rain gage, an instrument shelter, maximum and minimum thermometers, hygrothermograph, and microbarograph. A three-terminal soil thermograph was available at the station for determining soil temperatures. There were several Stevens type F weekly water-stage recorders, which were moved from tank to tank as needed for special studies. In addition, one class A evaporation pan and a rain gage were installed in a thicket to obtain records of evaporation and rainfall under shaded conditions (shaded pan, table 3), and another class A evaporation pan and a rain gage were installed in a large open tract 1,000 feet southeast of the experiment station to obtain records of evaporation and rainfall in an exposed area (field pan, table 3).

The tool shed was an open-sided building. The water-distributing system consisted of a buried tank for water storage, an air compressor to furnish pressure, and a distribution network with faucets near the tanks. Water was hauled by truck from the public water supply for Pima, as the local ground water was highly mineralized.

INSTALLATION OF TANKS

The tanks that were to contain phreatophytes, nos. 11-27, were located along the edge of the natural thicket, and the tanks that were to contain bare soil, nos. 28-39, were located along the axis of the clearing. The areas for the pits were outlined and cleared, but care was exercised to clear away no more natural vegetation than was actually necessary for installation of the tanks. The pits were excavated to a diameter approximately 1 foot greater than that of the respective tanks. During the excavating the material removed was placed in numbered individual piles, one pile for each foot of depth or for each type of material. Samples from each pile were collected for laboratory analysis of physical properties. The depth of the pits was such that the tanks, when in position, would extend about a foot above the ground surface for protection against local surface runoff. The bottoms of the excavations were leveled (see fig. 14) and inspected for boulders or debris that might injure the bottoms of the tanks. The deeper excavations extended below the water table, and cribbing was required to prevent caving.

The tanks were 10, 6, and 4 feet in diameter and 10, 8, 6, 5½, 4, and 3½ feet deep (see fig. 13). All but the tanks 10 feet in diameter were of 18-gage galvanized metal; the 10-foot tanks were 16-gage. The tanks were smooth inside, with riveted and soldered watertight seams. The top of each tank was constructed as shown in figure 15, in order to reduce the amount of surface exposed to the rays of the sun and yet pro-

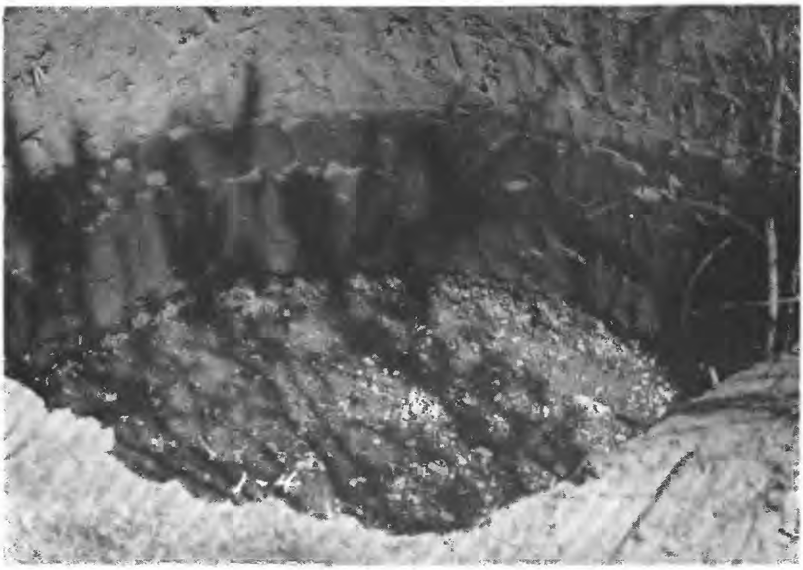

FIGURE 14.—Excavation for tank 14, Glenbar experiment station, showing materials encountered and upper part of capillary fringe of the water table. Photograph furnished by Phelps Dodge Corp.

vide strength against buckling. The tanks were tested for leaks and painted with one coat of red primer and one coat of black protective paint, inside and out. They were lowered into the excavations carefully to prevent damage that might cause leaks, and particular care was used to avoid scratching or breaking the coating of paint.

After each tank was in place, the bottom was covered with a 1-inch layer of screened sand for protection (see fig. 15).

A well of 28-gage galvanized metal 4 inches in diameter was then fastened vertically at the north side of each tank 1 inch from the wall, extending from 4 inches above the bottom of the tank to approximately 2 feet above the top of the tank. The lower 6 inches of each well was perforated with 30 holes, three-sixteenths of an inch in diameter, and a cover was made to protect the upper end. These wells were used to add water to the tanks and are therefore called "recharge wells" in this report. After the recharge well was installed, a 6-inch layer of gravel of a size passing a ¾-inch screen and retained on a ½-inch screen was added

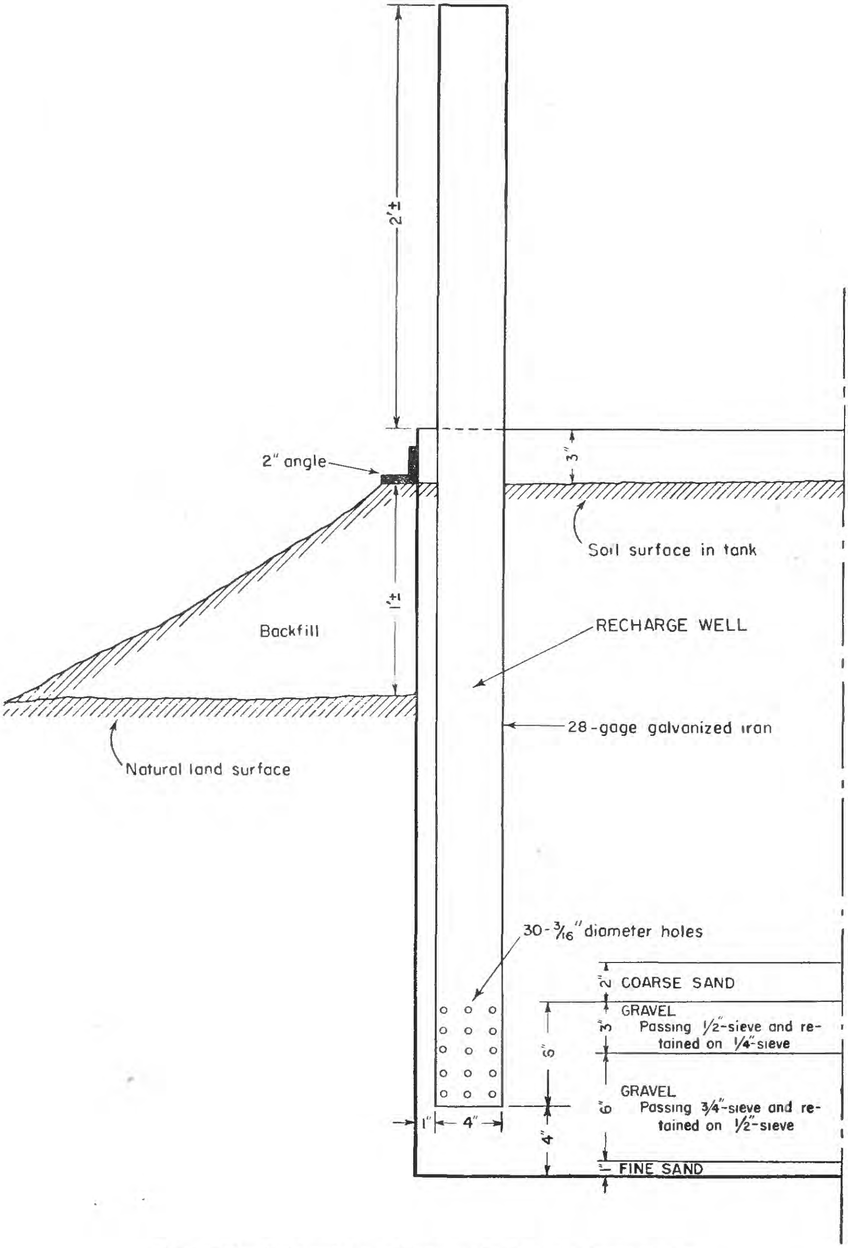

FIGURE 15.—Sectional view of tank at Glenbar experiment station.

to each tank; next a 3-inch layer of gravel of a size passing a ½-inch screen and retained on a ¼-inch screen was added; and then a 2-inch layer of coarse screened sand was added. The gravel was a distributing medium for water added to the recharge well, so that the water rose uniformly over the entire area of the tank. The overlying sand prevented the soil in the tank from filtering down into the gravel.

FIGURE 16.—Balled young cottonwood trees in tank 13, Glenbar experiment station. The burlap covering was slit open before backfilling proceeded. Photograph by J. F. Hostetter.

The materials excavated from the pits were then placed in the tanks on top of the layer of coarse sand in reverse order of excavation up to proper planting depth (see fig. 16). The materials were replaced under water (see fig. 17) to prevent formation of air pockets and to insure that the materials settled in a manner similar to that in which they were laid down by the river.

Three species of phreatophytes were transplanted: Saltcedar into tanks 11, 12, and 15-21, baccharis into tanks 22-27, and cottonwood into tanks 13 and 14. Representative clumps or individual plants were selected nearby, and the root systems were balled according to standard nursery methods. The balled plants were transported to the tanks and planted as rapidly as possible to minimize wilting from the heat, as the growing season was well advanced when the work was done. During the transplanting the plants were shaded with canvas, as daytime temperatures ranged from 90° to 103° F. Only one tank was planted at a time, so that transplanting could be accomplished rapidly. Despite the high temperatures and the fact that the season was well advanced, the transplanting, which was under the direction of J. F. Hostetter, was successful.

FIGURE 17.—Backfilling soil tank under water to insure elimination of air pockets. Photograph by T. W. Robinson.

After the plants were in each tank, the remaining part of the excavated material was replaced, under water, to within 3 inches of the rim of the tank. The excess material was then backfilled around the outside of the tank up to the reinforcing flange (see fig. 15).

Tanks 28-39 contained no plants. Tanks 28-30, 35, 36, and 39 were filled with material from their respective excavations, being filled under water from the numbered piles. Tanks 31 and 32 were filled with gravel from the channel of Gila River. Tanks 33, 34, 37, and 38 were filled with clay loam from nearby cultivated fields.

Operation of the Glenbar experiment station was begun July 1, 1943. However, the records from the tanks containing plants were of little value prior to September 1, 1943, as 2 months was needed for the plants to become accustomed to their new environment and to recover from the shock of transplanting. The station was operated until November 15, 1944, although a severe flood on September 25 of that year inundated the station to a depth of 3 feet and made subsequent records of water use valueless.

MEAN PRECIPITATION AND EVAPORATION BY REACHES

Evaluation of the precipitation and evaporation records was necessary before the records from the individual weather stations could be applied to the bottom land. Figures by time periods for mean precipitation in each reach were needed for the inflow-outflow method, and a figure of mean precipitation in each reach was needed for the period for which use of water was computed by all six methods. Figures of evaporation by periods were needed for the inflow-outflow method, and daily evaporation rates, for the days of the seepage runs, were needed for the three methods that utilized seepage-run figures.

PRECIPITATION

Rain gages were placed at several points in lower Safford Valley during the investigation, and the measurements of precipitation in these gages are given in table 2. The gages at Pima bridge, Geronimo gaging station, and Calva were metal cans 6.5 inches in diameter containing a thin film of oil to reduce evaporation between the time of precipitation and the time of measurement. The gages at the other stations were standard Weather Bureau copper nonrecording containers. With the exception of the gages at the Glenbar experiment station at which precipitation was observed daily, measurements of rainfall were usually made at weekly or semiweekly intervals.

The weighted mean precipitation for each reach of the valley was computed. The weight assigned to the measurements from each gage was based on the distance between gages and on the relative accuracy of measurements in the gages. The 6.5-inch cans were less accurate indicators of precipitation than the standard rain gages and were assigned lower weights. The weights assigned to each of the gages, by reaches, follow:

Thatcher-Glenbar reach:
- Safford evaporation station....................................1
- Pima bridge (incomplete record)............................0
- Glenbar experiment station, weather-station gage..............1

Glenbar-Fort Thomas reach:
- Glenbar experiment station, weather-station gage..............1
- Fort Thomas..1

Fort Thomas-Black Point reach:
- Fort Thomas..2
- Geronimo gaging station......................................4
- Bylas..1

Black Point-Calva reach:
- Geronimo gaging station......................................1
- Bylas..3
- Calva..2

Table 9 gives mean precipitation for each of the four reaches, by months and by fractions of some months.

Table 10 shows the precipitation, in inches and in acre-feet, for the

TABLE 9.—*Mean precipitation, in inches, in lower Safford Valley, 1943-44*

Period	Reaches			
	Thatcher-Glenbar	Glenbar-Fort Thomas	Fort Thomas-Black Point	Black Point-Calva
1943				
July	1.79	2.15	[1] 1.50	[1] 0.40
August	2.56	2.86	2.43	2.56
September	2.02	2.21	1.82	1.39
October	.20	.10	.07	.39
November	0	0	.03	.10
December	.94	1.06	1.00	1.10
August 18-23	0	0	0	.09
September 1-25	.48	.39	.44	.19
1944				
January	.36	.30	.26	.42
February	.40	.56	.51	.60
March	.65	.55	.46	.61
April	.12	.22	.46	.51
May	.16	.18	.32	.40
June	.08	0	.02	.06
July	2.05	1.45	1.65	1.84
August	1.12	1.05	1.58	1.52
September	4.42	1.51	2.88	2.08
August 1-15	.84	.88	.90	.72
August 22-31	.05	.04	.44	.12
September 1-22	.54	.28	.40	.49

[1] Estimated.

TABLE 10.—*Total precipitation on phreatophyte-covered part of the bottom land by reaches, October 1, 1943, to September 22, 1944*

Reach	Gross area (acres)	Precipitation (inches)	Precipitation (acre-feet)
Thatcher to Glenbar	2,159	6.62	1,190
Glenbar to Fort Thomas	2,011	5.75	964
Fort Thomas to Black Point	1,818	6.76	1,020
Black Point to Calva	3,315	8.04	2,220
Thatcher to Calva	9,303	....	5,390

phreatophyte-covered part of each reach for the period October 1, 1943, to September 22, 1944. Nearly all the precipitation on the phreatophyte-covered part of the bottom land was evaporated or transpired, and little or none infiltrated to the ground-water reservoir or left the area as surface runoff during the investigation. For this reason the figures for precipitation in acre-feet must be added to the figures for draft on ground water, as computed by each of the six methods, to obtain total use of water. The unusually heavy rainfall during the period September 22-30, 1944, was not included, because the precipitation during that period could not possibly have been transpired or evaporated by September 30, the date that marked the close of the 12-month period for which use of water was computed by most of the methods.

Table 10 does not include the precipitation on the river surface and on wet sand bars, as this precipitation is not a part of the use of water by bottom-land vegetation. However, this precipitation was needed in the computation of use of water by the inflow-outflow method. On the basis of areas for river surface and sand bars computed as described immediately following, figures of precipitation from October 1, 1943, to September 22, 1944, on the river surface and on wet sand bars were: Glenbar-Fort Thomas reach, 62 acre-feet; Fort Thomas-Black Point reach, 90 acre-feet; Black Point-Calva reach, 118 acre-feet. Figures for the Thatcher-Glenbar reach were not computed as the inflow-outflow method was not applied to that reach.

EVAPORATION

Records from four evaporation pans used during the investigation are given in table 3. The pans were of the standard Weather Bureau class A type. The total evaporation for each reach was based on the rate of evaporation from the weather-station pan at the Glenbar experiment station and on the computed area for which evaporation was to be determined. Coefficients were applied to the pan figures so that they would represent evaporation from the river surface or from wet sand bars. Figures for this evaporation were needed in order to correlate discharge of the river with inflow to the river from the ground-water reservoir.

RIVER SURFACE

The area of the river surface for any stage was computed by preparing curves of discharge versus river-surface area, a curve for each reach. The discharge was known for December 10, 1942, the day that the aerial photographs were taken, and the area of the river surface was measured on the photographs. As the discharge was high on that day, this gave a point for each reach that defined the upper end of the curve for that reach. A second point on each curve was determined by estimating, on the basis of field observations, the area of river surface at a discharge of 25 second-feet. The curves also were extended below 25 second-feet by estimating areas. An estimate of the area of river surface could be determined from the finished curves for any discharge within the range of the curves.

The coefficient applied to figures of evaporation from the pan to determine evaporation from the river surface was the product of two adjustments. The first adjustment, to convert the class-A pan record to apply to the open-water surface of a reservoir was 0.70, based on the work of Sleight.[18] Sleight noted further[19] that evaporation from a flowing stream was 1.075 times the evaporation from the open-water surface of a reservoir. Therefore, the coefficient used in this report to convert evaporation from the weather-station pan to evaporation from the river surface was 0.70 times 1.075, or 0.75.

WET SAND BARS

The area of wet sand bars in each reach was computed as 85, 81, 100, and 110 acres, respectively, for the four reaches in downstream order. The wet sand bars were assumed to be strips of uniform width on each side of the river for the length of each reach.

The coefficient to be applied to evaporation from the weather-station pan to convert to total evaporation from wet sand bars was the arithmetical product of (1) a coefficient that related evaporation from the pan to evaporation from the bare soil tanks at the Glenbar experiment station, and (2) a coefficient that related evaporation from the bare soil tanks to the evaporation from wet sand bars. The average depth to water in the area occupied by wet sand bars was about 1 foot, and data from the tank experiments indicated that evaporation for this depth was 0.83 times the evaporation from the class-A pan at the weather station.

Selection of the coefficient to convert from tank conditions to field conditions was based on an analogy: Evaporation from a sunken bare soil tank was assumed to bear the same relation to evaporation from wet sand bars along the river as evaporation of water from a sunken land pan bears to evaporation from a reservoir. This analogy was employed because no data are known that give the relation between evaporation from bare soil tanks and evaporation from wet sand bars. The coefficient chosen was 0.86, based on experiments to determine the relation between evaporation from a sunken land pan and a reservoir. The experiments were performed at Denver and Garrett, Colo., and

[18] Sleight, R. B., Evaporation from the surface of water and river-bed materials: Jour. Agr. Research, vol. 10, pp. 209-262, 1917.

[19] Idem., p. 229.

TABLE 11.—*Daily mean evaporation rates by reaches for selected dates, 1943-44*

Thatcher-Glenbar		Glenbar-Fort Thomas		Fort Thomas-Black Point		Black Point-Calva	
Date	Evaporation (feet per day)	Date	Evaporation (feet per day)	Date	Evaporation (feet per day)	Date	Evaporation (feet per day)
1943		*1943*		*1943*		*1943*	
June 24	0.0309	June 24	0.0309	June 24–25	0.0311	June 25	0.0306
Sept. 16–17	.0266	Sept. 17	.0278	Sept. 17–18	.0243	Sept. 18	.0217
Nov. 4	.0104	Nov. 5	.0141	Nov. 9	.0148	Nov. 9	.0148
Nov. 25	.0088	Nov. 26	.0079	Nov. 23	.0086	Nov. 23	.0086
Dec. 13	.0044	Dec. 16	.0088	Dec. 14	.0062	Dec. 14	.0062
1944		*1944*		*1944*		*1944*	
Jan. 13	.0051	Jan. 14	.0056	Jan. 15	.0052	Jan. 15	.0052
Feb. 14	.0102	Feb. 15	.0084	Feb. 18	.0100	Feb. 18	.0100
Mar. 15	.0141	Mar. 16	.0138	Mar. 17	.0104	Mar. 17	.0104
Apr. 12	.0212	Apr. 13	.0233	Apr. 14	.0234	Apr. 14	.0234
May 3	.0320	May 4	.0271	May 5	.0248	May 5	.0248
May 24	.0273	May 25	.0274	May 26	.0271	May 26	.0271
June 21	.0324	June 22	.0309	June 23	.0295	June 23	.0295
Oct. 28, 30	.0096	July 17	.0338	July 18	.0266	July 18	.0266
		Aug. 7	.0239	Aug. 8	.0141	Aug. 8	.0141
		Oct. 26	.0088	Oct. 27	.0108	Oct. 27	.0108

All measurements except June 24-25, 1943, from weather-station pan at Glenbar experiment station; June 24-25, 1943, from Safford evaporation station. Figures given are the mean for three days—the day indicated, the day before, and the day after.

East Park, Calif., as reported by Hall.[20] Combining the two coefficients, evaporation from the wet sand bars was 0.83 times 0.86, or 0.71 times the evaporation from the class-A pan at the weather station. The final coefficient was rounded to 0.70 in all the computations of evaporation from wet sand bars.

APPLICATION OF COEFFICIENTS

Two types of figures for evaporation from the river surface and wet sand bars were needed. The methods based on seepage runs required figures for rate of evaporation in second-feet at the time of each seepage run, and the inflow-outflow method required figures for volume of evaporation in acre-feet for definite periods of time. Table 3 shows the evaporation from the weather-station pan by months, table 11 shows evaporation from the weather-station pan by daily rates for selected days, and table 12 shows evaporation from the weather-station pan for selected periods. In determining the daily rate of evaporation in table 11, the rate given is the mean for three days—the day of the seepage run, the day before, and the day after.

Evaporation in second-feet was computed as follows:

$$\frac{\text{Pan evaporation in feet per day} \times \text{coefficient} \times \text{area in acres}}{1.983471 \text{ (acre-feet per second-foot day)}} = \text{evaporation in second-feet}$$

Evaporation in acre-feet was computed as follows:

$$\text{Pan evaporation during desired unit of time, in feet} \times \text{coefficient} \times \text{area in acres} = \text{acre-feet evaporated}$$

TABLE 12.—*Evaporation from weather-station pan during selected periods, Glenbar experiment station, 1943-44*

Period	*Evaporation (inches)*
1943:	
August 18-23	1.509
September 1-25	6.511
1943-44:	
December 14–January 13	2.056
1944:	
January 14–February 15	3.089
February 16–March 15	4.152
August 1-15	5.145
August 22-31	3.475
September 1-22	5.936

[20] Hall, L. S., discussion in Rohwer, Carl, Evaporation from different types of pans: Am. Soc. Civil Eng. Trans., vol. 99, table 16, p. 729, 1934.

As evaporation from the phreatophyte-covered part of the bottom land is closely related to transpiration, figures for evaporation in this part of the bottom land were not computed separately. However, evaporation from the river surface and wet sand bars is a factor that must be considered in the inflow-outflow method. Figures of evaporation have been computed for the 352-day period October 1, 1943, to August 15, 1944, and August 22 to September 22, 1944, for the three lower reaches as follows: Glenbar-Fort Thomas, 550 acre-feet; Fort Thomas-Black Point, 692 acre-feet; Black Point-Calva, 807 acre-feet.

GROUND-WATER RESERVOIR

The measurements of water levels that were made in the observation wells provided data from which the general configuration of the water table could be determined. From this, conclusions can be drawn regarding the source, movement, and discharge of the ground water.

EXTENT

There are two distinct ground-water reservoirs in the Safford Basin. The larger of these is in the older alluvial fill that forms the bulk of the deposits in the basin. The smaller ground-water reservoir is in the alluvial fill of the inner valley of Gila River, and it is this reservoir to which reference is made hereafter unless the larger reservoir in the older alluvial fill is specifically mentioned. The boundaries of the ground-water reservoir of the inner valley were determined during the investigation of 1939-41 [21] by geologic field mapping from aerial photographs. In 1943-44 these boundaries were checked by use of the large-scale maps prepared during the investigation, the aerial photographs, well logs, water analyses, and field studies. The areal extent of the ground-water reservoir of the inner valley was determined for lower Safford Valley by plotting the boundaries on a large-scale map (1:7,200) and measuring the area with a planimeter. The areal extent by reaches, both for the bottom land and for the entire ground-water reservoir, is given in the following table:

TABLE 13.—*Areal extent, in acres, of bottom land and of ground-water reservoir in lower Safford Valley, Ariz.*

Reach	*Bottom-land—phreatophyte-covered area, river channel, and bars*	*Total area of ground-water reservoir*
Thatcher-Glenbar	2,626	13,850
Glenbar-Fort Thomas	2,265	10,550
Fort Thomas-Black Point	2,218	6,050
Black Point-Calva	7,700	7,700
Total	14,809	38,150

[21] Turner, S. F., and others, Water resources of Safford and Duncan-Virden Valleys, Ariz. and N. Mex., p. 23, U. S. Geol. Survey, 1941. (See list of studies, p. 5.)

GENERAL CONFIGURATION OF THE WATER TABLE

The following discussion is based on contours that depict the shape of the water table on February 16, 1944, which was approximately the date of the highest stage of the water table during the winter of 1943-44. Plate 4 shows these contours and also a set of contours that depict the shape of the water table on June 22, 1944, during the period of lowest water levels in that year. For wells that were not measured on February 16 and June 22, the water levels were determined by interpolation from measurements made before and after those dates.

In general, the water table slopes toward the river and downstream. It slopes much less steeply toward the river than does the land surface. The depth to water below the land surface ranges from about 50 feet near the edges of the valley to 1 foot or less at places along the river channel. Upstream from localities where the valley fill becomes narrow, part of the underflow [22] is forced to enter the river, and the slope of the water table toward the river increases. Where the valley fill is narrow, the slope of the water table is downstream, parallel to the general course of the river. Where the valley widens, water from the river recharges the widening valley fill, and the water table slopes away from the river. Farther downstream in these wider reaches the water table generally slopes toward the river, except during periods of high flow in the river. The general slope of the water table is also influenced by the permeability of the aquifer and by irrigation and canal seepage, underflow from the various washes, upward percolation of deep-seated artesian water, pumping from wells, and the draft of bottom-land vegetation.

In addition to the evidence afforded by the water-level contours, the results of seepage investigations during 1943 and 1944 provide indications of the direction of movement and rate of flow of ground water. In the reaches from Thatcher to Glenbar and from Fort Thomas to Black Point the Gila River is always a gaining stream. In the reach from Glenbar to Fort Thomas the river is a losing stream during June, July, and August and a gaining stream the rest of the year. In the reach from Black Point to Calva the river is a losing stream from May to November, inclusive, and a gaining stream the rest of the time. These varying gains and losses are the result of a combination of the factors that influence the water table in such a manner that at times the slope of the water table may be toward the river and at other times away from it. Similarly, these factors may operate to flatten or steepen a slope that is always toward or always away from the river.

A more detailed discussion by reaches of the configuration of the water table on February 16, 1944, follows.

[22] Meinzer, O. E., Outline of ground-water hydrology, with definitions: U. S. Geol. Survey Water-Supply Paper 494, pp. 43-44, 1923.

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REACH FROM THATCHER TO GLENBAR

South side of river.—In the reach from Thatcher to Glenbar the water table always slopes toward the river, generally at a gradient of 10 to 20 feet per mile. Northwest of Thatcher near the river the water table is very close to the land surface, and drains have been installed. These drains, together with pumping from irrigation wells, are necessary to depress the water table so that land can be farmed in that area. Near Pima the slope of the water table toward the river is very steep. This steep slope results from the large amount of underflow entering the valley from Ash Creek and Cottonwood Wash and from the lower permeability of the poorly sorted alluvium that has been brought into the valley by these washes. The slope of the water table becomes parallel with the course of the river at the point where the valley fill becomes extremely narrow at the mouths of Matthews and Markham Washes. A part of the underflow is forced to the surface above these narrows. Below the narrows the slope of the water table is away from the river, as the valley widens and the flow in the river recharges the increased volume of alluvium.

North side of river.—On the north side of Gila River, from the vicinity of Thatcher to the vicinity of Central, the slope of the water table is parallel to or away from the general course of the river, because the valley fill widens and the river loses some flow to recharge this fill. From north of Central to the narrows at the mouths of Matthews and Markham Washes the water table slopes toward the river as a result of underflow entering the valley from several large washes. Deep-seated artesian water also may enter the alluvial fill of the inner valley in this area through seepage along fault zones. Through the narrows the gradient of the water table becomes parallel to the general course of the river, and further downstream the gradient is away from the river, as the valley fill widens.

REACH FROM GLENBAR TO FORT THOMAS

South side of river.—At the upper end of the reach the slope of the water table is away from the river. Farther downstream the slope of the water table is in a downstream direction, neither toward nor away from the river, with an average gradient of about 6 feet per mile. In the lower third of the reach the water table begins to slope toward the river, mainly because a part of the underflow of Black Rock Wash enters the valley in this vicinity. The narrowing of the valley, which forces a part of the valley underflow to the surface, is also a contributing factor.

North side of river.—About 1 mile south and west of Eden, there is a large downstream bulge or ridge in the water table, probably caused by artesian water entering the valley fill along a fault in the older alluvial fill. The increased total mineral content of the ground water in this area also suggests the possibility of artesian inflow. Downstream from this ridge the slope of the water table is neither toward nor away from the river to about the middle of the reach. In the lower part of the reach the water table slopes toward the river as a result of upward seepage of artesian water along the edges of the inner valley from faults in the older alluvial fill. The location of most of the seepage areas is hidden by the valley alluvium.

REACH FROM FORT THOMAS TO BLACK POINT

South side of river.—In the upper part of the reach the water table slopes moderately toward the river as a result of underflow from Black Rock Wash. The underflow of Black Rock Wash apparently divides south of the river valley, and part of it enters the valley southeast of Fort Thomas and part northwest of Fort Thomas. The underflow from Goodwin Wash causes a very steep gradient toward the river, almost a ground-water cascade, at Geronimo. West of Geronimo the slope of the water table is parallel to the general course of the river.

North side of river.—At the Fort Thomas gage the slope of the water table is away from the river. From a quarter of a mile below the Fort Thomas gage to a quarter of a mile below the mouth of Goodwin Wash the water table slopes toward the river. This reversal of the gradient is caused by seepage inflow from faults, similar to that in the reach upstream. The faults are well exposed in the Fort Thomas-Black Point reach. Below Goodwin Wash the present channel of the river is against the north edge of the valley. The river channel bends back toward the center of the valley west of Geronimo, the slope of the water table is away from the river, and water from the river recharges the valley fill. At the lower end of the reach the slope of the water table becomes parallel to the general course of the river.

REACH FROM BLACK POINT TO CALVA

A detailed study of the water table in this reach is not possible because the network of observation wells was not extended into the San Carlos Indian Reservation and because there were few existing wells. However, some conclusions may be drawn from the results of the seepage investigations along the river and from the shape of the water table west of Geronimo. There is very little irrigation or pumping in this reach, and there are no canals to provide recharge. A few springs occur along the north side of the river, and the presence of faults indicates some seepage inflow that is not visible at the surface. On the basis of these facts it is believed that the general slope of the water table in the reach is parallel to, or slightly toward, the general course of the river in the wintertime when there is no transpiration and is parallel to, or away from, the river in the summertime when the transpiration may exceed the local recharge.

FACTORS CAUSING FLUCTUATIONS OF THE WATER TABLE

The major fluctuations of the water table are caused by pumping from the ground-water reservoir, the use of ground water by phreatophytes, changes in the flow of the river, changes in the surface flow and underflow from the side washes, and infiltration from irrigation.

PUMPING

A cone of depression in the ground-water surface is formed by pumping from a well. When a number of wells are being pumped, these cones coalesce and effect a general lowering of the water table in the area. This lowering lessens the general gradient of the water table toward the river and in extreme cases may reverse the gradient.

The effect of pumping on the water table is clearly shown by the graph of well 22-31, figure 18. In 1943 no pump was operated near this well, and the graph shows only a small seasonal lowering, with recovery during the winter. However, beginning in the spring of 1944 a single irrigation well nearby was operated intermittently, and the effect of each period of operation was quickly reflected in the position of the water table at well 22-31.

The graph of well 282, figure 18, shows the regional effect of pumping. In 1943 and 1944 the highest water level in this particular well occurred in April, followed by a gradual decline until about September. The graph shows the effect of heavy pumping, which normally starts in April or May and lasts until September. In the fall of 1944 pumping was decreased because of heavy rains, and consequently less irrigation water was needed. This decrease is also reflected in the graph.

USE OF WATER BY PHREATOPHYTES

The phreatophytes growing on the bottom land withdraw large amounts of water from the ground-water reservoir and thus lower the water table. This lowering increases the movement of ground water from the nearby cultivated land and decreases or entirely prevents the movement of ground water into the river. This effect is seasonal, as indicated on the graphs showing the fluctuations in water level in wells 6-16 and 15-17, figure 18. The graphs of these wells are of the same general shape as the graph of well 282, which shows the regional effect of pumping. However, the water level in the wells in the phreatophyte area is drawn down early in the spring, before heavy pumping has started, indicating that the lowering is principally the result of the use of water by phreatophytes. This use starts in late March or early April and increases through June, remains practically constant through July and August, and gradually decreases until frost, when the use becomes negligible.

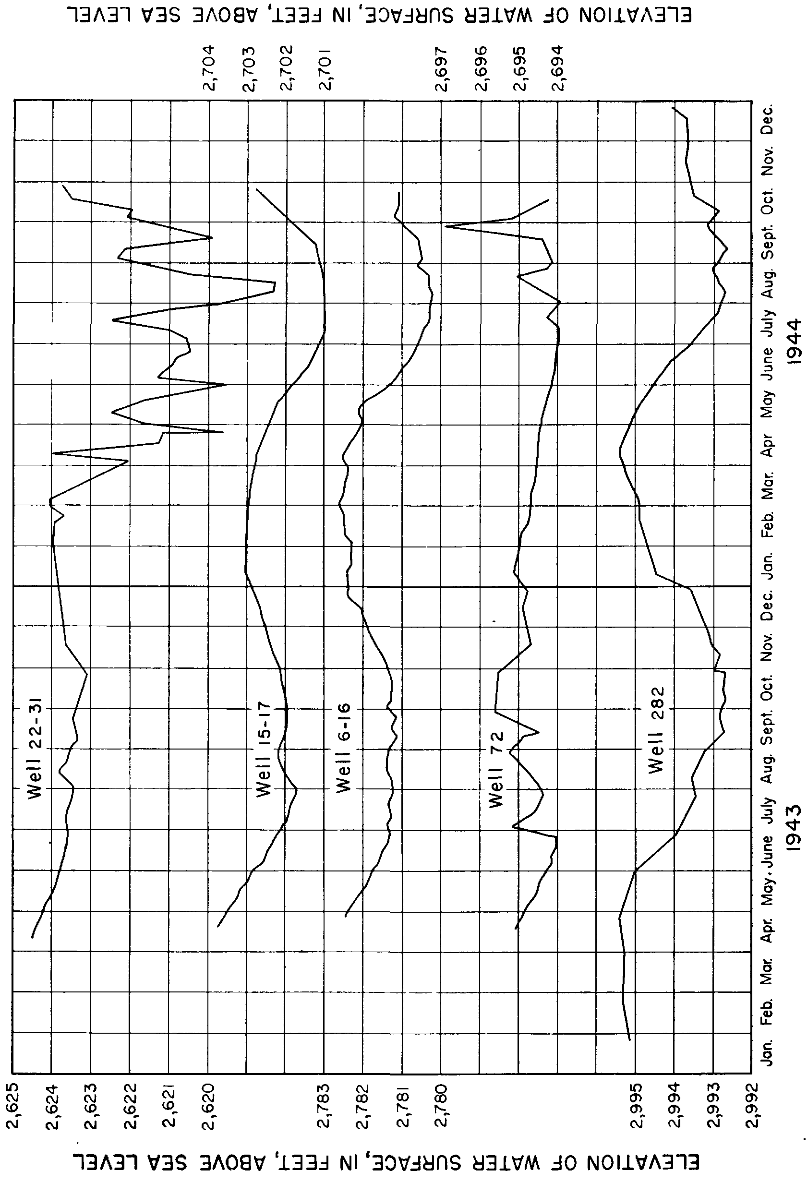

FIGURE 18.—Fluctuation of water level in typical wells in lower Safford Valley.

CHANGES IN RIVER FLOW

Changes in flow of the Gila River have an immediate influence on the water level in wells nearby and a somewhat delayed and lesser influence at greater distances from the river (see fig. 19). Part of the effect noted in wells near the river is not caused by water actually moving from the river but is the result of the higher water level in the river, which retards the movement of ground water into the river. A large part of the water that is fed to the water table during a flood stage is quickly returned to the river at the following lower stage and hence is ground water only temporarily. The rise in water level in wells that are a considerable distance from the river is probably the result of transmission of pressure from the river through partly confined water-bearing beds.[23] The graph of well 72, figure 18, clearly shows

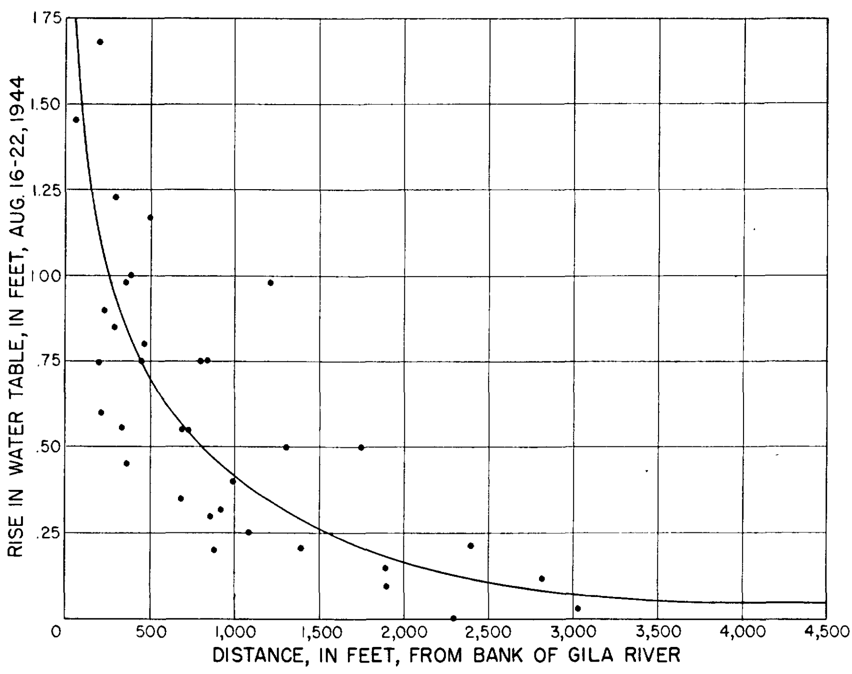

FIGURE 19.—Relation of distance from river to rise in water table, based on water-level readings in wells during periods of rise in river stage.

the effect of floods in the river. This well is about 175 feet from the edge of the river, and each of the peaks shown was caused by a flood. Wells 15-17 and 6-16 are about 1,000 feet from the edge of the river. Graphs for these wells show very little effect from floods, and the effects are somewhat delayed.

[23] Turner, S. F., and others, Water resources of Safford and Duncan-Virden Valleys, Ariz. and N. Mex., p. 14, U. S. Geol. Survey, 1941. (See list of studies, p. 5.)

SURFACE FLOW AND UNDERFLOW FROM WASHES

During wet seasons cones or ridges are formed in the water table near the mouths of the washes as a result of flow in the washes. After a wet season the cones or ridges gradually flatten, but near the major washes the underflow continues to have an effect for long periods both on the position of the water table and on the quality of water.

CANAL AND IRRIGATION SEEPAGE

According to a previous investigation [24] about one-third of the water diverted from the river is added to the ground-water reservoir through canal seepage losses. Seepage from the canals forms ridges on the water table along the canals.[25] The canal seepage losses are greatest during the spring months after the canals have been sluiced and cleaned. This cleaning removes the silt seal that had been deposited during the previous year and leaves the more permeable natural canal bed exposed. As the irrigation season progresses and the silt again partly seals the canals, seepage losses decrease. However, the canals are a constant means of recharge and therefore continuously influence the water-table fluctuations. Sometimes a depression in the water table caused by pumping is altered locally by recharge from a nearby canal. Irrigation water reaching the ground-water reservoir from cropped lands temporarily causes local water-table cones or ridges. About one-fourth of the irrigation water applied to fields in lower Safford Valley passes downward to the water table.[26]

About one-half of all water diverted from the river and one-fourth of all the water pumped reach the water table by infiltration from canals and irrigated lands.[27] This water constitutes a large part of the ground-water recharge occurring in the valley, especially in years of normal or subnormal precipitation.

QUALITY-OF-WATER STUDIES

OBJECTIVES

The investigations in lower Safford Valley included a detailed study of the chemical character of the surface waters and ground waters. The quality-of-water studies were made to determine the kinds and amounts of mineral matter carried in solution by the waters in the area and by waters entering and leaving the area. The chemical analyses made during the investigation are basic data, and several uses have been made of them in the preparation of this report. The analyses may be used to help determine the most economic use of the waters avail-

[24] Turner, S. F., and others, op. cit., 1941, p. 28.
[25] Unpublished data in files of the Geological Survey.
[26] Turner, S. F., and others, op. cit., 1941, p. 15.
[27] Turner, S. F., and others, op. cit., 1941, p. 28.

able in the valley. Considered with other data gathered during the study, they indicate the sources of the dissolved matter in the waters of the valley. Quality-of-water data also serve to indicate changes in the quality of the water supply as a result of use of water by agriculture and industry, as well as by natural bottom-land growth. In the preparation of this report some of the analyses have been used as the basis of a method to determine the quantities of water used by bottom-land growth.

ESTABLISHMENT OF LABORATORY

The water samples collected in the early stages of the investigation were analyzed in the Geological Survey laboratory in Roswell, N. Mex. In June 1943 a laboratory was established in Safford and was operated continuously until the end of the investigation. The Safford laboratory was equipped for making complete analyses of water.

COLLECTION OF SAMPLES

SURFACE WATER

In order to obtain basic general information, daily sampling was carried on throughout the investigation at or near the following four stream-gaging stations: San Francisco River at Clifton, Gila River near Solomonsville, Gila River at Safford, and Gila River at Bylas. Water analyses for the Bylas station were considered applicable to the Calva gaging station 10 miles downstream, as field studies showed no appreciable change in chemical character and concentration of the river water between these two points. Samples were also collected daily for about 9 months, beginning in July 1943, from Eagle Creek at the Phelps Dodge Corp. pumping plant west of Morenci. Discharge records were not obtained at this point by the Geological Survey.

More detailed information concerning the quality of surface waters within lower Safford Valley was obtained by collecting a water sample each time a stream-flow measurement was made. In addition, samples were taken at each measuring point during seepage runs, and of all inflows found during seepage runs. Also, in connection with special studies, such as that on the diurnal fluctuations of chloride content of Gila River, additional samples were obtained.

GROUND WATER

The large number of observation wells in the bottom land afforded an unusual opportunity for a detailed study of the quality of the ground water. Many of these wells were sampled when they were installed in the spring of 1943, and all were sampled during the summer of that year. Many were resampled in the spring of 1944. A group of 80 selected wells were sampled at bimonthly intervals to determine changes in quality of the water. The chemical character of ground waters outside the bottom land was determined by sampling all springs and privately owned wells in lower Safford Valley. Before sampling, particular care was taken to pump enough water from each well to insure that the sample was actually representative of the ground water in the aquifer supplying the well.

METHODS OF ANALYSIS

Analyses made during the investigation were of three general types—complete analyses, partial analyses, and tests. Complete analyses included determinations of specific conductance, total dissolved solids, loss on ignition, silica, iron, calcium, magnesium, sodium, potassium, carbonate, bicarbonate, sulfate, chloride, fluoride, nitrate, and borate. From these determined values total and noncarbonate hardness, percent of sodium, and sum of dissolved constituents were calculated. Partial analyses included determinations of specific conductance, calcium, magnesium, carbonate, bicarbonate, sulfate, chloride, fluoride, and nitrate. From these data sodium and potassium, hardness, percent of sodium, and sum of dissolved constituents were calculated. For the tests, specific conductance and one or more of the principal anions, such as chloride, bicarbonate, or sulfate, were all that were determined.

Complete analyses were made only for samples considered most important for the investigation as a whole. The chemical character of waters in lower Safford Valley was determined by means of a few complete and many partial analyses. The tests were used to show changes in concentration of dissolved matter from place to place or from time to time. The analytical methods used were those commonly employed by the Geological Survey.[28]

Daily river samples were made up into composite samples, usually for a 10-day period, according to procedures generally used by the Geological Survey for streams subject to sudden large changes in chemical character. For daily samples taken at times when discharge and concentration were fluctuating the procedure was to make composite samples covering shorter-than-normal periods, so that the composite samples contained only daily samples of similar concentration. Generally, river and canal samples taken at less frequent intervals were made up into composite samples covering a period of a month. Complete analyses were made of most of the composites of daily samples. Partial analyses were usually made of other composites of surface-water samples and of samples from washes and those taken during seepage runs.

[28] Collins, W. D., Notes on practical water analysis: U. S. Geol. Survey Water-Supply Paper 596, pp. 235-266, 1928.

For ground-water samples a sufficient number of complete and partial analyses were made to show the chemical character of ground waters in all parts of lower Safford Valley. However, for many samples of ground water only a few anions and cations were determined, to show variations in concentration of dissolved matter from place to place and from time to time.

EXPRESSION OF RESULTS

TERMS AND UNITS

Most of the analyses in the tables of this report are expressed in terms of parts by weight of dissolved matter per million parts of water. Conductance values are expressed as mhos (reciprocal ohms) multiplied by 10 to the 5th power. Dissolved solids for some analyses are reported in tons per acre-foot of water. Parts per million are converted to tons per acre-foot by multiplying the figures in parts per million by the factor 0.00136. For surface waters the dissolved solids are, in some instances, expressed in tons per day, as computed from the total dissolved solids of the water and the daily mean discharge. By similar computations, the tonnage of dissolved solids passing a gaging station during any period for which records are available can be determined. In figure 21, where analyses are shown in graphic form, constituents are expressed in equivalents per million. Equivalents per million are obtained by dividing the figure in parts per million by the combining weight of the corresponding anion or cation.

The significance of terms used in water analyses is discussed briefly in a recent report by Halpenny, Hem, and Jones.[29] With particular reference to conductance this paper states:

> The specific conductance is the reciprocal of the resistance of the water sample to an electric current measured under definite conditions. In general, the greater the dissolved solids concentration of a water, the greater is its conductance, but the conductance determination does not indicate the chemical nature of the materials in solution.

PUBLICATION OF ANALYSES

More than 5,000 water analyses were made during the investigation. Most of the surface-water analyses were included in the series of annual reports on quality of water.[30] A compilation of all available analyses of surface waters and ground waters in Safford Valley is contained in a report by Hem,[31] together with a discussion of the quality of water in this and adjoining areas in the Gila River Basin. Only a compara-

[29] Halpenny, L. C., Hem, J. D., and Jones, I. I., Definitions of geologic, hydrologic, and chemical terms used in reports on the ground-water resources and problems of Arizona, 29 pp., U. S. Geol. Survey, 1947. [Mimeographed.]

[30] Quality of surface waters of the United States, 1943-45: U. S. Geol. Survey Water-Supply Papers 970, pp. 117-119, 131-141, 148-157, 1945; 1022, pp. 227-241, 249-275, 278-305, 1947; and 1030—(in preparation).

[31] Hem, J. D., Quality of water of the Gila River Basin above Coolidge Dam, Ariz.: U. S. Geol. Survey Water-Supply Paper 1104 (in preparation).

tively small number of typical analyses are tabulated in the present report.

CHEMICAL CHARACTER OF SURFACE WATERS

An outstanding characteristic of the Gila River in Safford Valley is the rapidity with which the concentration of dissolved solids in the water may change during periods when the discharge is fluctuating rapidly. Figure 20 shows the effect of changes in discharge on the chloride content of the river water at Safford during September 1944. In this illustration daily mean discharge is plotted with daily chloride concentration of the water. The graph shows that low-flow waters are higher in chloride than flood waters. This trend is typical of all the river sampling stations in the Safford Valley. However, in the lower part of the valley concentrations of dissolved matter in the low-flow waters of the river are considerably higher than they are at Safford. The chloride at Safford ranged from 20 to slightly more than 400 parts per million during the month. During the same month the chloride concentration at Bylas ranged from about 30 to more than 1,000 parts per million. The wide range in concentration of water of Gila River and the tendency for concentrations to change suddenly require that samples be taken frequently to obtain a dependable record of the quality of water of the stream.

Table 14 contains a summary of the quality of river water at four daily sampling stations for which there were complete records for the year ending September 30, 1944. The summary includes the analyses of the composite samples of minimum and maximum concentration, and the weighted average analysis for the year, for each of the four daily sampling stations. The weighted average analyses were computed by multiplying the determined quantity of each constituent of each composite sample by the discharge of the stream in second-foot days for the period of the composite, and dividing the sum of these products for the year by the total discharge in second-foot days for the year. The weighted average analysis represents about the concentration that the water passing a sampling point during the year would have, if it were all collected in a large reservoir and thoroughly mixed.

The analyses in the table show that the average concentration of dissolved solids of the river water during the year at Bylas was about double the concentration at the gaging station near Solomonsville, and that the concentration of the water of San Francisco River at Clifton was appreciably higher than the concentration of the water of Gila River near Solomonsville. The quality of the water of San Francisco River is affected by inflows from salt springs at Clifton. The quantity and significance of these inflows is discussed in detail in another report.[32]

[32] Hem, J D., op. cit.

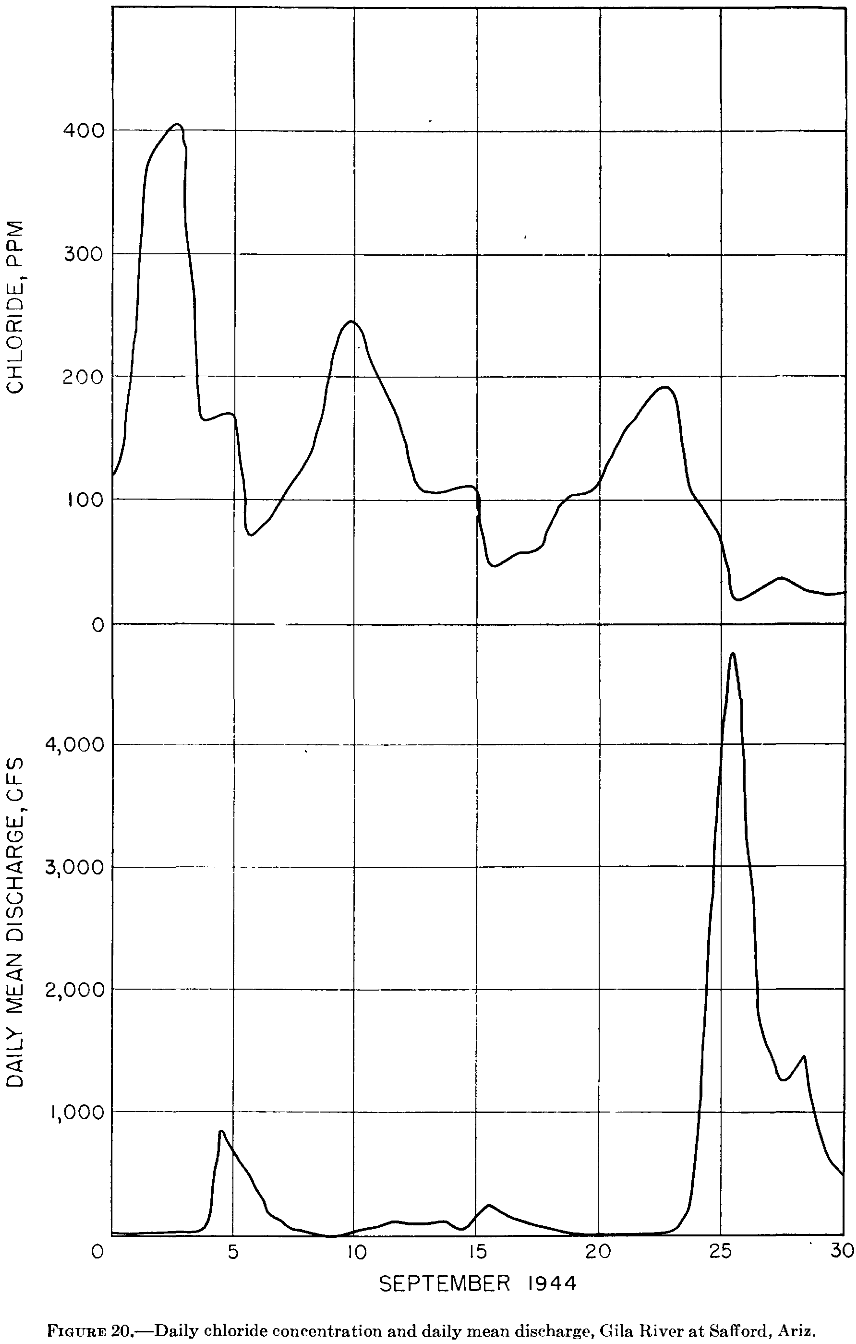

FIGURE 20.—Daily chloride concentration and daily mean discharge, Gila River at Safford, Ariz.

TABLE 14.—*Minimum, maximum, and weighted average dissolved-solids concentrations for year ending September 30, 1944, at daily sampling stations on Gila and San Francisco Rivers and minimum and maximum concentrations for period of record for Eagle Creek*

[Parts per million]

Source and date of collection	Specific conductance ($K \times 10^5$ at 25°C.)	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Borate (BO_3)	Dissolved solids	Total hardness as $CaCO_3$	Percent sodium
San Francisco River at Clifton, Ariz.:																
Sept. 25-29, 1944	31.3	35	0.46	34	8.7	18	3.1	143	13	21	0.5	0.2	0.0	204	121	24
June 21-30, 1944	160	48	.06	82	14	217	8.6	190	24	400	1.0	2.0	.2	890	262	63
Weighted average	91.8	41	.16	60	13	112	7.2	193	18	195	.7	1.3	.3	543	203	53
Gila River near Solomonsville, Ariz.:																
Sept. 25, 27-30, 1944	31.2	37	.60	33	8.7	21	3.3	158	18	17	.6	.1	.0	217	118	27
June 11-20, 1944	125	39	.14	65	19	165	12	209	60	262	1.6	4.3	.4	731	240	58
Weighted average	74.3	39	.17	51	12	87	6.0	204	39	117	1.3	1.1	.4	454	177	51
Gila River at Safford, Ariz.:																
Sept. 26-30, 1944	39.4	37	.31	36	9.7	38		183	23	26	.7	.2	.1	261	130	39
Sept. 2-3, 10, 1944	187	35	.14	70	22	300		265	189	345	1.7	15	1.5	1,110	265	71
Weighted average	66.2	36	.21	41	9.9	90		186	57	86	1.2	1.8	.5	415	143	58
Gila River at Bylas, Ariz.:																
Sept. 26-30, 1944	50.6	34	.40	36	8.6	58	2.6	176	42	49	.8	1.0	.2	319	126	49
May 5, 1944	548	......	......	205	78	889		178	605	1,410	......	.5	3.5	3,280	832	70
Weighted average	157	36	.22	69	21	246		212	161	316	1.2	2.2	1.6	957	258	67
Eagle Creek at pumping station near Morenci, Ariz.:																
Sept. 28, 1943	20.2	......	......	......	......	......	......	......	......	2.0	......	......	......	......	......	......
Oct. 28-31, 1943	45.7	42	.04	43	20	33	5.0	250	12	29	.6	6.9	.2	315	190	27

The changes that occur in the quality of water in the river between Thatcher and Calva, within lower Safford Valley, may be inferred from the analyses in table 14. The increase in concentration between Safford and Bylas is larger than the increase for the entire Safford Valley because the average concentration of the water at Safford is somewhat lower than the average at the station near Solomonsville. The changes that occur between the Solomonsville and Safford gaging stations are the result of large diversions for irrigation and of flood inflows from tributaries entering the river. These flood inflows dilute the water remaining in the river and cause a decrease in average concentration of the river water at Safford.

The increases in concentration in the river water in lower Safford Valley are due mainly to increases in the amount of sodium, chloride, and sulfate. These are the principal constituents added by ground-water inflows in the valley.

From the weighted average analyses and discharge records for the four gaging stations listed in table 14, the daily mean loads of dissolved solids and total loads of dissolved solids carried in the river past the stations during the year ending September 30, 1944, have been computed. (See table 15.) The data show that during the year San Francisco River contributed nearly half the load of dissolved matter brought into Safford Valley by Gila River. The apparent loss in load of dissolved solids between the gaging stations near Solomonsville and at Safford probably represents the considerable but unmeasured amount of soluble matter being carried past Safford in the flow of the three irrigation canals that bypass the gaging station. Table 15 shows that the river carried 21,000 tons more of dissolved solids from the valley past Bylas than it brought into the valley near Solomonsville during the year.

The extent to which the analyses for the water year ending September 30, 1944, may indicate conditions in other years is not known. Complete records for all four stations are available only for the water year 1944, which had subnormal runoff. However, the data indicate

TABLE 15.—*Loads of dissolved solids carried by Gila and San Francisco Rivers during year ending September 30, 1944*

Sampling point	Daily mean discharge (second-feet)	Daily mean load of dissolved solids (tons per day)	Total annual load of dissolved solids (tons)
San Francisco River at Clifton, Ariz.	70.1	103	37,500
Gila River near Solomonsville, Ariz.	188	230	84,100
Gila River at Safford, Ariz.	103	115	42,200
Gila River at Bylas, Ariz.	[1] 111	287	105,000

[1] Discharge measured at Calva, Ariz.

that an increase in the concentration of the river water and in the load of dissolved matter between Safford and Bylas is normal. The amount of increase in the load of dissolved solids probably would be larger in years of normal runoff.

Only a small amount of the dissolved matter reaching the head of Safford Valley comes from Eagle Creek. Table 14 shows that the water of Eagle Creek is comparatively low in dissolved matter and does not vary widely in composition. Minimum and maximum concentrations observed for the water of Eagle Creek during the period of record are given in the table.

The results of the sampling program at the river gaging stations in lower Safford Valley and at gaging stations on canals and washes are summarized in table 16. The table shows minimum and maximum concentrations of dissolved solids observed at each station during the period of record. Both discharge data and quality-of-water data are incomplete for flood periods at these stations; hence, concentrations lower than the minimum reported may have occurred during large ungaged floods. No weighted average analyses or figures for loads of dissolved matter can be computed for these stations, because the discharge records were incomplete and sampling was infrequent. The tabulated records show, however, about the maximum concentrations reached at most of the stations during the investigation and indicate the relative quality of water contributed by washes in lower Safford Valley during flood periods. The concentration of dissolved matter in the canal waters is increased at times by the addition of highly mineralized ground water to the canals through pumping or artesian flow. Hence. the water at some of the canal gaging stations may reach higher concentrations than the river water at the canal headings.

The analyses of samples of water taken from the river during seepage runs show the changes in chemical character that take place in the river water as it passes through lower Safford Valley. Figure 21 shows these analyses graphically for seepage measurements made at three points in February and June 1944. The graphs show that most of the change is an increase in sodium and chloride content and that most of the increase occurs between Glenbar and Geronimo. Also included in the illustration are graphs of typical analyses of water from bottom-land wells showing the chemical character of the ground water, which is the source of the dissolved solids that increase the concentration of the river water. All the analyses of samples taken during seepage runs and discussions of their significance are included in a report by Hem.[33]

[33] Hem, J. D., op. cit.

TABLE 16.—*Minimum and maximum dissolved-solids concentrations observed during periods of record at gaging stations on Gila River, tributary washes, and canals in lower Safford Valley, Ariz.*

[Parts per million]

Source and date of collection	Specific conductance (K×10⁵ at 25°C.)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Total hardness as $CaCO_3$	Percent sodium
Gila River near Thatcher Ariz.:												
Sept. 28-30, 1943	42.0	39	11	35	147	42	36	0.8	2.0	238	142	35
June 21, 1944	270	140	44	399	478	225	545	...	5.1	1,590	530	62
Gila River at Pima, Ariz.:												
Sept. 28-30, 1943	44.3	40	11	40	149	47	40	.8	2.1	254	145	37
May 24, 1944	305	74	36	560	476	274	615	...	8.8	1,800	332	79
Gila River near Glenbar, Ariz.:												
Sept. 28-29, 1943	41.3	38	11	36	146	51	30	.8	1.6	240	140	36
Aug. 7, 1944	370	54	41	703	342	392	810	...	.5	2,170	304	83
Gila River near Ashurst, Ariz.:												
Aug. 10-11, 22, 24-25, 1944	65.0	40	9.2	81	209	35	72	1.2	2.0	338	138	50
Aug. 7, 1944	891	330	155	1,540	336	1,120	2,390	...	.5	5,700	1,460	76
Gila River at Fort Thomas, Ariz.:												
Aug. 22, 1944	47.2	42	9.2	47	172	38	46	...	.2	267	143	42
Aug. 7, 1944	1,000	533	182	1,540	220	1,100	2,900	...	.5	6,360	2,080	62
Gila River near Geronimo, Ariz.:												
Aug. 22 1944	48.3	40	8.7	48	154	42	49	...	2.5	266	136	43
May 30, 1944	793	311	117	1,330	146	909	2,180	1.6	2.0	4,920	1,260	70
Gila River at Black Point, Ariz.:												
Sept. 29, 1943	50.5	...	...	...	...	...	40	...	...	...	...	...
July 9, 1944	628	302	86	1,000	218	727	1,660	1.5	7.4	3,890	1,110	66
Gila River at Bylas, Ariz.:												
Sept. 27-30, 1943	47.5	33	8.2	54	138	47	44	.9	1.6	[1] 282	116	50
May 5, 1944	548	205	78	889	178	605	1,410	...	.5	3,280	832	70
Gila River at Calva, Ariz.:												
Sept. 29 1943	45.2	...	...	...	...	...	33	...	...	...	...	...
May 26, 1944	551	210	73	899	195	536	1,460	...	.5	3,270	824	70

See footnotes at end of table.

TABLE 16.—*Minimum and maximum dissolved-solids concentrations observed during periods of record at gaging stations on Gila River, tributary washes, and canals in lower Safford Valley, Ariz.*—Continued

Source and date of collection	Specific conductance ($K \times 10^5$ at 25°C.)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Total hardness as $CaCO_3$	Percent sodium
Union Canal near Thatcher, Ariz.:												
Sept. 27, 30, 1943	44.6	38	11	42	165	33	42	.6	1.5	249	140	39
Sept. 6, 9, 13, 17, 23, 1943	195	58	21	337	320	178	355	2.7	11	1,120	231	76
Union Canal diversion along Ray Lane near Thatcher, Ariz.:												
Sept. 30, 1943	46.8	....	....	....	....	....	48	....	....	....	....	....
Sept. 20, 1943	225	78	24	393	369	217	425	3.1	14	1,340	293	74
Graham Canal near Thatcher, Ariz.:												
Sept. 30, 1943	50.4	....	....	....	....	....	63	....	....	....	....	....
Sept. 2 6, 13, 17, 20, 23, 1943	200	94	34	285	266	210	390	1.7	4.0	1,150	374	62
Smithville Canal near Thatcher, Ariz.:												
Sept. 27, 1943	35.7	....	....	....	....	....	8.8	....	....	....	....	....
July 12, 15, 19, 23, 26, 29, 1943	121	66	13	173	270	93	190	....	9.2	677	218	63
Smithville Canal wasteway near Thatcher, Ariz.:												
Sept. 2, 1943	77.7	....	....	....	....	....	114	....	....	....	....	....
Sept. 9, 13, 20, 1943	212	66	29	352	314	186	415	1.9	7.8	1,210	284	73
Dodge-Nevada Canal near Glenbar, Ariz.:												
Sept. 28, 1943	109	....	....	....	....	....	218	....	....	....	....	....
June 2, 5, 22, 26, 1944	469	66	21	948	220	353	1,240	3.9	7.1	2,750	251	89
Cottonwood Wash at Pima, Ariz.:												
Sept. 26, 29-30, 1943[2]	49.0	46	12	43	185	43	41	.8	1.7	279	164	36

See footnotes at end of table.

TABLE 16.—*Minimum and maximum dissolved-solids concentrations observed during periods of record at gaging stations on Gila River, tributary washes, and canals in lower Safford Valley, Ariz.*—Continued

Source and date of collection	Specific conductance ($K \times 10^5$ at 25°C).	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO^3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Total hardness as $CaCO_3$	Percent sodium
Curtis Canal near Glenbar, Ariz.:												
Sept. 27, 1943	42.6	...	...	...	...	...	19	...	...	...	...	...
June 19, 22, 26, 1944	577	72	64	1,170	278	911	1,270	2.0	8.0	3,630	442	85
Markham Wash near Eden, Ariz.:												
Sept. 26, 1943[2]	18.0	26	14	(3)	93	14	0	...	...	100	122	...
Matthews Wash near Glenbar, Ariz.:												
Aug. 7, 1943	73.2	28	11	122	239	84	66	.9	1.5	431	115	70
Aug. 8, 1944	169	24	7.6	346	329	168	275	1.9	6.2	991	91	89
Fort Thomas Consolidated Canal near Glenbar, Ariz.:												
Aug. 10-11, 21, 24-25, 1944	59.6	39	8.7	78	193	44	67	1.2	1.5	334	134	56
June 2, 5, 9, 12, 16, 19, 22, 26, 30, 1944	372	37	44	727	285	426	830	1.8	2.0	2,210	274	85
Fort Thomas Consolidated Canal at Fort Thomas, Ariz.:												
Aug. 11, 14, 17, 21, 24, 1944	78.2	44	9.5	113	207	71	104	1.4	1.5	446	149	62
May 19-20, 1944	894	410	180	1,430	234	1,180	2,420	1.1	58	5,790	1,760	64
Colvin-Jones Canal near Fort Thomas, Ariz.:												
Aug. 11, 14, 21, 1944	62.6	...	...	...	...	...	82	...	...	...	...	...
May 1, 4, 8, 11, 15, 18, 20, 25, 1944	647	226	105	1,060	204	733	1,680	2.1	1.5	3,910	996	70
Black Rock Wash at Fort Thomas, Ariz.:												
Sept. 26, 1943[2]	51.5	28	15	66	212	33	47	...	...	293	132	52

[1] Includes 25 parts per million silica (SiO_2).
[2] Only sample collected.
[3] Less than 10 parts per million.

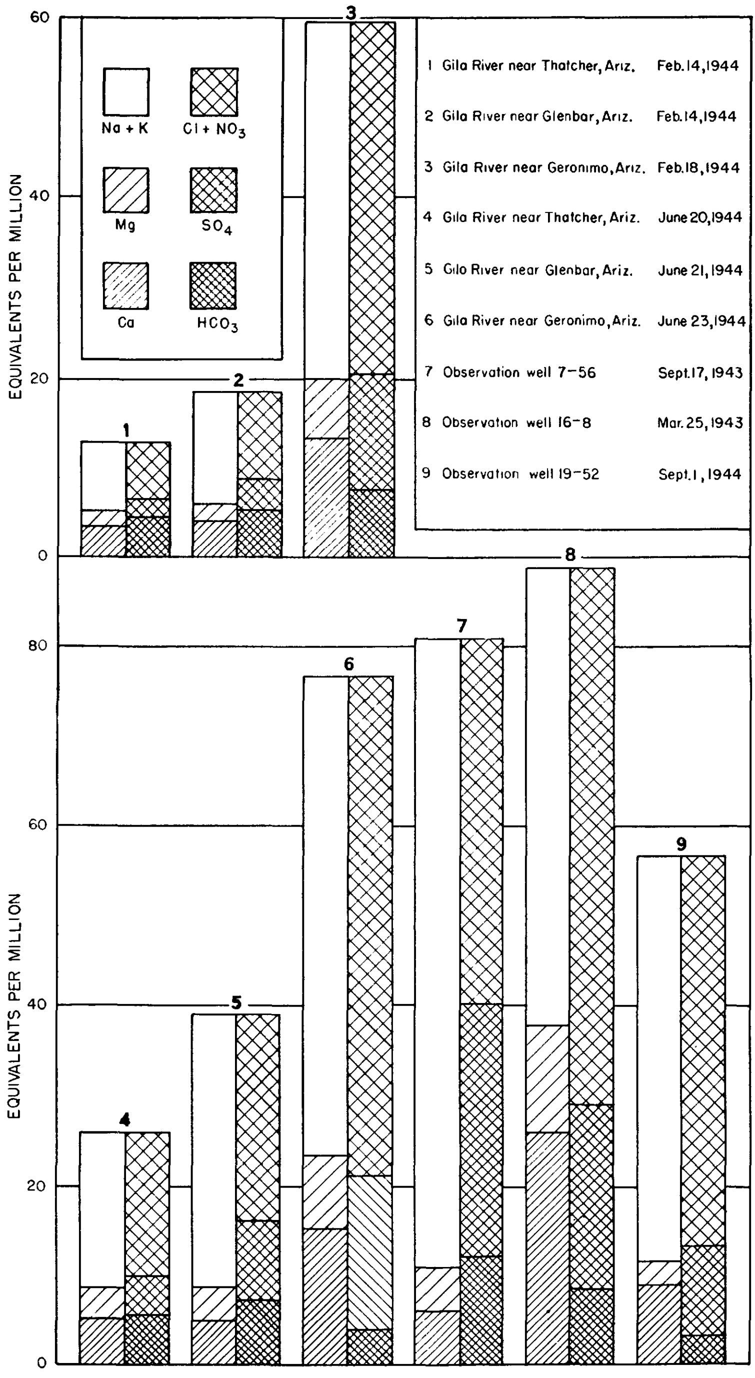

FIGURE 21.—Analyses of water from Gila River and of typical ground waters between Thatcher and Geronimo, Ariz.

Analyses of samples taken during seepage runs aid in interpreting the stream-flow measurements. Between measuring points, significant changes in total dissolved-solids concentration or in concentrations of the various constituents are reliable indications of inflow into the river. In some instances the changes in chemical character of the water are the only indication of inflow to the reach, because there may be both inflow to the river and compensating outflow from the river to the ground-water reservoir. In these instances the stream-flow measurements may show no gain and may even show a loss for the reach as a whole.

DIURNAL FLUCTUATIONS OF CHLORIDE CONTENT

The diurnal fluctuations in river flow observed at extreme low stages are discussed elsewhere in this report. In order to ascertain whether any similar fluctuation in dissolved matter was occurring, two temporary gaging stations were operated on the river between Fort Thomas and Geronimo while the flow was exhibiting this fluctuation. Samples were taken hourly at these two points for a period of 36 hours, and the concentration of chloride was found to fluctuate appreciably at both points. Figure 22 shows hourly discharge and hourly chloride concentrations observed at the upper station, 1.8 miles below Fort Thomas. The curves are similar in shape, and the daily maximum concentration of chloride occurs a few hours after the peak daily discharge. Approxi-

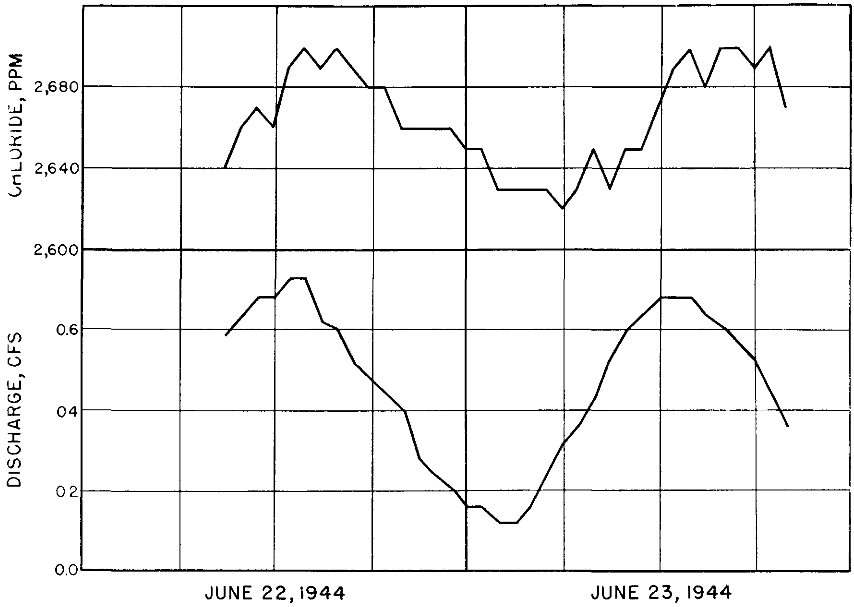

FIGURE 22.—Hourly chloride concentration and hourly discharge of Gila River 1.8 miles below Fort Thomas, Ariz.

mately the same fluctuations were noted at the station near Geronimo. The cause of these fluctuations in chloride content has been discussed by Hem [34] and may be a combination of several factors. During the hours of lowest flow part of the ground water seeping into the river channel was evaporated from the wetted sands of the channel, leaving behind its dissolved matter and causing an accumulation of soluble salts at the ground surface. When the water level rose with increase in river flow this soluble matter was at least partly redissolved, thus increasing the concentration of dissolved matter in the water of the river at the high points of the discharge cycle.

CHEMICAL CHARACTER OF GROUND WATERS

OLDER ALLUVIAL FILL

Analyses of the water from artesian springs and wells, illustrating the chemical character of ground waters from the older alluvial fill in lower Safford Valley, are given in table 17. In general, waters from the older alluvial fill are highly mineralized. They contain sodium and chloride principally and are high in fluoride. In some places waters from the older alluvial fill also may contain appreciable amounts of borate.

Two wells of importance in the older alluvial fill in lower Safford Valley are the Mack flowing well near Pima (well 301, table 17) and the Knowles flowing well at Geronimo (well 62, table 17). At several places within the valley ground water from the older alluvial fill reach the surface as springs. Probably faulting in these areas has caused openings through which the water rises under artesian pressure. The deep-seated origin of the water in these springs is indicated by the similarity in chemical character of the water from the springs and the water from the deep Mack well and by the high temperatures of water from the springs. The principal artesian springs in the area are the Indian Hot Springs, near Eden. Other, smaller, springs, probably of similar origin, occur north and south of Pima, northwest of Fort Thomas, and northeast of Bylas. In the vicinity of these springs the artesian water leaks into the shallower aquifers and influences the chemical character of the shallow ground water and of water in Gila River.

ALLUVIAL FILL OF THE INNER VALLEY

Practically all the wells in lower Safford Valley derive their water from aquifers in the alluvial fill of the inner valley. Consequently, nearly all the analyses of ground waters made for the investigation are of waters from these aquifers.

[34] Hem, J. D., Fluctuations in concentration of dissolved solids of some southwestern streams: Am. Geophys. Union Trans., vol. 29, no. 1, pp. 80-83, February 1948.

TABLE 17.—*Analyses of water samples from older alluvial fill of lower Safford Valley, Ariz.*

[Parts per million]

Well no. on pl. 5	Location	Date of collection	Depth (feet)	Specific conductance ($K \times 10^5$ at 25°C.)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Total hardness as $CaCO_3$	Percent sodium
30....	1½ miles northeast of Bylas post office.	Mar. 31, 1944.	....	426	120	26	776	183	303	1,150	1.9	1.5	2,470	406	81
62....	T. 4 S., R. 22 E., SE¼SE¼ sec. 31.	Jan. 6, 1944 ..	600	2,230	138	88	5,190	476	1,910	6,800	4.2	7.4	14,400	706	94
111C .	T. 4 S., R. 23 E., SW¼NW¼ sec. 22.	Feb. 10 1944.	....	445	103	14	852	118	381	1,180	3.5	1.0	[1]2,590	314	85
187...	T. 5 S., R. 24 E., SE¼NE¼ sec. 17.	Jan. 5, 1944...	....	440	77	12	879	104	351	1,200	3.5	2.0	2,580	242	89
301...	T. 6 S., R. 24 E., NW¼NE¼ sec. 13.	Oct. 27, 1943 .	3,767	582	72	9.2	1,210	98	416	1,640	5.8	.0	3,400	218	92

[1] Contains 2.7 parts per million of borate (BO_3).

Table 18 gives typical analyses showing the chemical character of ground water in the bottom land. Analyses of samples from three bottom-land wells are shown graphically in figure 21. Analyses of all samples from bottom-land wells are contained in a report by Hem.[35] Typical results of the bimonthly sampling of bottom-land wells are shown in figure 23, in which specific conductance and elevation of the water table are plotted against time for seven wells for the period of record. The seven wells are all near the river within the phreatophyte-covered area. Wells nearest the river showed the largest fluctuations in

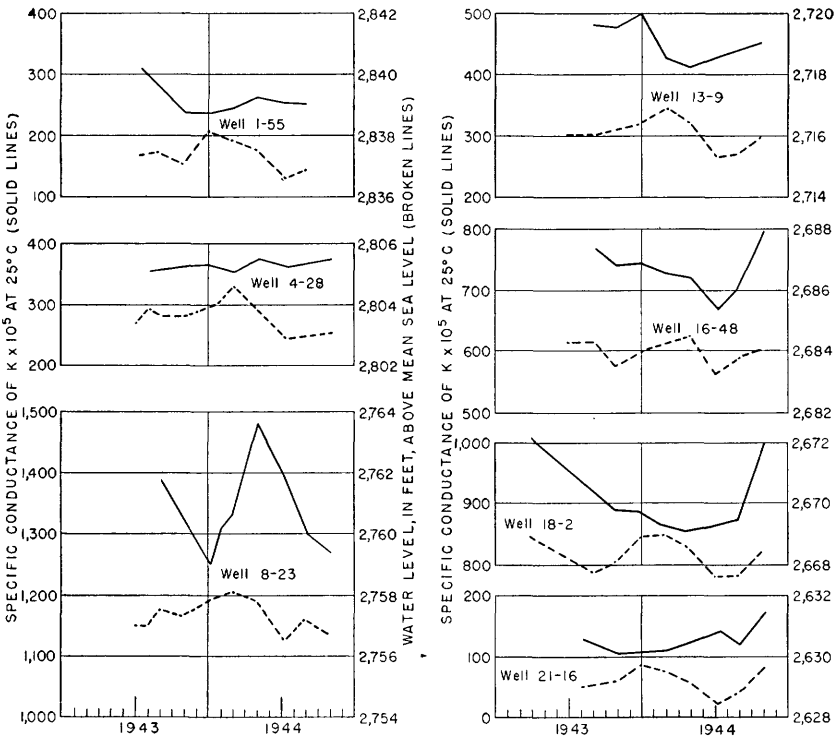

FIGURE 23.—Specific conductance and water level for seven typical observation wells in the bottom land of lower Safford Valley, Ariz., in 1943 and 1944.

concentration, and wells farthest from the river showed the least amount of change. Most of the wells outside the phreatophyte-covered area showed little change from month to month. Figure 23 indicates little consistent correlation between changes in water level and changes in dissolved-solids concentration for the seven wells.

[35] Hem, J. D., Quality of water of the Gila River Basin above Coolidge Dam, Ariz.: U. S. Geol. Survey Water-Supply Paper 1104 (in preparation).

TABLE 18.—*Analyses of water samples from alluvial fill of inner valley, lower Safford Valley, Ariz.*

[Parts per million]

Well no. on pl. 5	Location	Date of collection	Depth (feet)	Specific conductance ($K \times 10^5$ at 25°C.)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Total hardness as $CaCO_3$	Percent sodium
	T. 4 S., R. 22 E.														
22-11	SE¼SE¼ sec. 12	Sept. 1, 1944	....	282	93	27	487	304	288	600	1.9	1.0	1,650	343	76
57	SE¼NE¼ sec. 19	Mar. 16, 1944	80	49.7	32	7.4	66	142	52	54	1.6	2.9	286	110	56
	T. 4 S., R. 23 E.														
21-16	SW¼NW¼ sec. 18	Apr. 24, 1944	....	121	80	16	159	259	128	186	1.1	1.5	699	266	57
19-57	NE¼SE¼ sec. 21	Feb. 10, 1944	....	516	96	14	1,010	120	484	1,340	3.8	.5	3,010	297	88
87	SE¼NE¼ sec. 27	May 17, 1943	65	460	245	67	654	345	402	1,140	....	....	2,860	887	62
18-2	NE¼NE¼ sec. 34	Oct. 28, 1943	18.5	891	512	152	1,440	628	1,090	2,390	.7	23	5,920	1,900	63
17-23	NE¼SE¼ sec. 35	Sept. 8, 1943	18.2	1,770	1,080	382	2,790	538	2,120	5,440	1.6	....	12,100	4,260	59
	T. 5 S., R. 23 E.														
16-48	NE¼NW¼ sec. 1	Nov. 2, 1943	....	742	120	25	1,570	282	605	2,080	5.0	1.0	4,540	402	89
16-55	NE¼NE¼ sec. 2	Sept. 21, 1943	....	1,780	1,130	381	2,690	470	1,990	5,510	1.3	9.9	11,900	4,380	57
175	NW¼SE¼ sec. 2	June 28, 1944	....	43.6	23	6.0	65	128	58	38	.8	2.5	256	82	63
	T. 5 S., R. 24 E.														
15-50	NW¼NW¼ sec. 7	Oct. 30, 1943	....	1,370	768	312	2,290	583	2,410	3,680	2.6	2.5	9,750	3,200	61
14-12	SW¼SE¼ sec. 18	Mar. 18, 1943	18.1	569	362	99	809	638	626	1,340	1.4	2.0	3,550	1,310	57
13-9	NW¼NW¼ sec. 20	Aug. 30, 1943	....	486	181	77	795	538	511	1,060	....	44	2,930	768	69
199	NE¼NW¼ sec. 20	Apr. 19, 1944	72	452	186	79	714	410	523	1,000	1.4	58	2,760	789	66
12-50	NW¼NE¼ sec. 30	May 3, 1944	....	647	392	110	932	568	654	1,630	1.3	11	4,010	1,430	59
	T. 6 S., R. 24 E.														
8-23	SE¼NW¼ sec. 3	Aug. 26, 1943	....	1,390	419	176	2,910	876	2,710	3,230	....	....	9,880	1,770	78
9-36	NE¼SW¼ sec. 4	May 2, 1944	....	339	157	48	536	484	344	705	1.0	5.0	2,030	590	66
266	SE¼NE¼ sec. 4	Apr. 15, 1944	52	883	350	128	1,620	732	1,490	1,960	1.4	4.0	5,910	1,400	72
275	SE¼NE¼ sec. 10	May 1, 1943	53	340	56	44	647	522	329	680	....	....	2,010	321	81
6-73	NE¼NE¼ sec. 14	Oct. 29, 1943	....	158	102	36	203	378	144	255	.3	30	956	402	52
	T. 6 S., R. 25 E.														
312	SW¼SW¼ sec. 6	Apr. 20, 1943	....	940	176	89	1,990	802	1,830	1,790	8.2	24	6,310	805	84
4-28	SW¼SE¼ sec. 17	Oct. 27, 1943	....	363	162	45	630	684	329	730	3.9	21	2,260	590	70
5-29	SE¼NW¼ sec. 18	......do......	....	82.8	24	12	155	231	61	136	.9	.2	503	110	76
328	NE¼SW¼ sec. 18	Mar. 31, 1944	66	222	111	30	351	488	174	395	1.5	27	1,330	440	66
1-55	NW¼SW¼ sec. 26	Jan. 4, 1944	....	233	112	33	390	584	202	400	3.5	.5	1,430	415	67

The analyses of samples from the bottom-land wells show that ground waters differ considerably in concentration from place to place. In general, the most dilute waters contain mostly sodium or calcium and bicarbonate, and the more highly mineralized waters contain mostly sodium and chloride. Many of the waters contain unusually large amounts of nitrate and fluoride. The most dilute waters occur near Geronimo, where the underflow of Goodwin Wash enters the valley. The most highly mineralized waters occur between Ashurst and Fort Thomas.

Water in some parts of the valley shows the effect of artesian leakage from the older fill through fault zones. These inflows occur in the vicinity of fault springs, such as those near Fort Thomas along the north edge of the valley. Waters from some wells in this area had temperatures of 90° F. or more, probably caused by leakage of warm artesian water. Available data show that temperatures of the water in wells in the bottom land normally range from 60° to 70° F. Waters of abnormally high temperature from wells usually are very similar in chemical character to waters from the fault springs of the valley. For example, water from well 19-57 (table 18) is similar to water from spring 111C (table 17). The well is a few hundred yards from the spring. Artesian leakage occurs in other places along the north side of the river from Eden to Geronimo, and in some places the leakage is sufficient to maintain an appreciable and continuous seepage of ground water into the river.

The chemical character of ground water in the alluvial fill of the inner valley outside the bottom land was determined largely by sampling privately owned irrigation and domestic wells. Typical analyses are given in table 18. Most of the waters outside the bottom land in lower Safford Valley are rather highly mineralized. The most dilute waters contain principally calcium and bicarbonate. The most concentrated waters contain mostly sodium and chloride.

Preparation of map showing quality of water.—All the analyses of ground water made in 1943-44 for lower Safford Valley were used to prepare the map showing mineral content of ground water, plate 5. The map shows the total dissolved-solids content of ground waters in the alluvial fill of the inner valley from Thatcher to the San Carlos Indian Reservation.

In preparing this map it was assumed that all aquifers in the alluvial fill of the inner valley were interconnected, and therefore that waters at different depths in a well that is entirely in this system of aquifers would have about the same dissolved-solids content. The finished map indicated that this assumption was valid for all but a very few wells. The map was made as follows: A figure for dissolved-solids content was obtained for each well from the available analytical data;

this figure was entered temporarily on the map at the location of the well to which it pertained; and then, by a process similar to that used in drawing elevation contours, lines were drawn joining the points where analyses indicated that the ground waters contained the same concentration of dissolved solids. The interval between lines was chosen as 1,000 parts per million. Areas where the concentration exceeded 5,000 parts per million were indicated on the map, and no attempt was made to draw lines for the higher concentrations within such areas.

The quality-of-water map shows the positions of the lines in the bottom land with considerable accuracy because of the large number of wells. The positions of the lines in the valley outside the bottom land are less definitely known because fewer wells exist.

SOURCES OF DISSOLVED MATTER

As stated in the section of this report dealing with geology, during a part of the time when the older alluvial fill was being deposited Safford Valley contained a more or less saline lake or playa. Many of the sediments deposited in this lake-bed zone were impregnated with soluble salts. Indeed, deep wells in Safford Valley have penetrated beds containing nearly pure sodium chloride (common salt) or calcium sulfate in the form of gypsum. The beds are several feet thick. Beds of fine-grained material in the lake-bed zone contain rather large amounts of these readily soluble salts.

Since the establishment of exterior drainage of the valley by Gila River, the deposits of the old lake bed have been partly eroded, both by mechanical movement of the sediments and by solution of the soluble material. The process of erosion by dissolving soluble rocks, such as salt, gypsum, and limestone, is of considerable importance in Safford Valley, as shown by the large tonnage of soluble material carried annually by Gila River past the gaging station at Bylas. Because of the large quantities of soluble matter in the lake beds, Gila River will probably long continue to carry much mineral matter in solution.

The salts dissolved from the lake beds may reach the river in surface runoff. Some of the tributaries of the river, such as Matthews Wash, drain large areas where finely grained lake-bed sediments are exposed. Rain falling on these areas leaches some of the soluble salts from the deposits, and running water removes some of the insoluble matter, exposing fresh beds for later rains to leach out. Analyses indicate that flood waters from Matthews Wash contain appreciable amounts of sodium, bicarbonate, sulfate, and chloride. (See table 16.) These flood waters are not highly mineralized, but they are nearly always more concentrated than flood waters from washes that do not drain lake-bed areas and are considerably more concentrated than flood waters originating in areas of hard rock.

In addition to the salts washed into the river by surface drainage from lake-bed deposits, amounts of perhaps greater magnitude reach the river indirectly through inflows of artesian water from the lake beds. Little, if any, ground water enters the river directly by seepage from the lake beds, but large amounts enter indirectly after passing through the alluvial fill of the inner valley. If none of the mineral matter in the artesian water accumulated in the soil or alluvium of the inner valley, this accretion would show up as a gain in the salt load of the river.

EFFECT OF DISSOLVED-SOLIDS CONCENTRATION ON RATE OF WATER USE

Data obtained during the investigation indicate that the concentration of dissolved solids in the ground water of the bottom land has an effect on the rate of use of water by the bottom-land vegetation. In general, plants tend to use less water and grow less as the dissolved-solids concentration of the water increases. Extremely high concentra-

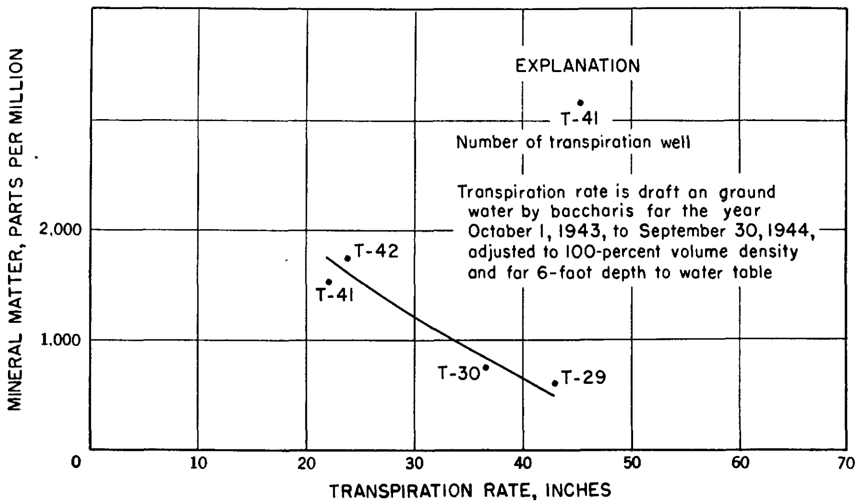

FIGURE 24.—Relation of concentration of dissolved mineral matter in ground water to annual rate of transpiration of ground water by baccharis.

tions of dissolved matter may be capable of killing some species of vegetation, thus permitting no water use by these species at such concentrations.

Figure 24 illustrates the relation between concentration of dissolved solids in ground water and the rate of water use by baccharis.

In preparing this illustration, water use for the year ending September 30, 1944, was computed on a basis of 100-percent volume density for each of four transpiration wells located in baccharis thickets. This rate of use was adjusted to the equivalent rate of use at a depth to the water table of 6 feet, using the relation between rate of use by baccharis in tanks and depth to water shown by figure 39. The dissolved-solids concentration of ground water at the location of each transpiration well was determined from plate 5.

The graph shows that baccharis apparently uses more water where dissolved-solids concentrations are low than where dissolved-solids concentrations are high.

An attempt was made to determine the relation between dissolved-solids concentrations and rate of water use by saltcedar, using data obtained from transpiration wells and from tanks at the Glenbar station. The data indicated that changes in concentration of dissolved solids may have an effect on rate of water use by saltcedar, but the relation was not shown conclusively by the data available. In a very general way, however, the data indicate that rates of water use are lower for highly mineralized water than for water of lower mineral content.

The relation between rates of water use and concentration of dissolved solids is another factor requiring consideration in determining the amount of water used by phreatophytes. Additional data need to be obtained in order to establish the relationship more definitely. In the present investigation no adjustment was made for this effect in relating consumption of water in the tanks to use of water in the field, as quantitative data were not available for making such an adjustment. In any event, the water in the tanks became concentrated by evaporation and transpiration, and its concentration approached that of the natural ground water (tables 19 and 25).

EFFECT OF WATER USE ON DISSOLVED-SOLIDS CONCENTRATION

IRRIGATION

Irrigation tends to increase the dissolved-solids concentration of ground waters in an irrigated area. This effect is the result of evaporation and transpiration, which remove water from the area but leave behind the soluble matter originally in the water. Under good drainage conditions this soluble matter may be carried down to the water table by irrigation water and eventually into drains or surface streams. The net effect of irrigation is to increase dissolved-solids concentrations in the drainage waters leaving an area, but with perfect drainage the total quantities of soluble salts leaving the area during a given period would be nearly the same after the development of irrigation as before. In actual practice ideal conditions do not exist. Usually drainage is not complete enough to remove all the soluble matter applied to the land in the irrigation water; hence, under irrigation the total amount of soluble salts leaving the area is likely to be reduced. Some of the soluble matter left behind in the soil may react chemically with the soil, producing substances that cannot be dissolved later.

Irrigation in lower Safford Valley is a contributing cause of the high concentration of dissolved matter in ground waters and in the low-flow waters of Gila River. The effect of irrigation in lower Safford Valley on the total salt load of Gila River at Calva cannot be closely evaluated from the available data. However, ground water entering the inner valley from the older alluvial fill probably carries enough soluble matter into lower Safford Valley to account for the increase in load of dissolved solids of the river between the Solomonsville gaging station and Calva. It should be noted that this inflow of water from the older alluvial fill containing soluble matter is not a result of irrigation.

NATURAL VEGETATION

Vegetation in the bottom land transpires large quantities of water in the form of vapor. This large use of water has an appreciable effect on the quality of ground water in the bottom land and on the quality of the ground water that enters the river. In some respects the effects of water use by natural vegetation are similar to the effects of irrigation. Assuming perfect drainage, both tend to increase the concentration of dissolved solids in ground water and surface drainage water without increasing total loads of dissolved matter. The bottom land in lower Safford Valley approaches conditions of complete drainage much more closely than does the irrigated land.

The analyses of water samples from wells in the bottom land show that the ground water tends to increase in concentration as it moves through the areas covered by vegetation, and this fact was used in this investigation as a basis for determining the amount of water transpired. The movement of ground water through the areas of growth goes on continually, and there probably is no area where the bottom-land growth permanently prevents ground water and the soluble salts from reaching the river.

SALTCEDAR

Saltcedar has become the dominant species of plant in the bottom land in lower Safford Valley. It has several characteristics that are not shared to any great extent by other plants in the area. The ability of saltcedar to thrive in localities of highly mineralized ground water is well known and may be observed in lower Safford Valley, where its growth approaches optimum volume density in several areas where the dissolved-solids concentration of the ground water is more than 8,000 parts per million. Other species, such as baccharis and mesquite, are found in areas of rather highly mineralized ground water but only in relatively sparse growths. Saltcedar is able to grow vigorously using a more saline water supply than most other plants can tolerate, and hence saltcedar has little competition in areas where the ground water is highly mineralized.

Probably one of the mechanisms by which saltcedar is able to thrive in areas of salty water supply is its practice of exuding water, known as guttation. During the growing season water is exuded on the fronds of the plants, sometimes in sufficient amounts to weigh down the plants and cause them to droop noticeably. The water exuded is very salty, as shown by the analysis (table 19) of a sample shaken from fronds of saltcedar in a thicket near the Glenbar experiment station. This sample had a dissolved-solids concentration of 41,000 parts per million, about 20 times as high as the dissolved-solids concentration of ground water in the vicinity (table 19). The concentration of the single sample of exuded water collected may have been affected by evaporation and by salts left behind on the fronds from previous exudations. Apparently, in the process of guttation, the plant has developed a mechanism for disposing of excess soluble matter taken up from the ground water. Possibly it is significant that the percentages of sodium and chloride in the water exuded are higher than in the ground water available to the plants. This may indicate that the plants are able to reject sodium and chloride in the water while using a part of the other salts in building plant tissue.

A number of observations have been made in the field of the effects of the circulation of soluble mineral matter in saltcedar plants. During dry periods part of the water exuded is evaporated from the fronds, leaving small salt crystals. The fronds have a distinctly salty taste, and the salt crystals can be observed. The salt crystals are washed by rain or dew from the fronds to the ground beneath the trees, and wind blows both the crystals and the exuded water to the ground. The net effect is to increase temporarily the percentage of soluble matter in the soil in the saltcedar thickets. An effect observed in the field was the rapid corrosion of the parts of observation-well casings that protruded above the ground in the thickets.

In the generally sandy and gravelly soils of the bottom land in lower Safford Valley the salt dropped on the ground by saltcedars probably is intermittently removed, either as a result of infiltration from occasional rains heavy enough to recharge the ground-water reservoir or as a result of leaching by flood waters that occasionally inundate the areas of growth. Therefore saltcedar probably causes no

TABLE 19.—*Analyses of water exuded from natural saltcedar growing near Glenbar experiment station and of shallow ground water near the experiment station*

[Parts per million]

Source of sample[1]	Date of collection	Specific conductance ($K \times 10^5$ at 25°C.)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na+K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids	Total hardness as $CaCO_3$	Percent sodium
Exuded water	Oct. 18, 1944	5,550	986	333	13,800	34	7,800	18,200	41,100	3,830	89
Well 10–2	Aug. 30, 1943	281	104	29	487	490	229	560	1,660	378	74
Well 11–14	Mar. 15, 1944	326	168	47	518	489	315	715	2,000	613	65
Well 11–18	Mar. 13, 1943	351	116	37	629	584	336	690	2,100	442	76
Well 11–21	Aug. 30, 1943	330	174	45	492	496	300	685	1,940	619	63

[1]Well numbers correspond with numbers on plate 5.

appreciable permanent accumulation of salt in the soil of the bottom land. However, the effect of the salt dropped by the plant should be considered in any area where it is proposed that lands covered with saltcedar be cleared for agricultural use.

DETERMINATION OF SPECIFIC YIELD

A knowledge of the specific yield of the water-bearing materials was needed to determine quantitatively the amount of water yielded or stored as a result of a decline or rise in the water table. Changes in water level in the tanks or in the ground-water reservoir had to be expressed in terms of the actual volume of water involved in those changes. This information on specific yield was required, in one way or another, for each of the methods applied in computing use of water.

Each of the places where a knowledge of specific yield was required involved an expression of the yield with respect to time and with respect to the position of the water table. For example, the specific yield with respect to time to be applied to computations of use of water at a transpiration well was the yield in 12 hours of each day. The specific yield with respect to position of the water table to be applied to a transpiration well was the yield of the layer of materials unwatered during a given 12-hour period. For these reasons, the term "specific yield" has been qualified in this report by introducing the elements of time and of depth of the water table below the land surface. The terms "coefficient of drainage" and "coefficient of saturation" are used in this report to designate the specific yield computed with respect to the interval of time for which the determination was made, the depth for which the yield was determined, and whether the water-level was rising (coefficient of saturation) or declining (coefficient of drainage). The term "coefficient of drainage and saturation" is used in this report to designate the mean of all determinations for a given tank or portion of the ground-water reservoir. These terms are approximately equivalent to Wenzel's "coefficient of storage."[36]

Three methods of determining the coefficient of drainage were used, the second of which was also used to determine the coefficient of saturation. Experimental work was done on a fourth method. The methods were the cylinder method, tank method, laboratory method, and miniature pumping tests.

FIGURE 25.—Driving cylinder to collect sample of bottom-land materials for determination of coefficient of drainage. Photograph by T. W. Robinson.

CYLINDER METHOD

The coefficient of drainage was determined in long cylinders for three samples of undisturbed materials obtained close to transpiration

[36] Wenzel, L. K., Methods for determining permeability of water-bearing materials, with specia reference to discharging-well methods: U. S. Geol. Survey Water-Supply Paper 887, p. 89, 1942.

wells in different parts of lower Safford Valley. Each cylinder was 42 inches in length and 14 inches in inside diameter. For each sample, a pit was excavated and the cylinder was then driven downward into the bottom of the pit. The pit was deepened outside the cylinder in order to reduce friction as the driving proceeded (see fig. 25).

After the undisturbed, or only slightly disturbed, column of soil had been obtained, the material in the bottom 4 inches of the cylinder was removed. Perforated pipe was inserted through the side of the cylinder into this open space and welded into place, and the remaining space was filled with fine screened gravel. A steel plate was welded to the bottom of the cylinder so that a watertight tank was formed. A tee and a stopcock were attached to the outer end of the pipe. Glass tubing was attached vertically to the tee, parallel to and 4 inches from the wall of the cylinder, so that the position of the water level in the cylinder could be observed at all times. The cylinders were placed vertically on a recessed shelf in a pit 5 feet deep at the Glenbar experiment station. The tops of the cylinders were insulated with a 4-inch layer of rock wool, and the sides and tops of the cylinders were then covered with a 2-inch to 4-inch layer of earth, held in place with planks. Thus, all that was visible in the pit was the gage glass and stopcock for each cylinder. The part of the pit containing the cylinders was covered with a roof, about 18 inches above the land surface. The cylinders were thus protected from rainfall and from rapid or decided changes in temperature and relative humidity. The effect of changes in barometric pressure could not be reduced or eliminated, but it was minimized by using only the readings of water level that were made within a narrow range of barometric pressure.

Holes were bored to the top surface of each of the samples and water was added, a little at a time, until the water level stood at depths of about 1, 1.5, and 1.75 feet, respectively, above the bottoms of the three samples. Water levels in the gage glasses were observed daily and sometimes twice daily for a 15-day period, and barometric pressure was recorded each time a reading was made. A measured quantity of water was then withdrawn through the stopcock from each of the samples, and the resulting changing position of the water level was observed for about 25 days. The water level in the three samples had ceased to decline at the end of 9, 10, and 15 days, respectively. The volume of water withdrawn from each sample was divided by the volume of material unwatered and multiplied by 100 to obtain the coefficient of drainage, in percent, for the period. The results are given in table 20. The computation of drainage coefficient was based on the difference between the mean of a group of measurements obtained within a narrow range of barometric pressures during the 15-day period of equilibrium before draining and the mean of a group of measurements obtained at

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similar barometric pressures during the period of equilibrium in the last 15 days after draining.

TABLE 20.—*Coefficients of drainage as determined by cylinder method*

Well at which sample was taken	Mean depth of sample (feet below measuring point of well)	Length of drainage period (days)[1]	Coefficient of drainage (percent)
T-37	5.6	9	16.6
T-33	6.7	10	21.4
T-42	5.5	5	12.4

[1] Limited to periods of approximately uniform barometric pressure.

TANK METHOD

The tanks at the Glenbar experiment station were well suited for the determination of drainage and saturation coefficients. Their diameter was sufficient to accommodate samples that were very large in comparison with those in the long cylinders, and their depth was sufficient to include a water table, a capillary fringe, and, in the tanks containing sand and gravel, a zone of intermediate vadose water.[37] The bare soil tanks were especially adaptable for the determinations, as there was no vegetation in them to draw on the water supply.

Determinations of coefficients of drainage and saturation were made for bare soil tanks 29, 30, 37, 38, and 39 in the period from March 1 to July 1, 1944. Most of the determinations were completed during the month of May. The determinations were planned and executed with particular reference to reduction or elimination of errors introduced by changes in temperature, barometric pressure, relative humidity, and soil moisture. A second recharge well was installed in each tank so that the water level could be observed at two points, in order to be sure that there was a uniform water level across the tank.

Each tank was first covered with a layer of tar paper to prevent evaporation from the soil surface. This cover was not sufficiently airtight to prevent movement of air into and out of the unsaturated material as the water table declined and rose, respectively. A 4-inch layer of rock wool was placed on top of the tar paper to reduce the effect of rapid changes in air temperature. A canvas cover with a center pole was placed over the rock wool, producing a tentlike shelter against wind and rain. A water-stage recorder was installed over the recharge well of each tank in order to obtain continuous records of changes in water level. The thermocouples of the soil thermograph were installed in tank 30, with one thermocouple 12 inches below the surface, another 4 inches below the surface, and the third on the surface of the soil beneath the insulation.

[37] Meinzer, O. E., Outline of ground-water hydrology, with definitions: U. S. Geol. Survey Water-Supply Paper 494, p. 26, 1923.

Coefficients were determined in two ways. The coefficient of saturation was determined by adding measured amounts of water to the tanks and evaluating the resulting rises in water level; the coefficient of drainage was determined by withdrawing measured amounts of water from the tanks and evaluating the resulting declines in water level. The tanks were allowed to stand undisturbed for 8 days or more after each addition or withdrawal of water. The computations of coefficients of saturation were based on the difference between the mean of a group of measurements of water level obtained within a narrow range of barometric pressures during the period before raising the water table and the mean of a group of measurements obtained at similar barometric pressures during the period after raising the water table. Similar techniques were used to determine the coefficients of drainage.

The results showed that under the same conditions the coefficient of saturation was usually greater than the coefficient of drainage. The reason for this difference is believed to be that a declining water table leaves a small amount of moisture in the zone of unwatering that drains out very slowly, in contrast to the rapid process of saturation. With much longer periods of drainage it is probable that the difference between the coefficients would be reduced.

In addition to the determinations made for bare soil tanks, coefficients of drainage and saturation were determined for all the odd-numbered tanks containing vegetation during January and February 1944, when the plants were not transpiring. These tests were made in the same manner as the tests for the bare soil tanks, except that the tanks containing vegetation were covered with straw instead of tar paper. In addition to the determinations made within the tanks, coefficients of drainage for the materials in the tanks were determined from about 75 samples tested in the hydrologic laboratory.

LABORATORY METHOD

APPARATUS

A hydrologic laboratory was assembled at Safford in the building occupied by the water-analysis laboratory. The apparatus consisted of a series of permeameters of different volumes, graduated cylinders, two drying ovens, a trip balance, and miscellaneous laboratory equipment. Figure 26 shows a complete permeameter with extra percolation cylinder and reservoir pipe. The base of the permeameter contains a length of 1-inch pipe that connects the reservoir pipe to the percolation cylinder. The pipe was set in concrete in order to lower the center of gravity of the apparatus and thus reduce the possibility of tipping.

The over-all height of each percolation cylinder was 7 inches. A circular piece of ¼-inch mesh hardware cloth was soldered to the inside

FIGURE 26.—Variable-head permeability apparatus used in hydrologic laboratory, Safford, Ariz. Photograph by S. F. Turner.

1 inch above the bottom. This cloth supported a 60-mesh wire screen with a ¼-inch hole in the center and formed the supporting base for the sample to be tested. The net volume of each percolation cylinder above the screen was determined and marked on the side. (See fig. 26.) Each reservoir pipe was 12 inches long, thus making the maximum available head (height of the water column in the reservoir pipe above the top of the percolation cylinder) 5 inches. A ⅛-inch ell was inserted in the side of the reservoir pipe about 6 inches above the base as a manometer opening. The manometer consisted of a vertical glass tube connected to the ell and a white celluloid scale, graduated in centimeters, held against the back of the glass tube with rubber bands. By means of a drain cock in the 1-inch pipe water could be drained from the apparatus. A 3/16-inch hole was drilled through the side of the percolation cylinder, just above the bottom, in order to allow the entrance of air below the screen during draining. Figure 27 is a diagrammatic sketch of the apparatus.

TECHNIQUE

A standard procedure was adopted in preparing the samples for testing in order to assure comparable results. The sample to be tested was thoroughly mixed and the necessary amount selected, care being taken to make sure that it was dry and free from lumps. The sample was then set aside temporarily while the permeameter was prepared.

With the apparatus level, de-aerated water was added until the apparatus was completely full. Care was taken to be sure that no air was trapped below the wire screen. A round rod was then placed across the top of the percolation cylinder to break the meniscus, so that the water surface would be level with the top rim of the cylinder. The zero of the celluloid scale was set at the bottom of the meniscus in the manome-

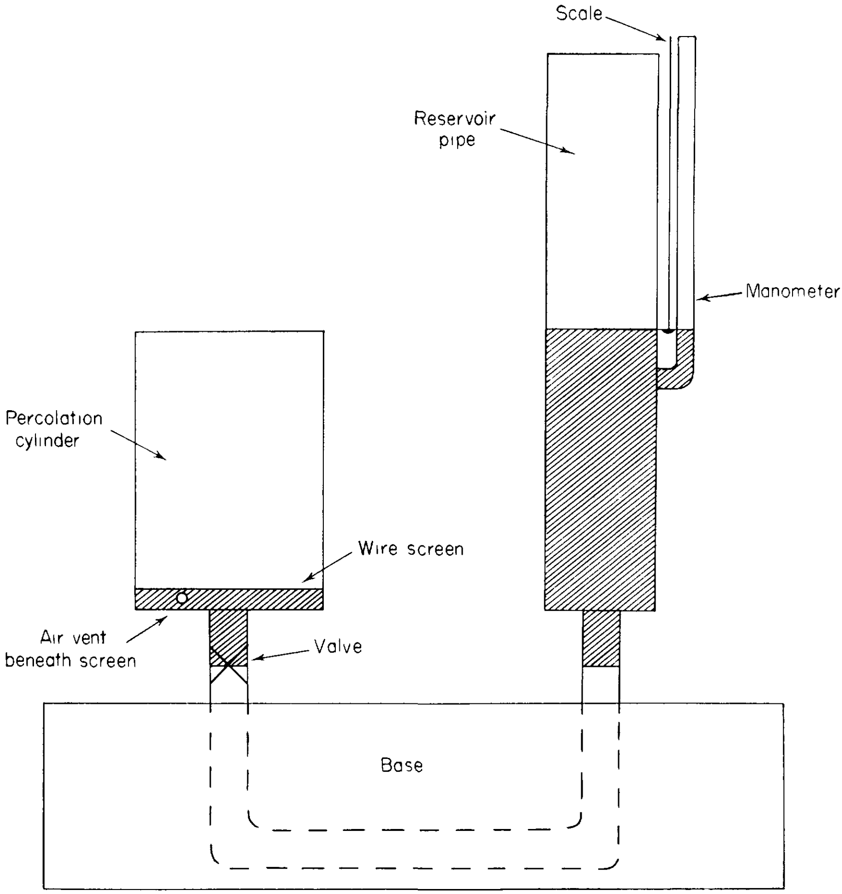

FIGURE 27.—Diagrammatic sketch of variable-head permeameter. Hatched area represents volume of "blank."

ter. The drain cock was then opened and all the water was drained into a graduated cylinder and the amount recorded. The volume of water drained represented the gross volume of the permeameter below zero on the manometer and above the drain-cock level. The net volume of the percolation cylinder above the screen was subtracted from this measured gross volume, and the remainder was termed the "blank." (See fig. 27.)

De-aerated water was then added to the apparatus until the percolation cylinder was one-third full. The sample material was poured evenly into the cylinder with a small scoop, each scoopful being added from a different direction after all bubbling from the previous addition had stopped. Water was added occasionally to keep the water surface above the top of the sample material at all times. When the percolation cylinder was about one-third filled with the sample, the material was tamped vertically 25 times with a wire rod about a tenth of an inch in diameter. The tamping process was repeated when the cylinder was two-thirds filled and again when completely full. After the last tamping, material was coned above the top of the cylinder, and the side was tapped 25 times with a hard rubber tube. The material on top of the percolation cylinder was then leveled with a round rod, and all adhering material was wiped from the outside of the cylinder. The round rod was then laid across the top of the cylinder to break the meniscus so that the water surface was again level with the zero of the manometer scale.

Water was then drained out of the sample by opening the drain cock. As soon as the water level had declined to the level of the wire screen the 3/16-inch hole at the base of the percolation cylinder was opened to allow air to enter below the screen. The water removed during this preliminary drainage period of 5 to 15 minutes was measured and recorded. The volume of the blank was subtracted from the volume drained at this stage; the remainder represented water drained from the sample. This completed the first step in obtaining data for the determination of the coefficient of drainage.

The percolation cylinder was next removed from the permeameter and prepared for further draining. A paraffin-paper cap, held in place by rubber bands or string, was placed over the top to prevent evaporation from the sample. A wick of turkish toweling was then forced through the bottom of the permeameter, through the 1/4-inch hole in the screen, and up into the sample about 5 inches. The wick was about 18 inches long and 1 1/2 inches wide, except for the part forced into the sample, which was cut to 1/4-inch width. The wick provided a rapid means of removing much of the remaining water from the sample and disposing of this water by dripping and by evaporation. Paper toweling was packed around the wick in the space below the wire screen. The 3/16-inch hole in the side of the permeameter was plugged. The paper cap, paper toweling, and plug prevented air from reaching the sample freely, but it is not believed that the cylinder was sufficiently airtight to prevent air from entering to replace the water withdrawn by the wick, which would have impeded draining and introduced an error. The application of the paper cap and the toweling was done rapidly, and care was taken to see that no water was lost.

The percolation cylinder was then weighed and placed on a draining rack with the free part of the wick exposed to the air. During development of the method the samples were left to drain on the rack for 192 hours and were weighed twice a day. Results indicated that draining for 48 hours was all that was necessary, but to insure sufficient time for drainage a 72-hour period of draining was adopted.

The wick probably removed some water that would not have drained by gravity in the periods of the tests. However, the error introduced by this factor is believed to be small. Sediments of the kind tested characteristically yield small amounts of water by gravity for long periods after the major part of the water has drained out.[38] This would tend to compensate for errors introduced by use of the wick where the results of the laboratory tests are applied to declines of the water table in the field that persist over several months, even where an adjustment such as that in figure 28 is not made (see below).

COMPUTATION AND EVALUATION OF RESULTS

A graph showing rate of drainage was prepared by plotting the gross weight of the percolation cylinder and sample, in grams, versus elapsed time. The loss of weight in grams by draining on the rack for any period was the difference between the ordinates at the beginning and end of the period, and this was considered equal to the loss of water in cubic centimeters during the period. The total loss by draining was equal to the volume of water lost during the preliminary draining period, before the percolation cylinder was removed from the permeameter, plus the volume of water lost during the period that the sample was drained on the rack. The percentage of loss by draining was the total loss divided by the volume of the sample (previously determined volume of percolation cylinder), times 100.

In relating the percentage of loss by draining of a laboratory sample to the coefficient of drainage, several periods of drainage (24, 48, 72, and 96 hours) were considered. The 48-hour period was finally adopted because it was the shortest period that gave a consistent relation between the percentage of loss by draining and the coefficient of drainage.

The coefficient of drainage was obtained indirectly. Coefficients were determined in long cylinders and in tanks as previously described. Samples from these cylinders and tanks were then tested in the laboratory for percentage of loss by draining. A curve for sand and gravel was prepared by plotting the drainage coefficient determined from the long cylinders and tanks versus the loss by draining determined by the laboratory method. (See fig. 28.) The approximate coefficient of drainage could then be determined for any sample of similar composition by

[38] Meinzer, O. E., The occurrence of ground water in the United States, with a discussion of principles: U. S. Geol. Survey Water-Supply Paper 489, p. 65, 1923.

applying the laboratory results to the curve. A different curve would be obtained for clay.

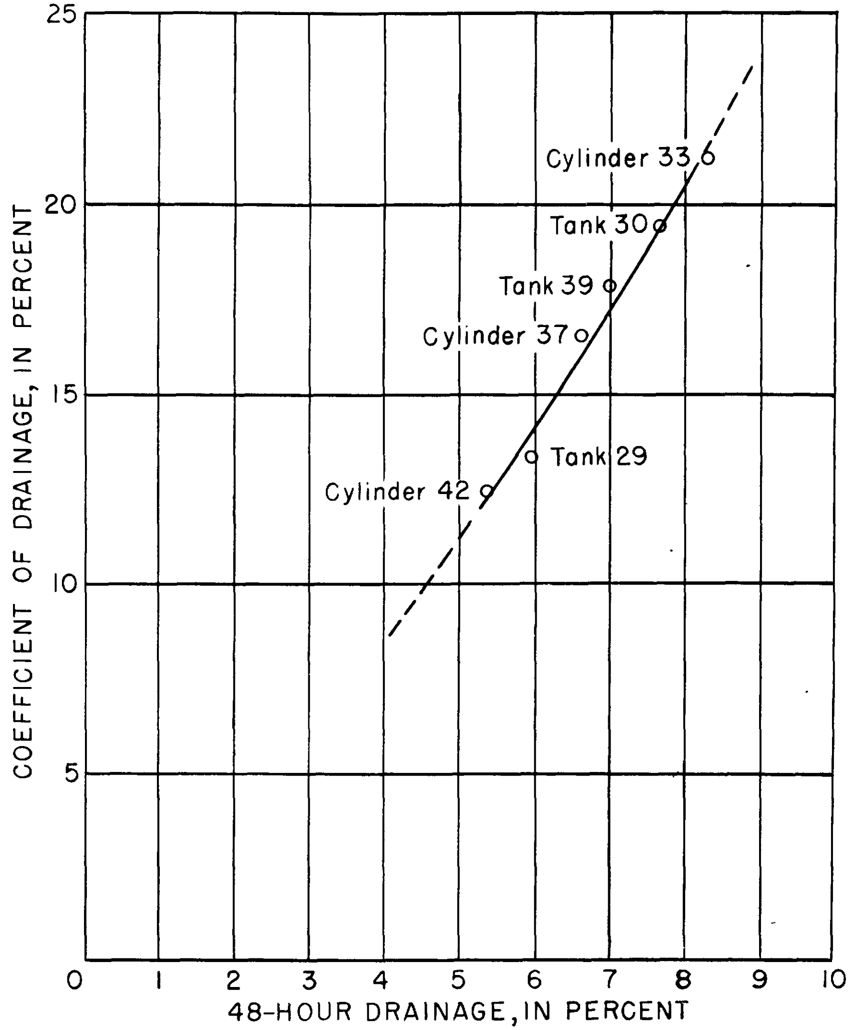

FIGURE 28.—Relation between 48-hour drainage of laboratory sample and coefficient of drainage as determined from cylinders and tanks for sand and gravel.

The percentage of loss by draining, as determined by the laboratory method, provides an index for correlating the water-yielding capacity of samples of water-bearing materials. The percentage of loss by draining cannot be applied to the field directly, however, as the results by draining 48 hours are low and must be adjusted according to a curve similar to figure 28.

An inherent weakness of the laboratory method lies in the possibility of variation in the rate of disposal of water from the wick while the sample is on the draining rack. The rate of evaporation, and hence the amount lost, varies with the humidity, being low when the humidity is high. In Safford, where the humidity is low most of the time, this did not present a serious problem.

The ideal method of determining in the laboratory the coefficient of drainage from a sample would be to work with a percolation cylinder of sufficient length to include a water table, a capillary fringe, and a zone of vadose water. However, as it is not feasible to make large numbers of determinations at reasonable cost using long cylinders or tanks, the laboratory method described, correlated with the data obtained from the cylinders and tanks, was of necessity adopted for most of the work on yield. The materials underlying the bottom land are extremely heterogeneous. The errors that may result from applying to a large area the coefficient as determined from about 10 long cylinders will be as great as the errors that may result by determining the coefficient in 3 long cylinders and in about 200 laboratory samples.

Samples of water-bearing materials were collected from each foot of depth in all the tanks and transpiration wells. In addition, samples of water-bearing materials were collected from many of the large irrigation wells that were drilled in the valley during the investigation. As the number of samples collected exceeded 500, determinations of coefficient of drainage were made only for the range through which the water table fluctuated during the investigation. A total of 233 samples of water-bearing materials was tested for coefficient of drainage in the Safford hydrologic laboratory during 1943 and 1944.

MINIATURE PUMPING TESTS

One of the methods of determining the coefficient of drainage or saturation for an aquifer is by making pumping tests on a well that penetrates the aquifer. The general method has several modifications,[39] such as measuring the drawdown in nearby observation wells as pumping proceeds or measuring the recovery of the water level in the pumped well and the observation wells after pumping has ceased.

The coefficients of drainage and saturation desired for lower Safford Valley during the investigation were those of the relatively narrow range of materials through which the water table fluctuated. As most pumping tests result in coefficients that apply to the entire saturated thickness of the aquifer, standard procedures could not be applied. An attempt was made to determine the water-bearing characteristics

[39] Wenzel, L. K., Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods: U. S. Geol. Survey Water-Supply Paper 887, 192 pp., 1942.

of this zone by means of a pumping test that would affect only a few feet in the upper part of the saturated zone.

One of the miniature pumping tests attempted was in an 8-inch bored well that penetrated only 2 feet of saturated material. The well was located in the bottom land near Pima in a clearing among thickets of saltcedar. One-inch sand-point observation wells were driven to about 3 feet below the water table. Four of the wells were in a line with the pumped well, spaced about 3 feet apart, two to the north and two to the south. Two more observation wells were installed about 100 feet from the pumped well, one to the north and one to the south. The four observation wells near the pumped well were used for determining the cone of depression, and the two distant wells were used for determining the general upward or downward trend of the water table during the test.

The pump was a small rotary type, powered with a gasoline engine. One of the tests covered a period of 7 hours 45 minutes on December 28, 1943. The average discharge of the pump was 0.783 gallon a minute. The maximum drawdown in the pumped well was 1.55 feet. The mean transmissibility [40] of the material for a zone of unknown thickness, was computed to be about 5,000 gallons a day per foot, but the computed coefficients both of transmissibility and storage were erroneous because existing formulas assume flow through the entire thickness of the aquifer.

The conclusion reached as a result of the tests was that the method has promise but must be developed further before it can be successfully used in field determinations of the coefficients of drainage and saturation in a narrow zone.

COMPUTATION OF MEAN COEFFICIENTS

For each transpiration well the coefficient of drainage was determined as the mean of all tests on samples from that well. For the tanks, tables were prepared showing the mean coefficient of drainage and saturation for each foot of depth, and where available, for each 6 inches of depth. The tables were applied in making computations of water use by the tank method.

The mean coefficient for lower Safford Valley was computed from the results for the three long cylinders, all of the tanks, and the 233 samples tested in the laboratory. This figure was 16 percent and has been used in all the computations involving a change in ground-water storage in the valley.

[40] The transmissibility may be expressed as the amount of water, in gallons a day, that will percolate, under prevailing conditions of temperature, through a section of the aquifer 1 foot wide under a hydraulic gradient of 1 foot per foot, or through a section 1 mile wide under a hydraulic gradient of 1 foot per mile.

CHANGES IN GROUND-WATER STORAGE

Quantitative information was needed regarding changes in ground-water storage for computations of water use by four of the methods. Computations by the inflow-outflow method required that the changes be expressed as a volume; that is, that the changes for a given area in a given period be expressed in acre-feet. Computations of net underground inflow by the seepage-run method required that the changes be expressed as a rate, in second-feet or in acre-feet per day, for a period of about a week preceding each seepage run. Figure 29 illustrates graphically the difference between volume of change and rate of change. The example given shows that, although the net amount of change in position of the water table between the two dates is zero, the rates of change for the week preceding the two dates are about +0.05 foot per day.

VOLUME OF CHANGE

In the computations by the inflow-outflow method, information was needed on the volume of water involved in changes in the position of the water table during specified periods. For example, it was necessary to know how much water was involved in a rise or fall of the water table underlying the bottom land during a specified period, such as a calendar month.

The first step in the method used to evaluate these changes was to determine the algebraic difference between the mean elevation of the water table in a reach at the beginning of the period and at the end of the period. The resulting mean change in water level, in feet, was then multiplied by the area of the reach, in acres, and by the mean coefficient of drainage and saturation, in percent, to obtain the amount of water in acre-feet.

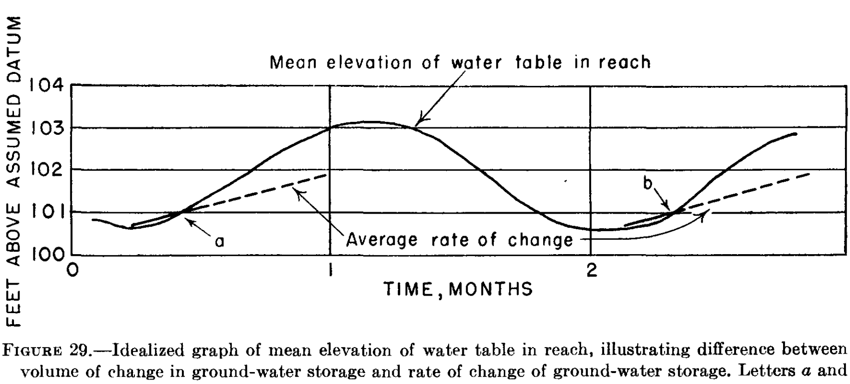

FIGURE 29.—Idealized graph of mean elevation of water table in reach, illustrating difference between volume of change in ground-water storage and rate of change of ground-water storage. Letters *a* and *b* indicate dates between which volume of change is desired and for which rate of change is desired. Change in storage between *a* and *b* is zero, although the rates of change shown at *a* and *b* are about +0.05 foot per day for the week preceding the dates.

The mean elevation of the water table for any date for the upper three reaches was determined by plotting contours of the water table as of that date and measuring with a planimeter the area between successive 4-foot contours. Each area between contours was multiplied by the mean elevation of the water table in that area, and the sum of these products was divided by the total area of the reach, to determine the mean elevation of the water table in the reach. For the Black Point-Calva reach the mean elevation of the water table for any date was estimated from the position of the water table at the three lines of observation wells.

RATE OF CHANGE

Information on the rate of change in the contents of the ground-water reservoir beneath the bottom-land area was needed in order that the net amount of underground inflow might be determined from the seepage-run results. The rate of change in contents of the ground-water reservoir in a given area was computed from the equation

$$\text{Rate of change in contents (in second-feet)} = \frac{0.16}{1.983471} \times \text{area (in acres)} \times \begin{array}{l}\text{rate of change of elevation of}\\ \text{water table (in feet per day).}\end{array}$$

The figure 0.16 is the mean coefficient of saturation and drainage for the entire bottom land. The figure 1.983471 is a factor to convert from acre-feet per day to second-feet.

All graphs of water-table fluctuations available for a given area were used to compute rate of change in elevation of the water table for that area. These graphs were of two kinds: Those from water-stage recorders operated on transpiration wells and those plotted for observation wells on which weekly readings were made. The rate of change that was used was the average, in feet per day, for about a week preceding the date of the seepage run. Usually it made little difference whether the rate of change for a week or for a few days was used, because the seepage runs were always made after a period free from storms or fluctuations in the river discharge, that is, during a period when the rate of change of ground-water storage was fairly uniform.

The number of wells on which the rate of change in elevation of the water table was based was about 30, 14, 17, and 16, respectively, for the four reaches in downstream order between Thatcher and Calva. In the three upstream reaches, the rate of change of elevation of the water table was computed as the mean of the change for all wells in the reach, as the geographic distribution of the wells was almost uniform. In the reach from Black Point to Calva, the mean rate was computed by weighting the results from two lines of wells in the reach (see pl. 3) and a line of wells just upstream from the reach.

SEEPAGE RUNS

Gains and losses by seepage through the sides and bottom of a river channel are an index to hydrologic changes in the valley of a river flowing over a permeable bed. The general plan for determining these gains and losses in lower Safford Valley was to make a series of river-discharge measurements about once a month between the gaging station near Thatcher and the station at Calva and to compute gains and losses in flow between each two consecutive points at which the river discharge was measured. Each series of measurements was called a seepage run.

Seepage runs were made when the flow of Gila River was low and approximately steady. Small differences between the discharge at the beginning and at the end of a reach could be determined more accurately from measurements of low flow than from measurements of high flow. When the flow of the stream was fairly steady, failure to calculate the correct amount of time required for water to travel between successive measuring points did not cause appreciable errors in the computed gains and losses. Determined gains and losses were considered representative of periods of several weeks, because the flow of the river had been reasonably stable for some time before seepage runs were made.

FIELD MEASUREMENTS

The first seepage run for the investigation was made in June 1943. The flow of the river was measured at 14 points between the gaging stations near Thatcher and at Calva. Diversions into canals were measured. Known surface inflows to the river were measured, but no special effort was made to locate all inflows. However, as the flow of the irrigation canals was very low, probably no large inflows were missed. No additional seepage runs were made until September because of fluctuating river discharge. In the September run and in the next two, made during November, measurements of river discharge were made at the same 14 points as in the first run. In runs made after November two additional measuring points were included in the Fort Thomas-Black Point reach. For all except the first seepage run an engineer walked downstream along the river as far as the gaging station at Black Point to measure any inflow that otherwise might have been missed. Inspection for inflow from Black Point to Calva was considered unnecessary because little water was used for irrigation in that reach, and probably none was wasted to the river.

Interpretation of the results of the seepage runs was aided by the fact that nine of the points at which measurements of the river were regularly made during the runs were gaging stations equipped with water-stage recorders. At the other measuring points a maximum of six water-stage recorders were operated in temporary wells and shelters for the period of each seepage run.

In all, 15 seepage runs were made, 13 of which were completed from the gaging station near Thatcher to the station at Calva. Two seepage runs were made from the station near Glenbar to the station at Calva in July and August 1944, despite fluctuations in discharge caused by summer rains. These two runs could not be made in the Thatcher-Glenbar reach.

COMPUTATION AND ADJUSTMENT

Table 21 shows the measured discharge at points on the river at times of seepage runs, and the net tributary inflow or net diversion outflow between consecutive points at which measurements of river discharge were made. Figures of gain or loss unaccounted for by direct measurement of tributary inflow and diversion outflow are given in table 22. These figures of gain or loss between successive river-measuring points have been adjusted to eliminate the effect of changes in stage. They do not show the true seepage into the river, however, as they are too small by the amount of evaporation from the river surface and from wet sand bars.

In order to make adjustments for changes in stage, the river in lower Safford Valley was divided into segments, each segment limited by two successive points of river measurement. Thus, for each segment there was a measurement of river discharge at each end and measurements of all surface inflows and diversions occurring within the segment. One of the measurements of inflow, diversion, or river flow in each segment was chosen as a base with respect to time. All other discharge measurements in the segment were then adjusted to a time equivalent to that of the base measurement, and the discharge for each adjusted measurement was called the "equivalent discharge." For a given pair of river measurements the equivalent discharge at the downstream point was the discharge that would have occurred at that point if the flow in the segment were unaffected by changes in channel storage or changes in surface-water inflow or diversion. The difference between the river discharge at any point and the equivalent river discharge at the succeeding point, adjusted for equivalent surface inflows and diversions, represents the seepage gain or loss without correction for evaporation from the river surface and wetted sand bars.

The basic information for computing equivalent discharge was the time of travel of any designated point on the hydrograph as it moved downstream. That rate of travel is not identical with the rate of travel of the equivalent discharge as defined, but it is easily computed and with the procedures used in this investigation is believed to be a sufficiently accurate substitute. Time of travel was determined for the

TABLE 21.—*Measured discharge, in second-feet, of Gila River and net tributary inflow or net diversion outflow, Thatcher to Calva, Ariz., 1943-44*

Distances by river between points of measurement are given in table 22. Where two figures for river discharge are shown, the upper figure indicates measurement at end of a day, and the lower figure indicates measurement at same point at beginning of next day]

Point of measurement on river	1943										1944					
	June 24, 25		Sept. 16–18		Nov. 4, 5, 9		Nov. 23, 25, 26		Dec. 13, 14, 16		Jan. 13–15		Feb. 14, 15, 18		Mar. 15–17	
	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)
Near Thatcher	1.6		3.1		6.1		4.0		10.8		34.5		23.9		5.5	
		0		+0.3		+28.1		+15.1		+22.9		+47.3		+15.9		+1.7
Above Dodge-Nevada Canal heading	.1		2.9		35.3		17.3		32.4		83.5		39.3		9.5	
		+.5		0		−21.8		−8.0		−2.5		−16.9		+.6		−1.8
At Pima	4.0		5.4 9.2		20.9		17.1		41.9		77.7		69.9 56.6		17.2	
		−2.7		−7.4		+8.9		+7.7		+5.2		+3.6		+3.2		−11.0
Above Fort Thomas Canal heading	2.7		5.6		37.3		35.7		67.8		89.3		76.7		12.8	
		−1.1		−2.6		−36.9		−35.4		−66.9		−86.0		−75.0		−12.0
Near Glenbar	.6		2.1		1.7 1.8		2.4 2.2		2.3 1.8		5.9 6.6		6.1 3.1		2.9 3.1	
		0		0		+13.1		+6.5		+30.1		+72.6		+19.3		+.1
At Eden crossing	.2		2.7		16.7		9.9		34.2		81.5		26.4		6.2	
		0		0		+15.4		+11.6		+6.0		+.6		+3.7		+2.8
Near Ashurst	.7		1.7		31.4		25.1		44.7		82.0		34.8		14.4	
		0		0		0		0		0		0		0		0
Above Colvin-Jones Canal	1.0		2.9		32.9		29.6		48.4		94.9		38.2		17.7	
		0		0		+4.5		+3.3		+8.1		+1.9		+4.3		+.2
At Fort Thomas	.5		2.5		36.0 29.0		31.8 26.8		56.8 50.7		94.6 73.9		46.2 24.6		20.0 19.3	
		0		0		0		0		0		0		+1.0		0
Above wash 1.8 miles below Fort Thomas									50.6		70.8		26.1		19.4	
		0		0		+4.7		0		+3.8		+.6		0		0
Near Geronimo	3.5		6.0		40.0		30.6		62.2		80.4		33.0		27.0	
		0		0		+1.8		0		+8.0		+.4		+.7		0
1 mile below Goodwin Wash									78.6		91.7		42.7		32.6	
		0		0		0		0		0		0		0		0
At Geronimo crossing	5.5		10.6		49.7		38.8		76.0		89.2		46.8		33.7	
		0		0		0		0		0		0		0		0
At Black Point	2.1 2.8		6.6 9.3		50.8		38.0		79.2		92.5		48.0		35.5	
		0		0		0		0		0		0		0		0
At Bylas	2.3		9.0		52.9		41.0		79.1		101.2		53.4		38.3	
		0		0		0		0		0		0		0		0
At Calva	0		3.7		46.8		38.3		84.3		107.6		57.5		40.8	

TABLE 21.—*Measured discharge, in second-feet, of Gila River and net tributary inflow or net diversion outflow, Thatcher to Calva, 1943*—Continued

Point of measurement on river	1944													
	April 12–14		May 3–5		May 24–26		June 21–23		July 17, 18		Aug. 7, 8		Oct. 26–28, 30	
	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)	River discharge	Net inflow (+) or outflow (−)
Near Thatcher	4.3		3.9		5.8		0.8						31.2	
		+11.3		+2.2		+1.0		0						+23.1
Above Dodge-Nevada Canal heading	16.9		6.4		4.9		0						54.6	
		+1.9		−3.8		−3.1		+.5						−17.3
At Pima	29.0 26.5		7.5 9.4		6.0 6.4		2.7 3.0						43.3 33.7	
		−21.3		−.3		−5.7		−2.1						+2.8
Above Fort Thomas Canal heading	13.1		15.9		7.0		3.9						42.7	
		−12.4		−15.3		−6.6		−3.2						0
Near Glenbar	2.7 2.8		2.2 2.6		1.4 1.5		.8 .8		1.5		0.7		40.9 36.1	
		0		+1.3		0		0		0		0		+.6
At Eden crossing	4.4		5.6		1.7		.1		.6		0		38.4	
		0		+2.3		0		0		0		0		+.6
Near Ashurst	8.9		9.0		1.9		.5		.4		.3		37.8	
		0		0		0		0		0		0		0
Above Colvin-Jones Canal	12.3		11.9		5.0		1.8		1.2		1.1		39.2	
		−4.0		+.5		+1.2		0		0		−.2		+1.0
At Fort Thomas	8.9 9.6		11.4 10.0		6.1 6.6		1.1 1.1		.4 .8		.3 .7		43.0 41.2	
		0		0		+.4		0		0		0		0
Above wash 1.8 miles below Fort Thomas	11.2		10.8		6.1		.6		.2		.3		39.9	
		0		0		0		0		0		0		0
Near Geronimo	17.4		16.3		9.7		2.9		2.5		3.6		42.1	
		0		0		0		0		0		0		0
1 mile below Goodwin Wash	24.0		21.0		14.0		6.2		4 9				48.1	
		0		0		0		0		0		0		0
At Geronimo crossing	23.6		22.2		15.5		7.2		5.8		7.5		50.7	
		0		0		0		0		0		0		0
At Black Point	21.2		19.9		12.0		3.1		3.9		5.3		47.4	
		0		0		0		0		0		0		0
At Bylas	25.6		20.7		12.8		2.1		5.1		4.2		49.2	
		0		0		0		0		0		0		0
At Calva	25.1		18.5		8 9		0		0		0		48.7	

TABLE 22.—*Gains (+) and losses (−), in second-feet, in Gila River between Thatcher and Calva, Ariz., during seepage runs, 1943-44, and unaccounted for by measured tributary inflow and diversion outflow*

Segment of Gila River	1943 June 24, 25	1943 Sept. 16–18	1943 Nov. 4, 5, 9	1943 Nov. 23, 25, 26	1943 Dec. 13, 14, 16	1944 Jan. 13–15	1944 Feb. 14, 15, 18	1944 Mar. 15–17	1944 Apr. 12–14	1944 May 3–5	1944 May 24–26	1944 June 21–23	1944 July 17, 18	1944 Aug. 7, 8	1944 Oct. 26–28, 30
Thatcher to Dodge-Nevada Canal heading (2.7 miles)	−1.2	+0.6	+1.5	−1.7	−1.3	+1.7	+0.7	+2.4	+0.1	+0.2	−0.8	−0.6	......	......	+0.6
Dodge-Nevada Canal heading to Pima (2.6 miles)	+2.7	+3.3	+6.0	+8.3	+10.3	+11.1	+17.6	+9.8	+7.6	+6.1	+4.0	+2.2	......	......	+6.1
Pima to Fort Thomas Canal heading (4.1 miles)	+.9	+3.5	+5.1	+11.2	+12.6	+8.0	+15.5	+10.3	+7.3	+10.3	+5.8	+2.7	......	......	+5.9
Fort Thomas Canal heading to Glenbar (1.2 miles)	+.3	+.5	+1.3	+2.1	+1.4	+1.4	+2.0	+2.1	+2.2	+1.7	+.9	+.1	......	......	+.2
Glenbar to Eden crossing (1.7 miles)	−.3	+.7	+1.8	+1.2	+2.3	+2.3	+4.0	+3.0	+1.3	+.8	+.3	−.7	−0.8	−0.7	+1.7
Eden crossing to Ashurst (5.5 miles)	+.4	−1.3	−.7	+.5	+2.1	+1.4	+3.5	+6.7	+4.5	+2.8	0	+.4	−.2	+.2	−1.2
Ashurst to Colvin-Jones Canal heading (2.2 miles)	+.2	+1.8	+1.5	+3.6	+3.7	+12.9	+4.6	+3.3	+3.4	+2.6	+2.1	+1.2	+.6	+.6	+2.6
Colvin-Jones Canal heading to Fort Thomas (1.7 miles)	−.5	−.9	+.8	−.6	+.3	−2.2	+3.7	+2.1	+.5	−.1	−.2	−.7	−.6	−.5	+2.8
Fort Thomas to wash 1.8 miles below Fort Thomas (1.8 miles)	+2.6	+3.8	+5.4	+3.8	−.1	−3.1	+.5	+.4	+1.6	+.9	+.9	−.4	−.4	0	−1.3
Wash 1.8 miles below Fort Thomas to Geronimo (2.1 miles)					+5.6	+7.8	+6.9	+6.8	+5.2	+4.4	+3.6	+2.1	+2.1	+1.4	+2.2
Geronimo to 1 mile below Goodwin Wash (1.8 miles)	+3.2	+5.3	+7.0	+8.2	+11.7	+12.1	+9.0	+6.4	+7.6	+5.0	+4.5	+3.1	+2.4	+2.9	+6.0
One mile below Goodwin Wash to Geronimo crossing (0.7 mile)					−2.6	−2.5	+4.1	+1.1	+.4	+2.0	+1.5	+1.0	+.9		+2.6
Geronimo crossing to Black Point (3.5 miles)	−4.4	−3.3	+1.1	−2.2	+2.1	+3.3	+1.2	+1.2	−2.2	−1.6	−3.2	−3.9	−2.4	−2.0	−3.3
Black Point to Bylas (4.1 miles)	−.2	+.6	+1.0	+2.5	−1.2	+2.3	+2.6	+1.3	+2.0	−.4	+.3	−.8	−.8	−.1	+.4
Bylas to Calva (10.1 miles)	−1.8	−5.0	−6.1	−2.7	+1.3	0	+4.1	+4.0	+.7	−.7	−3.2	−1.9	−5.1	−2.6	−1.8
Thatcher to Calva (45.8 miles)	+1.9	+9.6	+25.7	+34.2	+48.2	+56.5	+80.0	+60.9	+42.2	+34.0	+16.5	+3.8	......	......	+23.5
Daily discharge at Fort Thomas	0.4	2.9	32	26	56	91	49	21	9.0	9.9	4.9	0.9	0.4	0.8	42

distance between a given pair of successive gaging stations. Peaks, troughs, and other points that could be identified easily on the recorder charts of the two stations were listed. The time required for each identifiable point at the upstream station to reach the downstream station was plotted on logarithmic graph paper against the average discharge for the two stations. A curve was drawn through the plotted points. This curve showed the relation between the average time of travel and the average discharge. Similarly, time of travel was computed for the distances between all other pairs of successive gaging stations.

In general, for a given segment of the river, discharge measured in those seepage runs that were not complicated by diurnal fluctuations was adjusted according to the following procedure: First, the time of travel of the equivalent discharge within the segment was determined from the applicable logarithmic curve on the basis of the average discharge. Second, the time of measurement of discharge at one of the points of measurement of river flow, inflow, or diversion was selected as the base time from which the equivalent discharge was computed. The time of occurrence of equivalent discharge at any other point within the segment was then automatically fixed by the time of travel. Third, the equivalent discharge was computed for each point. Finally, the gain or loss unaccounted for by tributary inflow or diversion outflow was computed from the equivalent discharge. This process was repeated for each segment of the river. There was not necessarily any relation among the base times used for successive segments of the river.

Equivalent discharge was computed easily for points where both the gage-height record and the relation between gage height and discharge were known. For points where these data were not available, the difference between the time when the equivalent discharge occurred and the time when the discharge was measured was made as small as possible by suitable selection of the base time. Then the equivalent discharge was either assumed to be equal to the measured discharge, an assumption usually made for very small inflows, or was computed from records of gage height or discharge at nearby points.

When the flow of the river was low during the growing season, the flow fluctuated during each 24-hour period according to a more or less standardized pattern (see fig. 22). The fluctuations were due to changes in the rate of evaporation from the river surface and wet sand bars and changes in the rate of seepage flow to or from the river channel. The difference between the discharge at successive points of measurement on the river during the growing season depended, therefore, partly on the time of day when the measurements were made. In the growing season the difference in river flow between two successive points was determined by comparing the average flow at one point during a 24-hour period with the average flow at the other point during a 24-hour period. The beginnings and ends of the 24-hour periods were made to differ by the time of travel between the two points.

The computation of the gains and losses for seepage runs made during the growing season thus consisted of four steps. First, time of travel between all measuring points was computed. Second, the end of the 24-hour period to be used at each measuring point on the river or on inflows or diversions was chosen. For a given pair of points, the 24-hour period at the downstream point lagged by the time of travel behind the end of the period at the upstream point. Third, the mean equivalent discharge during each 24-hour period was computed. Finally, the gains and losses unaccounted for by tributary inflow or diversion outflow were computed from the mean equivalent discharge for the 24-hour periods.

The details of the method of adjusting seepage runs were varied extensively to fit the basic data available for the different runs.

ACCURACY

The accuracy of the computed gains and losses depends on the accuracy of the discharge measurements and of the computations of equivalent discharge. Measurements of discharge of more than 30 second-feet could not be used to compute gain or loss accurately to fractions of a second-foot. Many measurements of discharge greater than 10 second-feet probably were correct within 2 percent, but some measurements were less accurate because available measuring sections were not always satisfactory. Errors may have been introduced because of rapid change in rate of surface inflows to the river. The rate of inflow may have increased or decreased greatly soon after measurement. Errors of this type probably are compensating. Unless an equivalent discharge differed greatly from the measured discharge, the equivalent discharge probably was nearly as accurate as the corresponding measured discharge. Most figures of gain or loss for periods when the flow of the river was low probably are accurate to tenths of a second-foot.

NET UNDERGROUND INFLOW

SOURCES OF NET UNDERGROUND INFLOW

An evaluation of net underground inflow was necessary for four of the methods applied to determine use of water. Net underground inflow, as used in this report, is the difference between flow of ground water into a reach and flow of ground water out of a reach. Such inflow might remain in the reach as stored ground water or might leave the reach by seepage to a surface channel or by evaporation or transpiration.

The principal sources of water that eventually enters a reach as ground water are: (1) Seepage from artesian sources; (2) seepage from washes; (3) seepage from canals; (4) seepage from irrigated fields; (5) the part of the precipitation that percolates to the water table; and (6) seepage from the river. As the net underground inflow is the difference between inflow and outflow and was obtained from computations based on surface flows, the total amount of underground flow was not important. It was not practicable to make direct quantitative measurements of ground-water movement.

It was not possible to measure all the small surface flows entering and leaving each reach. They were mostly irrigation surface wastes and surface flow of small washes. By the computation procedures adopted, the net underground inflow is too great by the amount of those inflows and too small by the amount of those outflows. The net amount of water from these sources that was not measured during the investigation is believed to be negligible and is not considered in the computations by the methods that require figures for net underground inflow.

For the winter, when evaporation and transpiration were zero or negligible, the net underground inflow was computed as the flow represented by the difference between surface inflow and outflow after adjusting for precipitation and evaporation in the river channel and for all changes in storage. The annual fluctuation in this inflow is small, as shown in the discussion that follows; hence, the inflow computed for the winter months may be assumed to represent, approximately, the net underground inflow at any time during the year.

PROBABLE RANGE OF ANNUAL FLUCTUATION

In applying the seepage-run method, the inflow-outflow method, and the chloride-increase method, it was necessary to assume that the net underground inflow was constant throughout the year, or that it varied within sufficiently narrow limits that it did not introduce large errors in the computation of water use. Such an assumption appeared reasonable for the period of the investigation. It might not be a reasonable assumption for other periods.

Net underground inflow consisted of the net general movement of ground water across the boundaries of the reach under consideration, plus the difference of underflow of the river into and out of the reach, plus underflow of washes into the reach, plus seepage from artesian sources within the reach. The rate of seepage from artesian sources changes very slowly and any changes during the year probably can be neglected. The greater part of the water year October 1943 to September 1944 was exceptionally dry and it is believed that variations in underflow during that year were small and can be neglected.

The rate of general ground-water movement across the boundaries of a reach is controlled mostly by the slope of the water table across that boundary.[41] Any appreciable variation in the supply of ground water from the various sources of net underground inflow listed previously will tend to change the slope of the water table and thus the rate of ground-water flow. All the sources of supply are subject to some monthly and seasonal variation. Water percolating through the beds of the washes in the highlands and closely adjacent areas during periods of runoff builds up the water table in those areas and increases the slope of the water table at the north and south margins of the bottom lands. This increase is followed by a gradual decline of the water table during succeeding dry periods, and reduction of the slope at the margin. The washes had a substantial flow during and immediately after heavy rains in August 1943, but the discharge from them during the succeeding 11 months was relatively small, being on the order of magnitude of a few hundred acre-feet. Heavy flows of water occurred again during August 16-21, 1944. From this it is inferred that the rate of inflow to the bottom-land areas from wash seepage during the year was greatest in October 1943 and September 1944, and that from October 1943 to the middle of August 1944 there was a gradual decline. On this basis the average inflow during the winter months, in the first half of the period of decline, probably was somewhat greater than the average during April to July. The canals carried substantial quantities of water throughout the year, even during the winter months, and, therefore, it is likely that inflow from that source did not vary much. In some localities percolation to the water table from lands that were irrigated from canals, and resulting increases in the slope of the water table and inflow at the north and south edges of the bottom lands, probably were greatest during the summer and least during the winter. In other localities where pumping from wells for irrigation was heavy the reverse may have been true. The part of the precipitation that percolated to the water table doubtless was small except during the periods of heavy rain on August 16-21, 1944. Moreover, rainfall percolation occurs on both sides of the boundary of a reach and thus tends to cancel out so far as the slope of the water table is concerned. Transpiration of plants during the growing (non-winter) season causes a decline of the water table in the bottom lands and increases the hydraulic gradient and consequently the inflow at the outer border of those areas.

In considering the effect of variations in the supply of ground water it should be noted that, in all probability, the average rate of movement in the bottom lands and adjacent areas is low, perhaps less than 100 feet a year—computations based on figures for apparent transmissi-

[41] Wenzel, L. K., Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods: U. S. Geol. Survey Water-Supply Paper 887, p. 2, 1942.

bility and slope, given in the section on the slope-seepage method, indicate that such is the case. This slow movement tends to spread out over a period of months the effect on the inflow of intermittent recharge from all sources. If the area between these sources and the bottom lands is wide, variations in inflow might be largely eliminated. The conclusion was reached, therefore, that the total average net underground inflow to the bottom lands during the winter months, when the plants were dormant or nearly so, did not vary greatly from the average during the growing season April to November, and that the rate of inflow throughout the year was constant within reasonable limits.

RATE OF NET UNDERGROUND INFLOW TO BOTTOM LAND

The rate of net underground inflow to the bottom-land area was computed by the inflow-outflow method for the three reaches from Glenbar to Calva only. Computations for all four reaches from Thatcher to Calva were made as part of the seepage-run method. The two methods followed independent lines of reasoning and thus two independent sets of data were provided. Although both methods gave results that were fairly accurate, the means of the two methods—for the three reaches where both methods were employed—were used in subsequent computations as being more accurate.

Computations of net underground inflow are described in part 3; the figures for the inflow-outflow method are given in tables 47-49. The results of those computations are summarized below. The means of the inflow-outflow and seepage-run (see p. 158) methods are also included for comparison and because they are part of the base data for the chloride-increase method.

TABLE 23.—*Net underground inflow, in second-feet, to bottom land*

Reach	*Inflow-outflow method*	*Mean of inflow-outflow and seepage-run methods*
Thatcher-Glenbar		27.8
Glenbar-Fort Thomas	17.0	15.5
Fort Thomas-Black Point	18.8	18.8
Black Point-Calva	3.2	4.0
Thatcher-Calva		66.1

PART 3. COMPUTATIONS OF USE OF WATER

The use of water by bottom-land vegetation has been computed by six different methods in this part of the report. The order in which the methods are given is governed by the type of basic data used. The first two methods, the tank method and the transpiration-well method, involve determination of the volume density of bottom-land vegetation. The next two methods, the seepage-run method and the inflow-outflow method, are based on the stream-flow data that were collected during the investigation. The chloride-increase method, which follows the inflow-outflow method, utilizes figures for inflow of ground water to the bottom land derived from the seepage-run and inflow-outflow methods. The slope-seepage method is given last.

TANK METHOD

The installation of the large tanks for growing plants at the Glenbar experiment station has been described in part 2 of this report. The discussion that follows describes the theory of the method, the factors that affect the use of water in the tanks or that cause misleading results, and computations of results.

THEORY

For many years the tank method has been used to determine the amount of water transpired by different types of vegetation. Plants of the species for which the rate of transpiration is to be found are grown in watertight containers, sometimes called potometers, the size of the containers ranging from small cans to large tanks, depending on the size of the plants. Conditions of soil, soil moisture, weather, and general environment are provided that duplicate as nearly as possible the conditions of similar plants in the field. The amount of water used by the plants in the tanks is recorded. It is usually reported by months or growing seasons, in inches, and is computed by dividing the amount of water added, in cubic inches, by the surface area of the tank, in square inches. The figures can be converted to field use on the basis of the relation of density of growth in the tank to the density of growth in the field. Some investigators object to the tank method of determining rate of use of water by plants because of the difficulty in converting measured use to field use. During the investigation in lower Safford Valley the volume-density theory was devised principally to overcome this difficulty.

OBJECTIONS OF OTHER INVESTIGATORS TO TANK METHOD

Kiesellbach [42] lists the following sources of error in performing experiments with plants growing in tanks:

A. Character of potometer and contents.
  1. Limitation of amount of soil.
    a. Through size of potometer.
    b. Through number of plants grown in potometer.
  2. Limitation of fertility of soil.
  3. Improper distribution of soil moisture.
  4. Evaporation from surface of soil.
  5. Entrance of rain water.
  6. Exposure of potometer and consequent effect on soil temperature.
  7. Unintentional lack of uniformity in soil.

B. Environment.
  1. Testing under unnatural habitat.

C. The plant.
  1. Plant individuality.
    a. Insufficient number of replications.
    b. Disease and injury.
  2. Stage of maturity.
    a. Insufficient development.

D. Errors due to methods of computation.

E. The personal element in drawing conclusions.

The following paragraphs describe what was done to overcome or minimize these possible errors during the investigation.

The large tanks (4 to 10 feet in diameter) used at the Glenbar experiment station minimized the possible error of using tanks that were too small. The plants were placed near the center of the tank, in order to allow ample room for root growth. The fertility of the soil used was the same as that of the soil that supported the phreatophytes growing naturally in the bottom land, and the depletion of fertility of the soil in the tanks was comparable to that under natural conditions. With respect to the possibility of improper distribution of soil moisture, the water was added to the tanks through the recharge well and was distributed through the coarse gravel layer at the bottom of each tank. Thus, conditions in the tanks simulated natural ground-water conditions; there was a zone of saturation, a water table, and a capillary fringe. Evaporation of moisture from the surface of the tank was considered a part of the total use, and therefore the determination or elimination of this factor was not necessary. The entrance of rain water into the tanks could not be prevented without affecting the rate of transpiration. Use of ground water was considered to be equivalent to the amount of water added manually to the tanks, and use of water from precipitation was added to use of ground water after the re-

[42] Kiesellbach, T. A., Transpiration as a factor in crop production: Nebraska Agr. Exper. Sta. Research Bull. no. 6, 1916.

sults from the tanks were applied to field conditions. The effect of exposure on soil temperature in the tanks was reduced by installing the tanks so that the rims extended not more than three inches above the soil (see fig. 15), and as the tanks were large relatively little excess heat was absorbed from the metal rims of the tanks. The possibility of error caused by unintentional lack of uniformity in the soil was slight, as the soil in the tanks was identical with the soil occurring in the bottom land where the tanks were located. The soil materials were replaced in the tanks in the order in which these materials originally occurred in nature. All the sediments in the bottom land were deposited by the river, some from running water and some from silty pools or from back water. These sediments are heterogeneous, therefore, and layers and lenses of silt, sand, and gravel occur indiscriminately.

The environment of the plants in the tanks was considered during selection of the site for the experiment station. The tanks were installed along the sides of a narrow natural opening between dense thickets of phreatophytes (see fig. 12); hence the environment of the plants in the tanks approached conditions of natural environment more closely than if the tanks had been in the center of the clearing or in an open field.

Insufficient replications of the plants is a financial rather than a horticultural problem. The tanks at the Glenbar experiment station were installed and operated in pairs, so that there were nearly always two tanks operating under the same conditions of water level, tank diameter, type of soil, and type of plant (see tables 26 and 27). A total of 29 tanks was operated. The plants grown at the Glenbar experiment station, with one exception, were not injured during transplanting. A break-down of equipment caused a delay of several hours in transplanting the saltcedar in tank 11. These plants never fully recovered from the shock of transplanting, and the results from this tank were not used in the final computations. An infestation of alfalfa stem girdler (*Stictocephela festina*) occurred in the baccharis plants in the summer of 1944, causing some of the plants to lose as much as half their leaves (see fig. 31, *B*). However, the same infestation occurred in the baccharis plants growing naturally in the river bottom, and it was decided not to discard the data on water use obtained during the period of the infestation. The factor of insufficient development of the plants, not including disease and injury, was minimized by computing the use of water on the basis of volume density and by discarding the records obtained during the first 2 months or more after transplanting. The plants grown in the tanks were not stunted or held back by limitation of the size of the tanks and grew as rapidly as plants under natural conditions. (See figs. 30-32.)

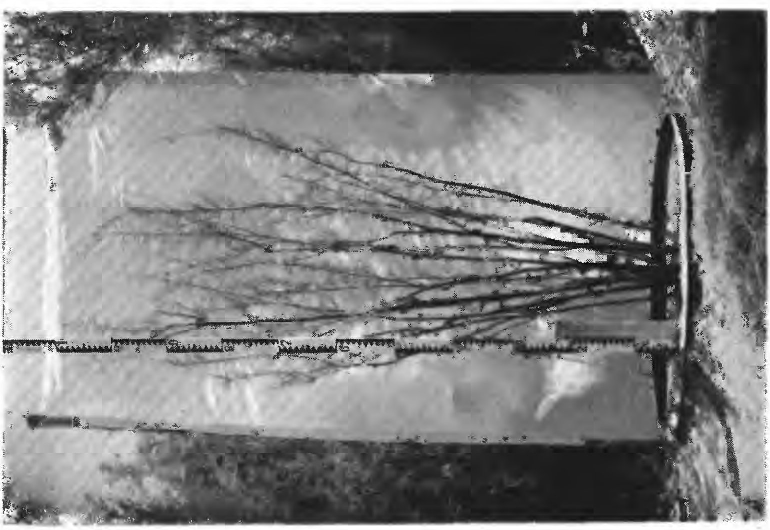

FIGURE 30.—Saltcedar growing in tank 20 at Glenbar experiment station. *A*, May 26, 1943, 7 days after transplanting. Photograph furnished by Phelps Dodge Corp. *B*, August 21, 1944. Photograph by T. W. Robinson.

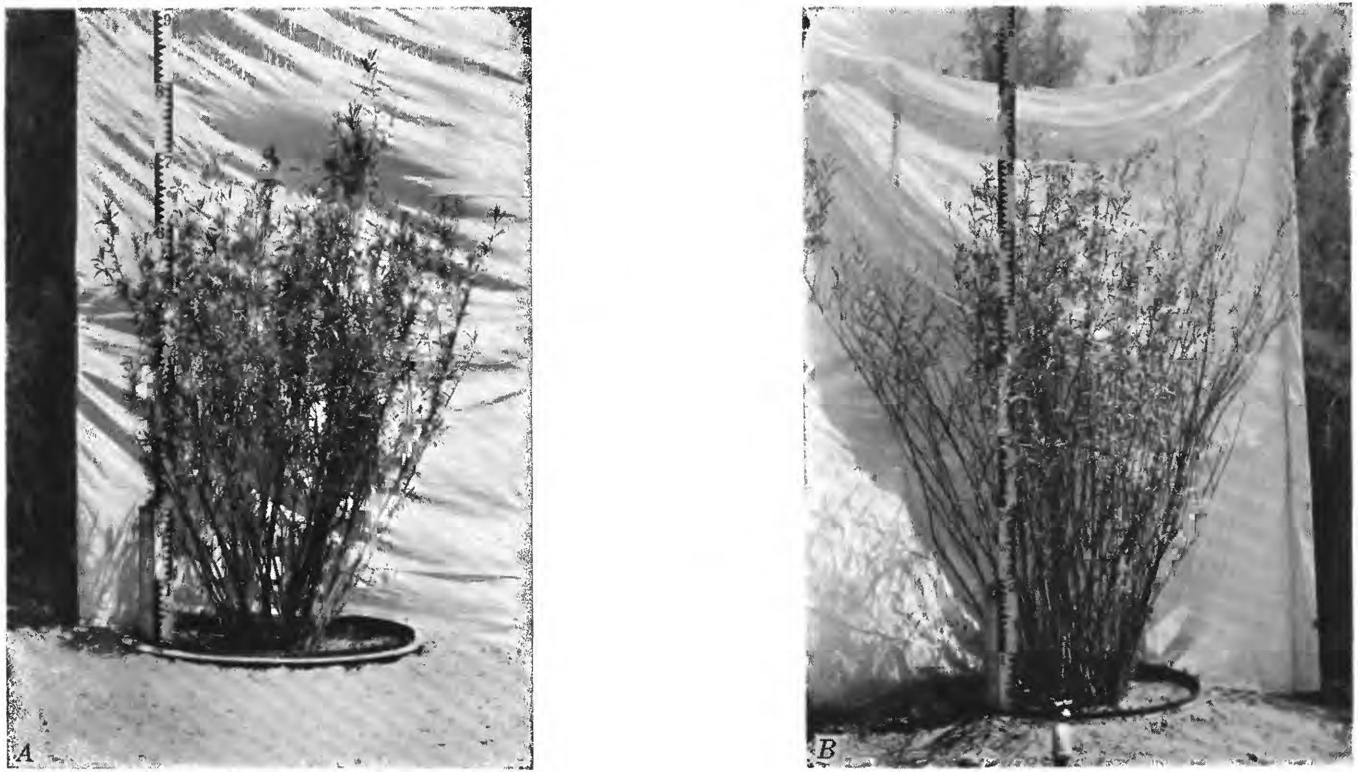

FIGURE 31.—Baccharis growing in tank 24 at Glenbar experiment station. *A*, May 20, 1943, 7 days after transplanting. Photograph furnished by Phelps Dodge Corp. *B* August 24, 1944. Note that infestation of stem girdler has reduced number of leaves. Photograph by T. W. Robinson.

FIGURE 32.—Cottonwood growing in tank 14 at Glenbar experiment station. *A*, June 7, 1943, 5 days after transplanting. Photograph furnished by Phelps Dodge Corp. *B*, August 21, 1944. Photograph by T. W. Robinson.

The possibility of error owing to methods of computation has been reduced by the application of the volume-density method.

Two factors reduce the effect of the personal element in drawing conclusions with respect to the data collected at the Glenbar experiment station: The conclusions were checked by many individuals and are the concensus of a group rather than the opinion of one man, and the results by the tank method were checked in lower Safford Valley with results by five other methods for determining use of water.

In addition to the discussion by Kiesellbach,[43] a comprehensive discussion of the value of tanks in determining transpiration rates is given in a report of the Committee on Transpiration and Evaporation of the American Geophysical Union.[44]

FACTORS THAT AFFECT COMPUTED USE OF WATER

The computed results may be affected by variations in natural phenomena. Some of the variations discussed in this part of the report actually affect the rate of transpiration, but other variations cause only an apparent effect on the rate of use of water. For example, fluctuations in relative humidity affect the rate of transpiration, but fluctuations in barometric pressure affect only the position of the water table in a tank and hence only the apparent rate of transpiration.

TEMPERATURE

Tank experiments may be affected by changes in soil temperature and air temperature.

SOIL TEMPERATURE

A soil thermograph was available throughout the period that the Glenbar experiment station was operated. The instrument included a revolving chart-covered drum operated by an 8-day clock. Three pens produced graphic records on the chart in response to temperature changes in three thermocouples. The thermocouples were attached to the ends of long cables, so that soil temperatures in three different places could be registered simultaneously on the instrument.

Experiments showed that diurnal fluctuations in temperature were not apparent 4 feet below the surface. At this depth the soil temperature was between 65° and 70° F., approximately the same as the temperature of ground water pumped from large irrigation wells in lower Safford Valley. The diurnal fluctuation in temperature was apparent, however, at a depth of 1 foot. The following table shows maximum and minimum temperatures on August 21, 1944.

[43] Kiesellbach, op. cit.

[44] Kittredge, Joseph, Report of Committee on Transpiration and Evaporation: Am. Geophys. Union Trans., 1941, pp. 906-915.

TABLE 24.—*Maximum and minimum temperatures on August 21, 1944, at Glenbar experiment station*

Point of observation	*Maximum (°F.)*	*Minimum (°F.)*
Air temperature (shaded)	103	61
Soil temperature at surface (unshaded)	110	70
Soil temperature 4 inches below surface	96	76
Soil temperature 12 inches below surface	90	83

Generally, changes in soil temperature in the capillary fringe were small and occurred slowly, so that the effect of these changes on the water table was small.

AIR TEMPERATURE

EFFECT ON WATER LEVEL

The effect on the tanks of rapid changes in air temperature was shown by a sudden drop in temperature that occurred on April 9, 1944. A cold front passed the experiment station at 5:45 a.m., and the temperature dropped 19° in 20 minutes. The water levels declined sharply in all the tanks and wells on which recorders were operating. The decline was so rapid that it apparently occurred before any change could occur in the soil temperature, as evidenced by the experiment described below. Unfortunately the clock on the soil thermograph was stopped during this period. Figure 33 contains graphs of barometric pressure, air temperature, and humidity, and of water-level fluctuations in five tanks and one well for the period April 7-10, 1944.

Although there was a small increase in barometric pressure during the time that the temperature fell rapidly, the barometric-pressure change was insufficient to account for the rapidity with which the water levels declined. It is interesting to note that tanks containing coarse materials (30 and 31) reflected a smaller change in water level than did the tanks containing fine materials.

To study further the effect of sudden changes in air temperature upon the water table, artificial heat was applied to one of the soil tanks under controlled conditions. Tank 30 was insulated with building paper, glass wool, and canvas in order to eliminate the effects of evaporation, humidity, and uncontrolled outside air temperatures. During the experiment records were made of the water level in the tank, soil temperature at 4 inches and 12 inches below the surface, barometric pressure, and air temperature. Large flat rocks were heated over an open fire and inserted on the soil surface of the tank beneath the insulating blanket. The tests were made between 9 p. m. and midnight, because at that time air temperature and barometric pressure were approximately at the mean for the day, and their rate of change was small. Figure 34 shows the results of the experiment. The water level in the tank rose at the times that hot rocks were applied (9 p. m. May 23 and 9 p. m. May 25), although there was no significant change in

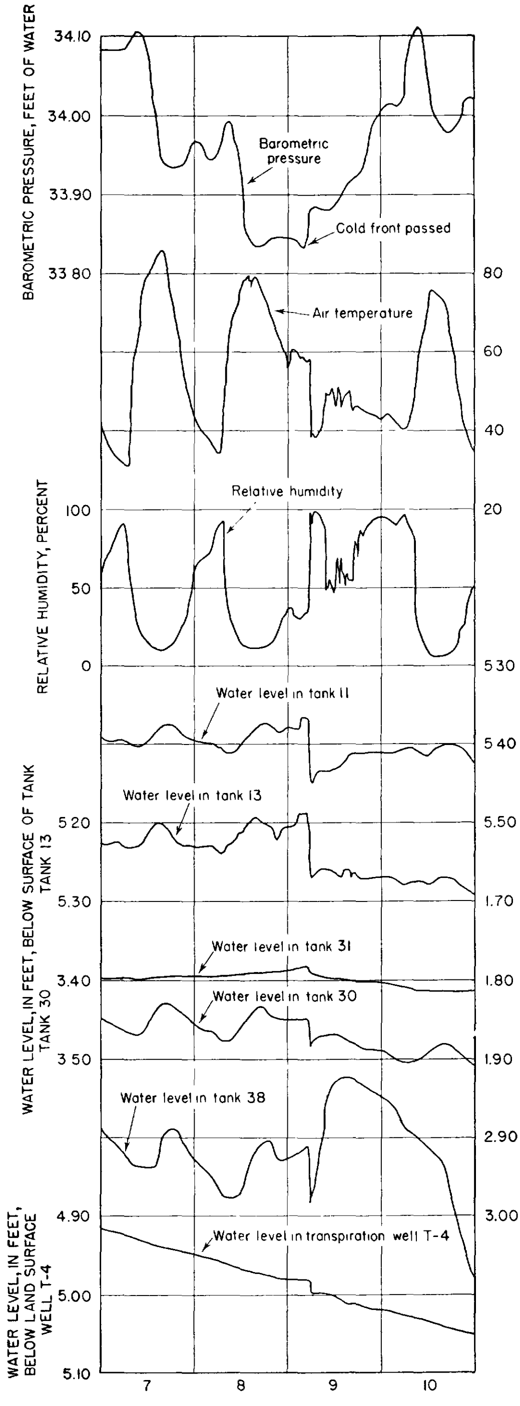

Figure 33.—Changes in water level in tanks and transpiration well as a result of cold front passing Glenbar experiment station at 5:45 a.m., April 9, 1944.

barometric pressure. The water level in the tank rose for about 1 hour before the temperature of the soil at a depth of 4 inches began to rise appreciably. This experiment indicated that the effect of sudden changes of air temperature at the surface of the tank was reflected rapidly in the level of the water table.

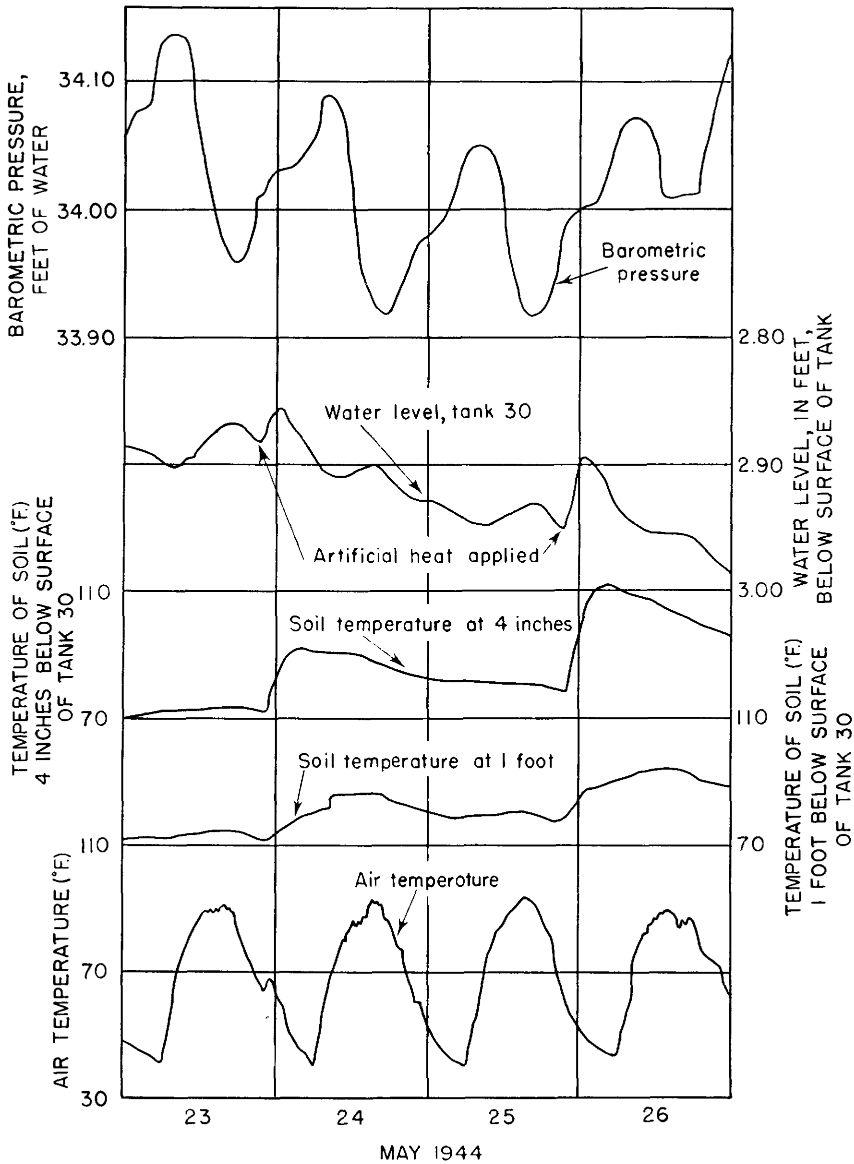

FIGURE 34.—Results of controlled experiments to determine effect upon water table of changes in temperature at surface of tank.

EFFECT ON RATE OF TRANSPIRATION

Figure 35 shows monthly means of daily maximum air temperature, monthly means of transpiration in the seven tanks 6 feet in diameter that contained saltcedar, monthly evaporation from tank 28 (bare soil), and monthly evaporation from the weather station evaporation pan, for the period September 1, 1943, to October 1, 1944. This graph shows that practically all transpiration by saltcedar ceased in the fall of 1943 when the monthly mean of daily maximum air temperatures became less than about 73° F., and that transpiration began in the spring of 1944 after the monthly mean of daily maximum air temperatures rose above about 73° F. The curve of transpiration has the same general shape as the curve of maximum temperature, and the curve of evapora-

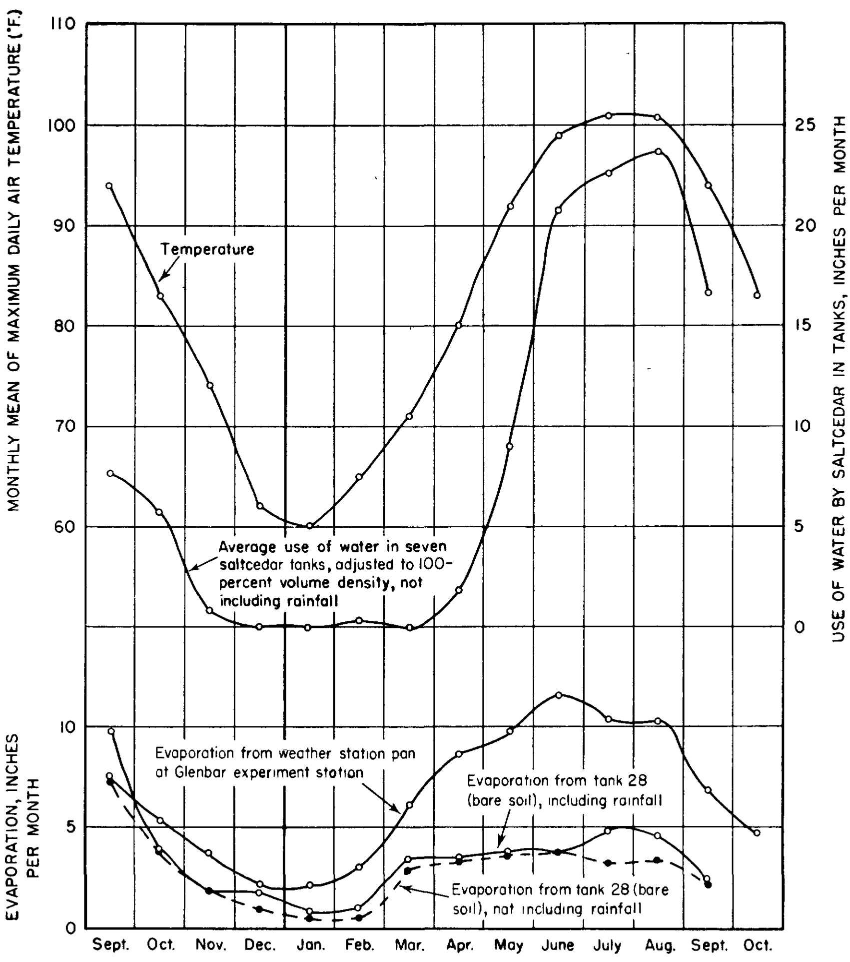

FIGURE 35.—Relation of use of water in tanks to evaporation and temperature.

tion from the bare soil tank has the same general shape as the curve of evaporation from the weather pan.

These data support the conclusions of Lowry and Johnson,[45] who, in discussing experiments by Briggs and Shantz,[46] state:

> A comparison of daily changes in solar radiation and temperatures indicates that the former is a function of the altitude of the sun and thus varies with the seasons, whereas the latter (temperature), which is dependent upon absorption of heat by air and earth and the circulation of the air, lags behind the seasons. Although solar radiation gives one of the best correlations with transpiration and evaporation, growing-season temperatures more nearly parallel the cycle of plant growth. * * * These variations [in consumptive use] are produced by differences in plant water requirement as related to plant development. * * * As their leaf area enlarges, their water requirements increase, and reach a maximum soon after maximum temperatures pass the peak of the season.

From this, it appears that evaporation from the pan and from the bare-soil tank is a function of solar radiation and that transpiration more nearly parallels maximum air temperatures. Field observations showed that new growth does not begin to appear on the saltcedar plants in lower Safford Valley until about April 1, although evaporation increases appreciably in early March. The plants attain their maximum amount of frondage by about July, and in August their frondage shows signs of age. Transpiration is greatest when the fronds are young and declines slowly as the fronds become more withered with the approaching fall season.[47] A severe frost kills all the fronds, and they turn yellow and drop to the ground within a few days, stopping transpiration by the plant.

Figure 36 is a graph showing the relation between maximum air temperature and transpiration. The curve shows that appreciable transpiration by saltcedar does not occur when the monthly mean of daily maximum temperatures is less than about 70° F.

EVAPORATION

The relation between evaporation from the weather-station pan and transpiration by saltcedar is shown in figure 35. Evaporation from bare soil tanks is closely related to evaporation from the pan. Transpiration is related in a general way to evaporation from the pan, being least when the evaporation is least. However, the rate of transpiration is less than the rate of evaporation in winter and greater in the growing season.

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[45] Lowry, R. L., Jr., and Johnson, A. F., Consumptive use of water for agriculture: Am. Soc. Civil Eng. Trans., vol. 107, p. 1248, 1942.

[46] Briggs, L. J., and Shantz, H. L., Hourly transpiration rate on clear days as determined by cyclic environmental factors: Jour. Agr. Research, vol. 5, pp. 583-650, Jan. 3, 1916; Daily transpiration during the normal growth period and its correlation with the weather: Jour. Agr. Research, vol. 7, pp. 155-212, Oct. 23, 1916.

[47] Raber, Oran, Water utilization by trees, with special reference to the economic forest species of the North Temperate Zone: U. S. Dept. Agr. Misc. Pub. 257, p. 22, 1937.

RELATIVE HUMIDITY

The relative humidity measured at the Glenbar experiment station had a wide range, from a low of 4 percent (4 p. m., July 12, 1944) to a high of 100 percent. The diurnal cycle usually ranged from a low of about 12 percent about 4 p. m. to a high of about 92 percent between 4 and 6 a. m. It was found that the transpiration rate was very much less on humid days than on dry days, but generally days of high humidity were associated with rainfall, which furnished water directly to the plants. No quantitative relation between relative humidity and rate of transpiration was developed.

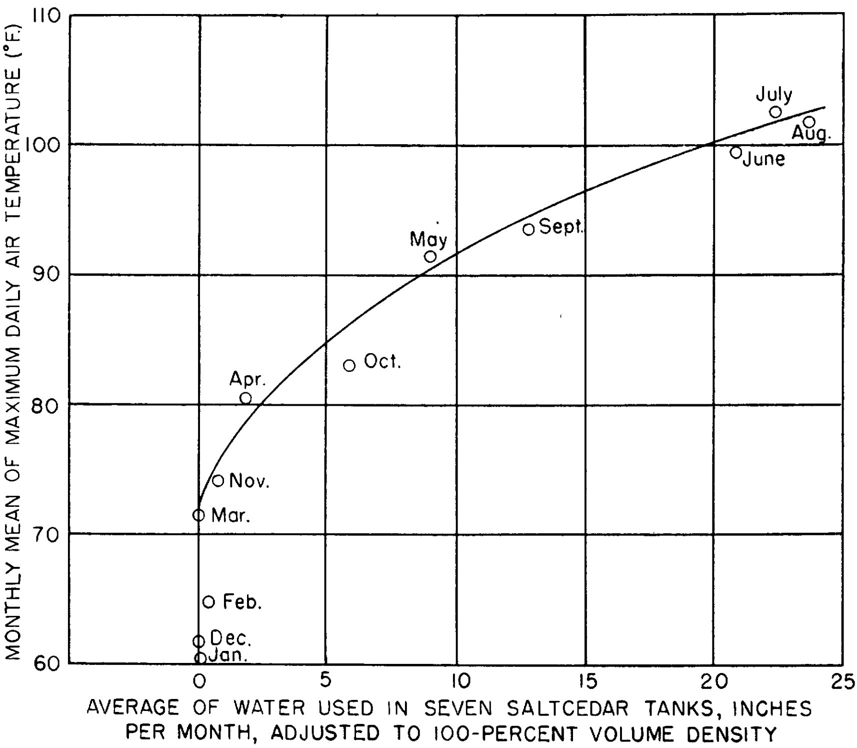

FIGURE 36.—Relation between maximum temperature and transpiration by saltcedar, October 1, 1943, to September 22, 1944.

PRECIPITATION

Precipitation affected the daily use of water in the tanks in three ways: by increasing the relative humidity and thus decreasing the rate of transpiration by the plants, by increasing the soil moisture above the capillary fringe, and by adding moisture to the capillary fringe and hence to the water table.

The increase in relative humidity and the reduction in rate of transpiration caused by rainfall occurred in the natural plant thickets as well as in the tanks, so that no correction was necessary.

The reduced draft on the water table, caused by rainfall increasing the soil moisture in the topsoil, also occurred in nature as well as in the tanks. The effect was considered in computing the use of water and will be discussed in the section on computations.

The amount of water that reached the water table in the tanks from rainfall was very small during the investigation. The principal factors that affected the amount of percolation were the depth to the water table, the amount and intensity of the rain, and the permeability of the materials in the tanks. Generally, the less the depth to the water table the greater the amount of rain water that reached the water table. Large amounts of rain, falling slowly and uniformly, were needed to cause a measurable rise in the water table. The water level in the tanks containing more permeable materials showed more effect from rainfall than did the water level in the tanks containing less permeable materials. Figure 37 shows the effect on tank 31 of a rain of 0.66 inch, July 18, 1944. The tank contained coarse gravel, and the water table was about 1.7 feet below the surface. The rain fell slowly during the night and was preceded by 0.26 inch the previous night. This graph represents the most extreme case of recharge to the water table in the tanks from rainfall. Based on 30 measurements in 9 tanks,

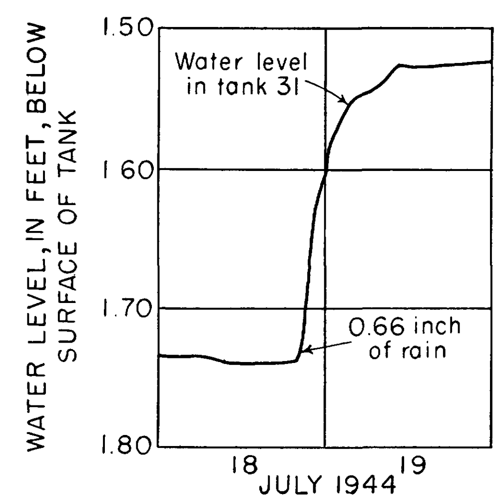

FIGURE 37.—Relation between rainfall and water level in tank containing coarse materials.

this rain water penetrated to an average depth of 4.6 inches below the surface. The least penetration measured was 3.1 inches, and the greatest penetration measured was 6.6 inches. In computing the use of ground water in the tanks it was immaterial whether rainfall penetrated to the water table, as the effect of rain was considered separately in the computations.

BAROMETRIC PRESSURE

Changes in barometric pressure at times produced changes in the water level in the recharge well of some tanks. As the recharge well was open to the atmosphere, an increase in barometric pressure at times would force water down the well and into the tank, causing the water level in the well to decline. Conversely, a decrease in barometric pressure at times would cause the water level in the recharge well to rise. These changes in water level were most noticeable after a rain had wetted the topsoil and became less noticeable as the topsoil in the tanks became drier. It is believed that rainfall on the surface of a tank produced a temporary seal in the soil, causing the tank to act as a barometer for short periods.

As the moisture content in the topsoil decreased, changes in atmospheric pressure were transmitted through the soil to the water table in the tank, equalizing the pressure on the water surface in the recharge well.

Changes in water level identifiable with changes in barometric pressure occurred generally during the winter months in tanks containing phreatophytes and throughout the year in bare-soil tanks. Probably the reasons that barometric changes did not appear during the growing season in tanks containing phreatophytes are: Shallow rootlets rapidly absorbed the moisture in the topsoil after rains, and the amount of water consumed by the plants was large in comparison with the change in water level caused by barometric fluctuations, so that the effect of barometric changes could not be detected.

The barometric changes in water level were more noticeable in tanks that contained fine materials than in tanks that contained coarse materials. Figure 38 shows a graph of barometric pressure and graphs of resulting changes in water level in two tanks. On the basis of the data shown in figure 38, it was calculated that in tank 37, which contained fine materials, the changes in water level were about 20 percent of the changes that would occur in a column of water that indicated barometric pressure, and in tank 31, which contained coarse materials, 4 percent.

DENSITY OF GROWTH

When the phreatophytes were first transplanted they were small. The plants quickly recovered from the shock of transplanting, and by September 1943 they were well established and growing rapidly. Volume-density determinations of the plants were made in 1944 to

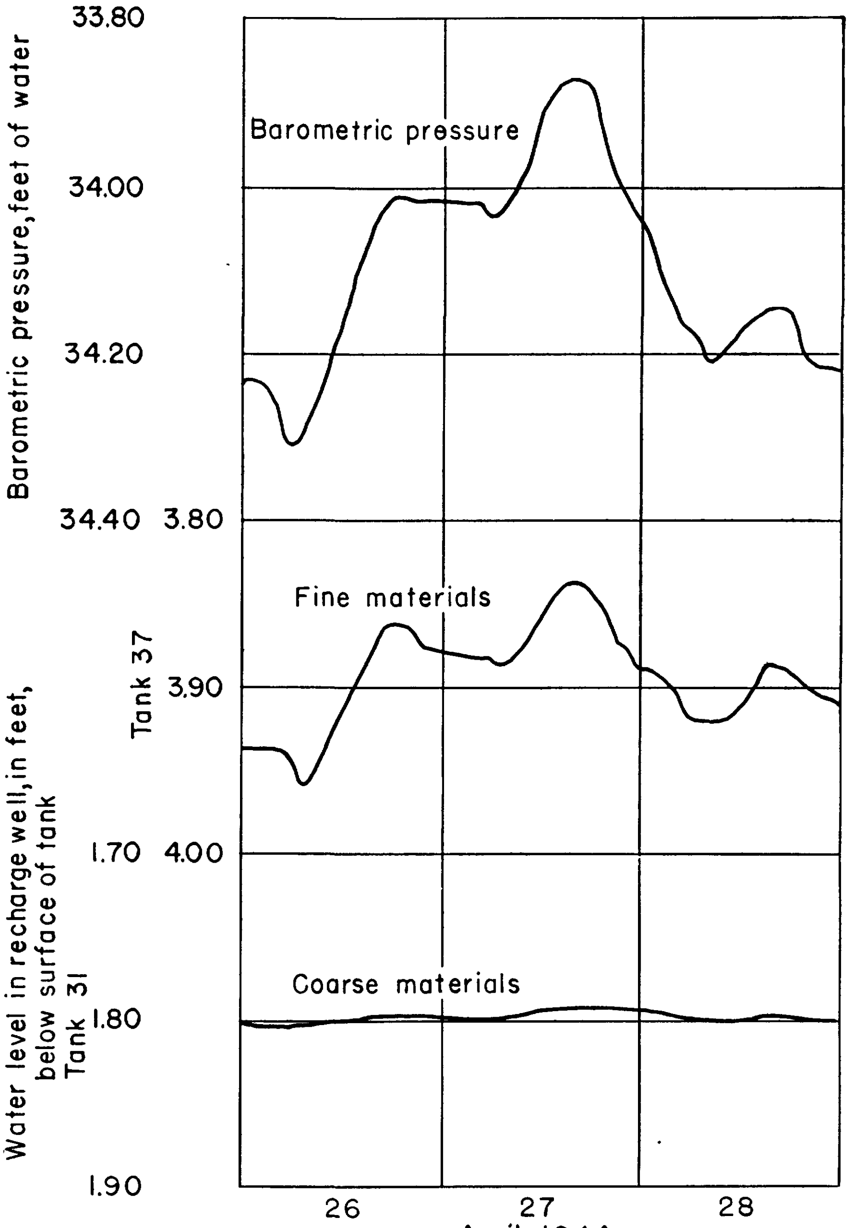

FIGURE 38.—Relation between barometric pressure and fluctuation of water level in recharge wells in tanks.

correlate the measured rate of use of water to the density of growth in the tanks. The method of making the determinations is described in the section entitled "Computation of results."

QUALITY OF WATER

Dissolved matter in water added to the tanks was not removed by transpiration or evaporation but accumulated in the tanks. If the water added had been highly mineralized, like the ground water at the experiment station, the water in the tanks would soon have become so highly mineralized that the plants would have been damaged. In order to avoid this difficulty, the water added to the tanks was hauled from the public water supply of Pima. This water was of low dissolved-solids concentration. In order to determine the rate of dissolved solids accumulation in the tanks, samples of water were collected periodically and analyzed. For a time at the beginning of the work samples were collected monthly, but as the rate of accumulation was found to be slow samples were later collected only once every 6 months.

Table 25 contains typical analyses of water from the tanks and from the Pima public supply. In general, the average concentration of dissolved matter in the water in the tanks containing baccharis and cottonwood approached the average concentration of water available to those species in the field. Concentrations in the tanks containing saltcedar however, were somewhat below the average concentration of water used by saltcedar in the field. Some of the saltcedar in the field grows in areas of highly mineralized waters, where baccharis or cottonwood do not grow.

TABLE 25.—*Quality of water in tanks, Glenbar experiment station, 1943*

[Parts per million]

Source of sample	Date sampled	Specific conductance (K ×10[5] at 25°C.)	Calcium (Ca)	Magnesium (Mg)	Sodium and potassium (Na +K)
Tank 11	Oct. 25	116			
Tank 13	Nov. 12	149	21	10	342
Tank 16	July 1	74.7			
Tank 18	Dec. 2	234			
Tank 27	Sept. 21	102			
Pima public supply	July 30	34.6	1.2	0.8	83

Source of sample	Date sampled	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Dissolved solids	Total hardness as $CaCO_3$	Percent sodium
Tank 11	Oct. 25						
Tank 13	Nov. 12	715	73	118	921	94	89
Tank 16	July 1			84			
Tank 18	Dec. 2						
Tank 27	Sept. 21						
Pima public supply	July 30	164	13	23	204	6	97

DEPTH TO WATER

As a result of earlier experiments [48] with tanks of saltcedar in Safford Valley, it was known that the amount of water transpired by the plants

[48] Turner, S. F., and others, Water resources of Safford and Duncan-Virden Valley, Ariz. and N. Mex., table 9, U. S. Geol. Survey, 1941. (See list of studies, p. 5.)

in the tanks was a function of the depth to the water table. For that reason the tanks were operated with water at 4, 6, and 7 feet below the surface for saltcedar, at 2, 4, and 6 feet below the surface for baccharis, and at 6 feet below the surface for cottonwood. For each of these species and depths a pair of tanks was operated. The effect of depth to ground water on rate of water use was considered in applying the tank method to the field.

In determining the use of water by the plants and evaporation from the soil, the water levels in the tanks were maintained, insofar as possible, at the predetermined depth below the surface. To do this the depth to the water level in each tank was measured each morning, and sufficient water was added to raise the water level slightly above the predetermined level in order to allow for plant use and evaporation during the ensuing 24 hours. Thus, the average water level for the 24-hour period would approximate the predetermined level. Water added to the tanks was measured volumetrically.

COMPUTATION OF RESULTS

Knowing the quantity of water, in gallons, added to each tank, three steps were necessary to compute the amount of ground water transpired monthly by the plants in each tank: Computation of inches of water over tank area; adjustment for changes in water level between beginning and end of month; and adjustment to 100-percent volume density. A curve of depth to water in each tank versus inches used at 100-percent volume density was then plotted for each species grown so that the results could be referred to field conditions. Figures for rainfall were added to the total after the final figure was applied to the field. The procedure was the same for the bare soil tanks except that adjustment to 100-percent volume density and the curve were not required.

WATER ADDED

Table 26 lists the amount of water added, by months, to each tank containing phreatophytes, and table 27 lists the amount of water added, by months, to each of the bare soil tanks. Each of the tables lists the water added, in gallons and in inches. The figures for water added, in inches, were obtained by dividing the volume added by the surface area of the tank. For the transpiration tanks the period of record was from September 1, 1943, to September 22, 1944, and for the soil tanks the period of record was from July 1, 1943, to September 22, 1944. The Glenbar experiment station was inundated by flood waters on September 25, 1944, and records collected after that date were of little value. The records for September 23 and 24 are not included in tables 26 and 27.

TABLE 26.—*Use of water by phreatophytes grown in tanks at Glenbar experiment station, 1943-44*

Tank no.	Water added		Average water level (feet)	Rise in water level during month (feet)	Coefficient of drainage and saturation (percent)	Adjustment for rise in water level (inches)[1]	Correction for recharge well (inches)	Water used in tank, less rain (inches)	Water used in tank at 100-percent volume density, less rain (inches)
	Gallons	Inches[1]							
				September 1943, rainfall 2.63 inches					
				SALTCEDAR					
11	92.5	1.89	5.29	0.26	13	−0.41	0	1.48	3.95
12	0	0	6.70	−.40	11	.54	.01	.55	.62
15	129.0	7.34	3.80	.20	11	−.26	−.01	7.07	9.87
16	151.5	8.62	3.56	−.10	13	.16	0	8.78	10.18
17	74.0	4.21	6.00	−.12	13	.19	0	4.40	6.15
18	44.5	2.53	6.01	−.10	16	.19	0	2.72	4.60
19	63.0	3.59	5.78	−.57	21	1.44	.02	5.05	7.70
20	153.0	8.71	5.84	.05	20	−.12	0	8.59	10.21
21	119.5	6.80	3.72	.77	14	−1.29	−.03	5.48	5.44
				COTTONWOOD					
13	0	0	5.47	−0.15	15	0.27	0	0.27	0.57
14	156.0	3.19	5.98	−.10	12	.14	0	3.33	2.12
				BACCHARIS					
22	46.0	5.91	1.73	0.71	17	−1.45	−0.06	4.40	7.67
23	67.5	8.68	1.78	.23	17	−.47	−.02	8.19	10.99
24	86.5	11.12	3.75	−.20	20	.48	.02	11.62	8.09
25	52.0	6.68	3.76	.02	25	−.06	0	6.62	7.51
26	50.0	6.43	5.98	.13	17	−.27	−.01	6.15	7.33
27	50.5	6.49	6.00	.07	20	−.17	−.01	6.31	6.46
				October 1943, rainfall 0.16 inch					
				SALTCEDAR					
11	0	0	5.69	−1.05	17	2.14	0.01	2.15	5.73
12	80.0	1.64	7.10	.37	11	−.49	0	1.15	1.30
15	62.5	3.56	4.00	−.22	11	.29	.01	3.86	5.39
16	118.0	6.72	4.05	.39	13	−.61	−.01	6.10	7.08
17	58.5	3.33	6.00	.03	13	−.05	0	3.28	4.59
18	61.5	3.50	6.01	.08	16	−.15	0	3.35	5.66
19	58.5	3.33	5.79	.09	21	−.23	0	3.10	4.73
20	127.5	7.26	5.87	.07	20	−.17	0	7.09	8.43
21	62.5	3.56	4.01	−.87	13	1.36	.03	4.95	4.91
				COTTONWOOD					
13	29.5	0.60	5.77	−0.61	15	1.10	0.01	1.71	3.61
14	268.0	5.48	6.03	−.16	12	.23	0	5.71	3.65
				BACCHARIS					
22	36.0	4.63	1.94	0.17	17	−0.35	−0.01	4.27	7.44
23	50.5	6.49	1.99	.01	17	−.02	0	6.47	8.69
24	71.5	9.19	4.04	.03	22	−.08	0	9.11	6.34
25	44.0	5.66	3.96	.17	25	−.51	−.01	5.14	5.83
26	32.5	4.18	5.98	−.04	17	.08	0	4.26	5.08
27	32.5	4.18	6.00	−.08	20	.19	.01	4.38	4.48
				November 1943, rainfall 0					
				SALTCEDAR					
11	0	0	6.01	−0.11	17	0.22	0	0.22	0.59
12	328.5	6.72	6.06	.51	25	−1.53	−.01	5.18	5.87
15	14.5	0.83	3.98	.01	11	−.01	0	.82	1.14
16	17.0	.97	3.98	.03	13	−.05	0	.92	1.07
17	12.0	.68	5.99	.08	13	−.12	0	.56	.78
18	7.0	.40	5.97	0	16	0	0	.40	.68
19	7.5	.43	5.79	.04	21	−.10	0	.33	.50
20	17.5	1.00	5.84	0	20	0	0	1.00	1.19
21	17.5	1.00	4.01	.14	13	−.22	−.01	.77	.76
				COTTONWOOD					
13	45.5	0.93	5.87	0.08	17	−0.16	0	0.77	1.62
14	85.0	1.74	6.01	.15	12	−.22	0	1.52	.97
				BACCHARIS					
22	14.0	1.80	1.92	−0.63	17	1.29	0.05	3.14	5.47
23	19.0	2.44	1.98	.10	17	−.20	−.01	2.23	2.99
24	28.0	3.60	4.01	.09	22	−.24	−.01	3.35	2.33
25	14.5	1.86	3.94	.07	25	−.21	−.01	1.64	1.86
26	13.5	1.74	5.99	−.01	17	.02	0	1.76	2.10
27	13.0	1.67	6.00	.06	20	−.14	−.01	1.52	1.55

See footnotes at end of table.

TABLE 26.—*Use of water by phreatophytes grown in tanks at Glenbar experiment station, 1943-44*—Continued

Tank no.	Water added		Average water level (feet)	Rise in water level during month (feet)	Coefficient of drainage and saturation (percent)	Adjustment for rise in water level (inches)[1]	Correction for recharge well (inches)	Water used in tank, less rain (inches)	Water used in tank at 100-percent volume density, less rain (inches)
	Gallons	Inches[1]							
December 1943, rainfall 0.89 inch									
SALTCEDAR									
11	0	0	5.97	0.23	17	−0.47	0	−0.47	−1.25
12	45.5	.93	6.02	0	10	0	0	.93	1.05
15	−1.5	−.09	3.78	.15	11	−.20	−.01	−.30	−.42
16	−4.0	−.23	3.54	.18	13	−.28	−.01	−.52	−.60
17	8.0	.46	5.99	−.06	13	.09	0	.55	.77
18	5.0	.28	5.99	−.04	16	.08	0	.36	.61
19	6.5	.37	5.81	−.05	21	.13	0	.50	.76
20	3.0	.17	5.81	.20	20	−.48	−.01	−.32	−.38
21	1.0	.06	3.68	.38	14	−.64	−.01	−.59	−.59
COTTONWOOD									
13	16.0	0.33	5.87	−0.03	17	0.06	0	0.39	0.82
14	6.0	.13	5.94	.12	12	−.17	0	−.04	−.03
BACCHARIS									
22	2.5	0.32	1.66	0.28	17	−0.57	−0.02	−0.27	−0.47
23	2.5	.32	1.74	.09	17	−.18	−.01	.13	.17
24	7.5	.96	3.88	.21	20	−.50	−.02	.44	.31
25	3.0	.39	3.83	.20	25	−.60	−.02	−.23	−.26
26	7.0	.90	5.98	.09	17	−.18	−.01	.71	.85
27	6.5	.84	6.00	−.01	20	.02	0	.86	.88
January 1944, rainfall 0.32 inch									
SALTCEDAR									
†11	...	...	...	...	...	...	...	...	...
12	14.0	0.29	6.07	−0.16	10	0.19	0	0.48	0.54
†15	...	...	...	...	...	...	...	...	...
16	2.5	.14	3.81	.36	13	−.56	−.01	−.43	−.50
†17	...	...	...	...	...	...	...	...	...
18	1.5	.09	6.03	−.10	16	.19	0	.28	.47
†19	...	...	...	...	...	...	...	...	...
20	0	0	5.78	−.12	20	.29	0	.29	.34
†21	...	...	...	...	...	...	...	...	...
COTTONWOOD									
†13	...	...	...	...	...	...	...	...	...
14	0	0	5.89	−0.04	12	0.06	0	0.06	0.04
BACCHARIS									
22	4.0	0.51	1.97	−0.06	17	0.12	0.01	0.64	1.16
†23	...	...	...	...	...	...	...	...	...
24	2.0	.26	4.08	−.38	22	1.00	.03	1.29	.90
†25	...	...	...	...	...	...	...	...	...
26	0	0	6.03	−.17	17	.35	.01	.36	.43
†27	...	...	...	...	...	...	...	...	...

See footnotes at end of table.

TABLE 26.—*Use of water by phreatophytes grown in tanks at Glenbar experiment station, 1943-44*—Continued

Tank no.	Water added		Average water level (feet)	Rise in water level during month (feet)	Coefficient of drainage and saturation (percent)	Adjustment for rise in water level (inches)[1]	Correction for recharge well (inches)	Water used in tank, less rain (inches)	Water used in tank at 100-percent volume density, less rain (inches)
	Gallons	Inches[1]							
February 1944, rainfall 0.50 inch									
SALTCEDAR									
[2] 11	195.0	3.99	5.22	1.19	13	−1.86	−0.02	2.11	5.63
12	35.0	.72	6.14	.18	10	−.22	0	.50	.57
[2] 15	6.0	.34	3.49	−.18	12	.26	.01	.61	.85
16	−.5	−.03	3.88	−.74	13	1.15	.03	1.15	1.33
[2] 17	27.0	1.54	5.33	−.13	13	.20	0	1.74	2.43
18	4.5	.26	6.09	.11	16	−.21	0	.05	.08
[2] 19	−36.5	−2.08	5.38	−1.71	21	4.31	.06	2.29	3.49
20	−75.5	−4.30	6.36	−1.94	18	4.19	.07	−.04	−.05
[2] 21	9.0	.51	3.13	−.36	14	.60	.01	1.12	1.11
COTTONWOOD									
[2] 13	196.0	4.01	5.32	0.95	15	−1.71	−0.01	2.29	4.83
14	10.0	.20	5.92	−.02	12	.03	0	.23	.15
BACCHARIS									
22	8.0	1.03	2.36	−0.20	17	0.41	0.02	1.46	2.54
[2] 23	9.0	1.16	1.94	−.16	17	.33	.01	1.50	2.01
24	6.5	.84	4.41	.15	22	−.40	−.01	.43	.30
[2] 25	4.0	.51	3.68	−.27	25	.81	.02	1.34	1.52
26	2.5	.32	6.09	.13	17	−.27	.01	.06	.07
[2] 27	19.0	2.44	5.56	.02	20	−.05	0	2.39	2.44
March 1944, rainfall 0.64 inch									
SALTCEDAR									
11	0	0	4.92	−0.67	13	1.05	0.01	1.06	2.83
12	23.0	.47	5.98	−.03	10	.04	0	.51	.58
15	14.5	.83	3.93	.01	12	−.01	0	.82	1.14
16	16.0	.91	3.83	.04	13	−.06	0	.85	.99
17	5.5	.31	6.00	.10	13	−.16	0	.15	.21
18	3.5	.20	5.98	.01	16	−.02	0	.18	.30
19	−18.0	−1.02	7.50	.14	21	−.35	−.01	−1.38	−2.10
20	−9.0	−.51	7.34	.55	18	−1.19	−.02	−1.72	−2.05
21	12.5	.71	3.93	−.26	14	.44	.01	1.16	1.15
COTTONWOOD									
13	0	0	5.01	−0.25	15	0.45	0	0.45	0.95
14	3.0	.06	5.90	−.15	12	.22	0	.28	.18
BACCHARIS									
22	22.5	2.89	1.96	0.12	17	−0.24	−0.01	2.63	4.58
23	15.8	2.03	1.97	−.35	17	.71	.03	2.77	3.72
24	17.0	2.18	3.99	−.12	20	.29	.01	2.48	1.73
25	4.2	.54	4.00	−.70	17	1.43	.06	2.03	2.30
26	4.0	.51	5.96	−.07	17	.14	.01	.66	.79
27	2.5	.32	5.98	0	20	0	0	.32	.33

See footnotes at end of table.

TABLE 26.—*Use of water by phreatophytes grown in tanks at Glenbar experiment station, 1943-44*—Continued

Tank no.	Water added		Average water level (feet)	Rise in water level during month (feet)	Coefficient of drainage and saturation (percent)	Adjustment for rise in water level (inches)[1]	Correction for recharge well (inches)	Water used in tank, less rain (inches)	Water used in tank at 100-percent volume density, less rain (inches)
	Gallons	Inches[1]							
April 1944, rainfall 0.15 inch									
SALTCEDAR									
11	0	0	5.52	−0.49	17	1.00	0.01	1.01	2.69
12	85.0	1.74	6.02	0	10	0	0	1.74	1.97
15	50.5	2.87	4.02	−.06	12	.09	0	2.96	4.13
[3] 16	37.0	2.11	4.00	.02	13	−.03	−.03	2.05	2.38
[3] 17	32.0	1.83	6.01	0	13	0	−.04	1.79	2.50
[3] 18	7.5	.43	5.98	−.07	16	.13	−.03	.53	.90
19	2.0	.11	7.38	−.02	21	.05	0	.16	.24
20	2.0	.11	7.22	−.02	18	.04	0	.15	.18
[3] 21	57.5	3.28	4.11	−.12	13	.19	0	3.47	3.44
COTTONWOOD									
13	0	0	5.36	−0.47	15	0.85	0.01	0.86	1.81
14	106.0	2.17	6.01	.02	12	−.03	0	2.14	1.37
BACCHARIS									
[3] 22	46.0	5.96	1.98	0.36	17	−0.73	−0.21	5.02	8.75
[3] 23	49.5	6.41	2.08	.21	17	−.43	−.12	5.86	7.86
[3] 24	39.0	5.05	4.04	.13	22	−.34	−.17	4.54	3.16
[3] 25	25.0	3.24	3.74	.54	25	−1.62	−.25	1.37	1.55
26	14.0	1.80	5.98	.15	17	−.31	−.01	1.48	1.76
27	16.0	2.06	6.00	−.07	20	.17	.01	2.24	2.29
May 1944, rainfall 0.18 inch									
SALTCEDAR									
11	0	0	6.16	−0.67	17	1.37	0.01	1.38	3.68
12	443.0	9.06	6.04	−.03	10	.04	0	9.10	10.32
[3] 15	176.0	10.05	4.03	.11	12	−.16	−.01	9.88	13.79
16	172.0	9.82	4.00	.04	13	−.06	0	9.76	11.32
17	114.5	6.54	6.07	.03	13	−.05	0	6.49	9.07
18	93.5	5.34	6.07	−.03	16	.06	0	5.40	9.13
19	11.5	.65	7.78	−.61	21	1.54	.02	2.21	3.37
20	0	0	7.56	−.80	18	1.73	.03	1.76	2.09
21	251.0	14.33	4.08	−.03	13	.05	0	14.38	14.26
COTTONWOOD									
13	0	0	5.97	−0.77	17	1.57	0.01	1.58	3.33
14	476.0	9.73	6.00	−.08	12	.12	0	9.85	6.29
BACCHARIS									
22	86.0	11.14	1.98	−0.57	17	1.16	0.10	12.40	21.61
23	110.5	14.31	2.08	.12	17	−.24	−.02	14.05	18.86
24	110.5	14.31	4.01	−.16	22	.42	.03	14.76	10.27
25	68.0	8.81	3.51	.27	25	−.81	−.05	7.95	9.02
[3] 26	33.5	4.34	6.03	−.29	17	.59	.05	4.94	5.89
[3] 27	52.5	6.80	6.09	.01	20	−.02	0	6.78	6.94

See footnotes at end of table.

TABLE 26.—*Use of water by phreatophytes grown in tanks at Glenbar experiment station, 1943-44*—Continued

Tank no.	Water added		Average water level (feet)	Rise in water level during month (feet)	Coefficient of drainage and saturation (percent)	Adjustment for rise in water level (inches)[1]	Correction for recharge well (inches)	Water used in tank, less rain (inches)	Water used in tank at 100-percent volume density, less rain (inches)
	Gallons	Inches[1]							
June 1944, rainfall 0									
SALTCEDAR									
11	175.0	3.58	6.61	−0.06	17	0.12	0	3.70	9.86
12	864.0	17.67	6.02	0	10	0	0	17.67	20.04
15	284.0	16.21	4.02	−.13	12	.19	.01	16.41	22.91
16	317.0	18.09	4.07	−.19	13	.30	.01	18.40	21.34
17	261.0	14.90	6.04	−.09	13	.14	.01	15.05	21.04
18	230.0	13.13	6.05	.01	16	−.02	0	13.11	22.16
19	216.5	12.32	7.79	.42	21	−1.06	−.02	11.24	17.14
20	295.5	16.82	7.32	1.42	18	−3.07	−.05	13.70	16.29
21	461.0	26.31	4.16	.54	13	−.84	−.04	25.43	25.23
COTTONWOOD									
13	220.0	4.50	6.86	−0.25	17	0.51	0	5.01	10.57
14	1063.0	21.74	6.08	−.02	12	.03	0	21.77	13.91
BACCHARIS									
22	128.0	16.58	2.15	−0.43	17	0.88	0.07	17.53	30.55
23	157.5	20.40	2.11	.30	17	−.61	−.05	19.74	26.49
24	172.0	22.28	4.10	−.05	22	.13	.01	22.42	15.60
25	109.0	14.12	4.03	−.40	17	.82	.06	15.00	17.01
26	59.5	7.71	6.03	.08	17	−.16	−.01	7.54	8.99
27	102.0	13.21	6.01	−.12	20	.29	.02	13.52	13.83
July 1944, rainfall 1.62 inches									
SALTCEDAR									
11	612.0	12.52	6.52	0.05	17	−0.10	0	12.42	33.11
12	872.0	17.83	6.00	.03	10	−.04	0	17.79	20.17
15	296.0	16.90	4.01	.08	12	−.12	−.01	16.77	23.41
16	341.0	19.46	3.95	.28	13	−.44	−.02	19.00	22.04
17	240.7	13.74	5.91	.07	13	−.11	−.01	13.62	19.04
18	226.0	12.90	5.97	.10	16	−.19	−.01	12.70	21.46
19	256.0	14.57	7.55	.04	21	−.10	0	14.47	22.07
20	344.0	19.58	6.51	0	18	0	0	19.58	23.28
21	474.0	27.06	4.05	.33	13	. −51	−.02	26.53	26.32
COTTONWOOD									
13	622.0	12.72	6.51	0.08	17	−0.16	0	12.56	26.50
14	1470.0	30.06	6.02	0	12	0	0	30.06	19.21
BACCHARIS									
22	100.0	12.95	1.83	0.71	17	−1.45	−0.12	11.38	19.84
23	121.0	15.67	1.95	.14	17	−.29	−.02	15.36	20.61
24	156.0	20.21	4.02	.25	22	−.66	−.04	19.51	13.58
25	113.0	14.64	3.95	.35	25	−1.05	−.06	13.53	15.34
26	62.0	8.03	5.95	0	17	0	0	8.03	9.57
27	92.5	11.98	6.00	.18	20	−.43	−.03	11.52	11.78

See footnotes at end of table.

TABLE 26.—*Use of water by phreatophytes grown in tanks at Glenbar experiment station, 1943-44*—Continued

Tank no.	Water added: Gallons	Water added: Inches[1]	Average water level (feet)	Rise in water level during month (feet)	Coefficient of drainage and saturation (percent)	Adjustment for rise in water level (inches)[1]	Correction for recharge well (inches)	Water used in tank, less rain (inches)	Water used in tank at 100-percent volume density, less rain (inches)
				August 1944, rainfall 1.19 inches					
				SALTCEDAR					
11	646.0	13.21	6.51	0.01	17	−0.02	0	13.19	35.16
12	917.0	18.75	5.99	.11	10	−.13	0	18.62	21.12
15	295.0	16.84	3.97	.07	12	−.10	−.01	16.73	23.34
16	362.0	20.66	3.96	.15	13	−.23	−.01	20.42	23.69
17	245.8	14.03	5.98	0	13	0	0	14.03	19.61
18	239.0	13.64	6.02	.11	16	−.21	−.01	13.42	22.68
19	286.0	16.28	7.45	.09	21	−.23	0	16.05	24.48
20	396.0	22.54	6.53	.09	18	−.19	0	22.35	26.57
21	451.0	25.74	3.95	−.13	14	.22	.01	25.97	25.76
				COTTONWOOD					
13	708.0	14.48	6.50	0.22	17	−0.45	0	14.03	29.60
14	1735.0	35.48	5.98	.19	12	−.27	0	35.21	22.50
				BACCHARIS					
22	92.5	11.98	1.93	−0.11	17	0.22	0.02	12.22	21.30
23	105.0	13.60	1.86	−.20	17	.41	.03	14.04	18.84
24	127.0	16.45	3.99	.07	20	−.17	−.01	16.27	11.32
25	95.5	12.37	3.88	.06	25	−.18	−.01	12.18	13.81
26	59.0	7.64	5.98	.21	17	−.43	−.04	7.17	8.55
27	76.5	9.91	5.98	.09	20	−.22	−.02	9.67	9.89
				September 1944, rainfall 0.31 inch[4]					
				SALTCEDAR					
11	358.0	7.32	6.48	0	17	0	0	7.32	19.52
12	457.0	9.35	6.11	−.27	10	.32	0	9.67	10.97
15	161.0	9.19	3.96	−.18	12	.26	.01	9.46	13.21
16	201.5	11.50	3.87	−.50	13	.78	.04	12.32	14.29
17	103.3	5.90	5.99	−.04	13	.06	0	5.96	8.33
18	119.6	6.83	5.92	.01	16	−.02	0	6.81	11.51
19	135.5	7.71	7.44	.13	21	−.33	0	7.38	11.25
20	231.0	13.15	6.45	−.20	18	.43	.01	13.59	16.16
21	270.0	15.41	3.91	−.07	14	.12	.01	15.54	15.42
				COTTONWOOD					
13	384.0	7.85	6.46	−0.24	17	0.49	0	8.34	17.60
14	1065.0	21.78	5.97	−.12	12	.17	0	21.95	14.03
				BACCHARIS					
22	50.5	6.54	1.89	0.24	17	−0.49	−0.04	6.01	10.48
23	56.5	7.32	1.97	−.36	17	.73	.06	8.11	10.88
24	60.5	7.84	3.95	−.13	20	.31	.02	8.17	5.69
25	53.0	6.86	3.90	−.12	25	.36	.02	7.24	8.21
26	30.5	3.95	5.99	−.10	17	.20	.02	4.17	4.97
27	40.0	5.18	5.98	−.04	20	.10	.01	5.29	5.41

[1] Based on area of tank minus area of recharge well.
[2] January and February combined. Rainfall, 0.82 inch.
[3] Additional 4-inch observation well installed during month, thus reducing area of tank less area of recharge well, table 28.
[4] Data are for September 1–22 only; inundated by flood on September 25.
† Tanks were being used for specific yield experiments, so readings could not be taken.
NOTE.—Negative figures occur in last column in some cases because some rainfall may have percolated to water table or because of small errors in adjustment for volume density or in coefficient of drainage and saturation.

TABLE 27.—*Use of water in bare soil tanks at Glenbar experiment station, 1943-44*

Tank no.	Water added: Gallons	Water added: Inches[1]	Average water level (feet)	Rise in water level during month (feet)	Coefficient of drainage and saturation (percent)	Adjustment for rise in water level (inches)[1]	Correction for recharge well (inches)	Water used in tank, less rain (inches)
July 1943, rainfall 2.15 inches								
SAND AND GRAVEL								
28	84.0	10.80	1.15	1.32	18	−2.85	−0.11	7.84
29	79.1	10.17	1.48	1.39	12	−2.00	−.12	8.05
30	80.7	10.37	1.79	1.21	12	−1.74	−.10	8.53
35	62.0	7.97	1.98	−2.56	10	3.07	.22	11.26
36	64.5	8.29	1.99	−2.67	12	3.84	.22	12.35
39	−14.5	−1.86	3.74	−1.54	15	2.77	.13	1.04
GRAVEL								
31	−4.5	−0.58	1.86	−0.64	11	0.84	0.05	0.31
32	−7.0	−.90	1.93	−.91	15	1.64	.08	.82
CLAY LOAM								
33	35.5	4.56	1.93	−2.42	10	2.90	0.20	7.66
34	30.0	3.86	2.02	−2.44	10	2.93	.20	6.99
37	8.0	1.03	3.71	−2.89	5	1.73	.24	3.00
38	−1.0	−.13	3.54	−3.96	10	4.75	.33	4.95
August 1943, rainfall 3.56 inches								
SAND AND GRAVEL								
28	27.2	3.50	0.48	0.43	17	−0.88	−0.04	2.58
29	29.5	3.79	.91	.13	12	−.19	−.01	3.59
30	32.0	4.11	1.15	.41	12	−.59	−.03	3.49
35	31.0	3.98	1.78	.52	10	−.62	−.04	3.32
36	31.5	4.05	1.73	.68	12	−.98	−.06	3.01
39	−6.0	−.77	3.75	.03	15	−.05	0	−.82
GRAVEL								
31	−13.0	−1.67	1.77	0.12	11	−0.16	−0.01	−1.84
32	−13.0	−1.67	1.74	.27	15	−.49	−.02	−2.18
CLAY LOAM								
33	18.0	2.31	1.72	0.42	10	−0.50	−0.04	1.77
34	16.0	2.06	1.61	.49	10	−.59	−.04	1.43
37	7.0	.90	3.61	−.08	5	.05	.01	.96
38	2.5	.32	3.59	.07	10	−.08	−.01	.23
September 1943, rainfall 2.63 inches								
SAND AND GRAVEL								
28	19.5	2.51	0.76	−2.25	17	4.59	0.19	7.29
29	10.5	1.35	1.16	−1.82	12	2.62	.15	4.12
30	7.0	.90	1.59	−1.83	12	2.64	.15	3.69
35	29.0	3.73	1.75	.35	10	−.42	−.03	3.28
36	31.5	4.05	1.81	.28	12	−.40	−.03	3.62
39	−7.0	−.90	3.85	.04	15	−.07	0	−.97
GRAVEL								
31	−13.0	−1.67	1.73	−0.04	11	0.05	0	−1.62
32	−18.0	−2.31	1.83	−.26	15	.47	.02	−1.82
CLAY LOAM								
33	11.0	1.41	1.79	0.42	10	−0.50	−0.04	0.87
34	5.5	.71	1.78	−.35	10	.42	.03	1.16
37	6.0	.77	3.64	.13	5	−.08	−.01	.68
38	1.0	.13	3.72	−.17	10	.20	.01	.34

See footnotes at end of table.

TABLE 27.—*Use of water in bare soil tanks at Glenbar experiment station, 1943-44* —Continued

Tank no.	Water added: Gallons	Water added: Inches[1]	Average water level (feet)	Rise in water level during month (feet)	Coefficient of drainage and saturation (percent)	Adjustment for rise in water level (inches)[1]	Correction for recharge well (inches)	Water used in tank, less rain (inches)
October 1943, rainfall 0.16 inch								
SAND AND GRAVEL								
28	28.5	3.66	3.05	−0.06	12	0.09	0	3.75
29	14.0	1.80	3.94	−.78	12	1.12	.07	2.99
30	−7.5	−.96	4.42	−1.17	12	1.68	.10	.82
35	30.5	3.92	1.97	−.62	10	.74	.05	4.71
36	33.0	4.24	2.03	−.78	12	1.12	.07	5.43
39	3.0	.39	3.98	−.10	15	.18	.01	.58
GRAVEL								
31	−2.0	−0.26	1.98	−0.19	11	0.25	0.02	0.01
32	0	0	1.99	−.04	15	.07	0	.07
CLAY LOAM								
33	25.0	3.21	1.95	−0.33	10	0.40	0.03	3.64
34	24.0	3.08	2.02	.35	10	−.42	−.03	2.63
37	13.5	1.74	3.96	−.16	5	.10	.01	1.85
38	11.5	1.48	3.98	.04	10	−.05	0	1.43
November 1943, rainfall 0								
SAND AND GRAVEL								
28	18.0	2.31	3.02	0.24	12	−0.35	−0.02	1.94
29	16.5	2.12	4.01	.12	12	−.17	−.01	1.94
30	10.0	1.29	4.45	.11	12	−.16	−.01	1.12
35	21.0	2.70	2.08	.11	10	−.13	−.01	2.56
36	21.0	2.70	2.00	.55	12	−.79	−.05	1.86
39	3.5	.45	3.93	.12	15	−.22	−.01	.22
GRAVEL								
31	0	0	2.02	−0.01	11	0.01	0	0.01
32	.5	.06	1.96	.07	15	−.13	0	−.07
CLAY LOAM								
33	11.0	1.41	2.00	−0.09	10	0.11	0.01	1.53
34	10.5	1.35	1.99	−.23	10	.28	.02	1.65
37	9.5	1.22	3.99	.11	5	−.07	−.01	1.14
38	7.0	.90	3.96	.09	10	−.11	−.01	.78
December 1943, rainfall 0.89 inch								
SAND AND GRAVEL								
28	5.5	0.71	2.92	−0.18	12	0.26	0.02	0.99
29	4.0	.51	3.91	.02	12	−.03	0	.48
30	1.5	.19	4.39	.14	12	−.20	−.01	−.02
35	6.5	.84	1.80	.08	10	−.10	−.01	.73
36	5.0	.64	1.68	.03	12	−.04	0	.60
39	1.0	.13	3.89	.10	15	−.18	−.01	−.06
GRAVEL								
31	0	0	1.99	0.17	11	−0.22	−0.01	−0.23
32	−3.5	−.45	1.93	−.11	15	.20	.01	−.24
CLAY LOAM								
33	3.0	0.39	1.69	0.03	10	−0.04	0	0.35
34	3.5	.45	1.72	.07	10	−.08	−.01	.36
37	2.5	.32	3.79	.03	5	−.02	0	.30
38	2.5	.32	3.78	0	10	0	0	.32

See footnotes at end of table.

TABLE 27.—*Use of water in bare soil tanks at Glenbar experiment station, 1943-44*—Continued

Tank no.	Water added: Gallons	Water added: Inches[1]	Average water level (feet)	Rise in water level during month (feet)	Coefficient of drainage and saturation (percent)	Adjustment for rise in water level (inches)[1]	Correction for recharge well (inches)	Water used in tank, less rain (inches)
January 1944, rainfall 0.32 inch								
SAND AND GRAVEL								
†28	...	...	...	...	...	...	...	...
†29	...	...	...	...	...	...	...	...
†30	...	...	...	...	...	...	...	...
†35	...	...	...	...	...	...	...	...
36	5.5	0.71	2.15	−0.76	12	1.09	0.06	1.86
39	0	0	3.94	−.12	15	.22	.01	.23
GRAVEL								
†31	...	...	...	...	...	...	...	...
32	0	0	1.99	0.14	15	−0.25	−0.01	−0.26
CLAY LOAM								
†33	...	...	...	...	...	...	...	...
34	4.5	0.58	2.17	−0.57	10	0.68	0.05	1.31
†37	...	...	...	...	...	...	...	...
38	2.5	.32	4.07	−.31	10	.37	.03	.72
February 1944, rainfall 0.50 inch								
SAND AND GRAVEL								
[2] 28	6.5	0.84	2.77	−0.10	12	0.14	0.01	0.99
[2] 29	22.5	2.89	3.37	.38	12	−.55	−.03	2.31
[2] 30	22.0	2.83	3.75	.37	12	−.53	−.03	2.27
[2] 35	7.5	.96	1.83	−.12	10	.14	.01	1.11
36	12.5	1.61	2.33	.43	12	−.62	−.04	.95
39	1.0	.13	4.00	−.02	15	.04	0	.17
GRAVEL								
[2] 31	−3.0	−0.39	1.66	−0.14	11	0.18	0.01	−0.20
32	0	0	1.87	.07	15	−.13	−.01	−.14
CLAY LOAM								
[2] 33	7.0	0.90	1.69	−0.01	10	0.01	0	0.91
34	7.5	.96	2.56	.36	10	−.43	−.03	.50
[2] 37	11.0	1.41	3.17	−.18	5	.11	.02	1.54
38	4.0	.51	4.22	.24	10	−.29	−.02	.20
March 1944, rainfall 0.64 inch								
SAND AND GRAVEL								
28	24.0	3.08	3.02	0.16	12	−0.23	−0.01	2.84
†29	...	...	...	...	...	...	...	...
†30	...	...	...	...	...	...	...	...
35	30.5	3.92	2.03	−.31	10	.37	.03	4.32
36	23.5	3.02	1.97	.05	12	−.07	0	2.95
†39	...	...	...	...	...	...	...	...
GRAVEL								
31	0	0	1.90	0.17	11	−0.22	−0.01	−0.23
32	0	0	1.69	.23	15	−.41	−.02	−.43
CLAY LOAM								
33	22.5	2.89	1.92	−0.43	10	0.52	0.04	3.45
34	14.0	1.80	1.93	.27	10	−.32	−.02	1.46
†37	...	...	...	...	...	...	...	...
†38	...	...	...	...	...	...	...	...

See footnotes at end of table.

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TABLE 27.—*Use of water in bare soil tanks at Glenbar experiment station, 1943-44* —Continued

Tank no.	Water added		Average water level (feet)	Rise in water level during month (feet)	Coefficient of drainage and saturation (percent)	Adjustment for rise in water level (inches)[1]	Correction for recharge well (inches)	Water used in tank, less rain (inches)
	Gallons	Inches[1]						
April 1944, rainfall 0.15 inch								
SAND AND GRAVEL								
28	26.5	3.41	2.98	0.09	12	−0.13	−0.01	3.27
†29	....	....	....	....	....	....	....	....
†30	....	....	....	....	....	....	....	....
35	39.5	5.08	2.04	.16	10	−.19	−.01	4.88
36	22.0	2.83	1.93	.34	12	−.49	−.03	2.31
†39	....	....	....	....	....	....	....	....
GRAVEL								
31	0	0	1.80	0.03	11	−0.04	0	−0.04
32	0	0	1.59	.03	15	−.05	0	−.05
CLAY LOAM								
33	30.0	3.86	2.01	0.20	10	−0.24	−0.02	3.60
34	17.5	2.25	1.94	.14	10	−.17	−.01	2.07
†37	....	....	....	....	....	....	....	....
†38	....	....	....	....	....	....	....	....
May 1944, rainfall 0.18 inch								
SAND AND GRAVEL								
28	25.0	3.21	2.99	−0.22	12	0.32	0.02	3.55
†29	....	....	....	....	....	....	....	....
†30	....	....	....	....	....	....	....	....
35	46.5	5.98	1.96	−.25	10	.30	.02	6.30
36	22.0	2.83	1.96	−.78	12	1.12	.07	4.02
†39	....	....	....	....	....	....	....	....
GRAVEL								
31	0	0	1.79	0.01	11	−0.01	0	−0.01
32	0	0	1.57	.01	15	−.02	0	−.02
CLAY LOAM								
33	32.0	4.11	1.94	−0.09	10	0.11	0.01	4.23
34	21.0	2.70	1.95	−.24	10	.29	.02	3.01
†37	....	....	....	....	....	....	....	....
†38	....	....	....	....	....	....	....	....
June 1944, rainfall 0								
SAND AND GRAVEL								
28	30.5	3.92	3.01	0.14	12	−0.20	−0.01	3.71
†29	....	....	....	....	....	....	....	....
†30	....	....	....	....	....	....	....	....
35	53.0	6.81	2.06	.20	10	−.24	−.02	6.55
36	30.0	3.86	2.06	.54	12	−.78	−.05	3.03
[3] 39	1.5	.19	3.98	−.01	15	.02	0	.21
GRAVEL								
31	0	0	1.78	−0.01	11	0.01	0	0.01
32	0	0	1.58	−.04	15	.07	0	.07
CLAY LOAM								
33	36.0	4.63	2.13	−0.11	10	0.13	0.01	4.77
34	27.0	3.47	2.00	.32	10	−.38	−.03	3.06
[3] 37	10.5	1.35	4.00	.18	5	−.11	−.02	1.22
[3] 38	9.5	1.22	4.08	.27	10	−.32	−.02	.88

See footnotes at end of table.

TABLE 27.—*Use of water in bare soil tanks at Glenbar experiment station, 1943-44* —Continued

Tank no.	Water Added: Gallons	Water Added: Inches[1]	Average water level (feet)	Rise in water level during month (feet)	Coefficient of drainage and saturation (percent)	Adjustment for rise in water level (inches).	Correction for recharge well (inches)	Water used in tank, less rain (inches)
July 1944, rainfall 1.62 inches								
SAND AND GRAVEL								
28	24.5	3.15	2.93	−0.02	12	0.03	0	3.18
†29	....	....	....	....	....	....	....	....
†30	....	....	....	....	....	....	....	....
35	41.5	5.33	1.97	.24	10	−.29	−.02	5.02
36	29.0	3.73	1.94	.25	12	−.36	−.02	3.35
39	2.0	.26	3.92	.08	15	−.14	−.01	.11
GRAVEL								
31	1.0	0.13	1.67	0.24	11	−0.32	−0.02	−0.21
[4] 32	−9.0	−1.16	1.69	−.44	15	.79	.04	−.33
CLAY LOAM								
33	27.5	3.53	1.92	−0.02	10	0.02	0	3.55
34	21.0	2.70	1.83	−.23	10	.28	.02	3.00
37	11.0	1.41	3.86	.02	5	−.01	0	1.40
38	8.0	1.03	3.88	.14	10	−.17	−.01	.85
August 1944, rainfall 1.19 inches								
SAND AND GRAVEL								
28	26.0	3.34	2.95	−0.02	12	0.03	0	3.37
[5] 29	11.0	1.41	3.56	−.04	12	.06	0	1.47
[6] 30	31.5	4.05	2.49	−.16	12	.23	.01	4.29
35	44.5	5.72	2.00	.41	10	−.49	−.03	5.20
36	28.0	3.60	1.88	.02	12	−.03	0	3.57
39	1.0	.13	3.92	−.07	15	.13	.01	.27
GRAVEL								
31	32.5	4.18	1.00	1.11	11	−1.47	−0.09	2.62
SAND								
32	58.0	7.45	1.06	0.48	15	−0.86	−0.04	6.55
CLAY LOAM								
33	32.0	4.11	1.87	0.81	10	−0.97	−0.07	3.07
34	23.0	2.96	1.96	−.04	10	.05	0	3.01
37	12.5	1.61	3.95	.03	5	−.02	0	1.59
38	7.5	.96	3.94	.05	10	−.06	0	.90
September 1944, rainfall 0.31 inch[7]								
SAND AND GRAVEL								
28	18.0	2.31	2.78	0.10	12	−0.14	−0.01	2.16
29	25.5	3.28	3.48	−.20	12	.29	.02	3.59
30	27.5	3.53	2.48	−.04	12	.06	0	3.59
35	24.0	3.08	1.84	−.50	10	.60	.04	3.72
36	19.5	2.51	1.93	−.07	12	.10	.01	2.62
39	4.5	.58	3.97	.04	15	−.07	0	.51
GRAVEL								
31	13.0	1.67	0.94	−0.57	11	0.75	0.05	2.47
SAND								
32	33.0	4.24	1.01	−0.25	15	0.45	0.02	4.71
CLAY LOAM								
33	17.5	2.25	1.93	−0.11	10	0.13	0.01	2.39
34	16.5	2.12	1.94	.50	10	−.60	−.04	1.48
37	9.5	1.22	3.94	.01	5	−.01	0	1.21
38	6.5	.84	3.93	−.15	10	.18	.01	1.03

[1] Based on area of tank minus area of recharge well.
[2] January and February combined. Rainfall, 0.82 inch.
[3] Data are for June 16-30, inclusive.
[4] Data are for July 1-24, inclusive. Gravel removed and tank filled with sand July 25.
[5] Data are for August 25-31, inclusive.
[6] Data are for August 16-31, inclusive.
[7] Data are for September 1-22 only; inundated by flood on September 25.
† Tanks were being used for specific yield experiments, so readings could not be taken.
NOTE.—Negative figures occur in last column in some cases because some rainfall may have percolated to water table or because of small errors in coefficient of drainage and saturation.

ADJUSTMENT FOR CHANGES IN WATER LEVEL

The change in water level, in feet, during a month was the algebraic difference between the water level on the morning of the first day of the month and the water level on the morning of the first day of the following month. This difference was multiplied by the coefficient of drainage and saturation of the materials in the tank and converted to inches. A rise in water level meant that more water was added to the tank than was transpired or evaporated, and hence when there was a rise in water level the increase was subtracted from the total water added. A small adjustment was needed to account for the change in water level in the recharge well, for which no coefficient was needed. The algebraic sum, in inches, of water added and the adjustment for changes in water level in the tank and recharge well was the total water discharged from the tank, less rainfall, during the month.

Results of many experiments with tanks have been published with rainfall included as a part of the water use, and for that reason the rainfall is given at the head of each set of monthly figures in tables 26 and 27. To obtain results including rainfall from tables 22 and 23, the monthly rainfall should be added to the figures in the last column.

ADJUSTMENT FOR VOLUME DENSITY

The volume-density theory can be applied to individual tanks as well as to the field, except that in dealing with the individual plants and clumps of plants grown in tanks at the Glenbar experiment station the crown area was used as the area of the plant. The area of a tank in which a plant was growing was not a factor in determining the volume density of the plant. The crown area was determined by projecting points on the perimeter of the crown to the land surface and measuring the area enclosed by a line connecting the projected points.

The density of frondage on a plant, expressed as percent of crown area, was used as the areal density of the plant. The density of frondage was estimated for each individual plant by two men independently, and the average of the estimates was used. The estimates were based on areal densities of similar plants growing in the bottom land, the plants in the tanks being rated in terms of the bottom-land plants of known areal density. As the saltcedar and baccharis plants in the tanks were not entirely shaded by surrounding vegetation, sunlight penetrated practically all parts of the plants sometime during the day, and as a result fronds grew more luxuriantly on the plants in the tanks than on the plants in the field. Thus, it was possible to have an areal density of more than 100 percent for the plants in the tanks without having areal densities of more than 100 percent in the field. For the same reason, the vertical density exceeded 100 percent if the depth of frondage of plants in the tanks exceeded the optimum depth of frondage of plants in the field.

Estimates of areal density in the tanks were made in the fall of 1943, but, as the volume-density theory had not yet been fully evolved, the estimates were incomplete and could not be used in the computations. Determinations of volume density were made twice in 1944, and the means of the two sets of determinations were assumed to represent average conditions of growth density during the period October 1, 1943, to September 22, 1944.

The volume density was computed as the product of areal density multiplied by vertical density. The volume density of the vegetation in each of the tanks was calculated as in the following hypothetical example.

Base data:

Tank No. X, Saltcedar:
Area of tank . . . . 78.45 sq. ft.
Crown area of vegetation in tank . . . . 83.42 sq. ft.
Areal density of vegetation in tank . . . . 90 percent
Average depth of frondage . . . . 14.0 ft.
Water used during month, less rain . . . . 10.23 in./unit area of tank

Calculations for vertical density:

$$\text{Ratio of average depth of frondage to optimum depth of frondage in field} = \frac{14 \text{ ft.}}{13 \text{ ft.}} \times 100 = 107.7 \text{ percent}$$

Calculations for volume density:

$$\text{Areal density} \times \text{vertical density} = 90 \text{ percent} \times 107.7 \text{ percent} = 96.9 \text{ percent}$$

The monthly amount of water used in each tank, not including rainfall, was calculated in terms of inches per unit area of 100-percent volume density. The calculations follow.

Crown area adjusted to area of 100-percent volume density:

$$\text{Crown area} \times \text{volume density} = 83.42 \text{ sq. ft.} \times 96.9 \text{ percent} = 80.83 \text{ sq. ft.}$$

Ratio, tank area to area of 100-percent volume density:

$$\frac{78.45 \text{ sq. ft.}}{80.83 \text{ sq. ft.}} = 0.971$$

Water used during month, less rain, in terms of 100-percent volume density:

$$\text{Water used, less rain, in./unit area of tank} \times \text{ratio of tank area to area of 100-percent volume density} = (10.23 \text{ in./unit area of tank}) \times 0.971 = 9.93 \text{ in./unit area of 100-percent volume density}$$

Table 28 contains figures showing the crown area, the densities, and the ratio of tank area to the area of 100-percent volume density for each

TABLE 28.—*Factors for converting use of water by plants in tanks to use of water by plants in field*

Tank no.	Type of plant [1]	Area of tank less area of recharge well (square feet)	Crown area of plants (square feet)	Areal density (percent)	Vertical density (percent)	Volume density (percent) [2]	Crown area adjusted to 100-percent volume density (square feet)	Ratio of tank area to adjusted crown area
11	SC	78.45	44.51	66.1	100.0	66.1	29.42	2.666
12	SC	78.45	78.69	90.0	97.7	87.9	69.17	1.134
13	C	78.45	53.27	69.8	100.0	69.8	37.18	2.110
14	C	78.45	105.29	87.5	133.3	116.6	122.77	.639
15	SC	28.19	31.90	84.0	75.3	63.3	20.19	1.396
16	SC	28.19	23.76	100.0	102.3	102.3	24.31	1.160
17	SC	28.19	27.48	86.8	84.6	73.4	20.17	1.398
18	SC	28.19	22.36	88.2	84.6	74.6	16.68	1.690
19	SC	28.19	25.40	78.2	93.1	72.8	18.49	1.525
20	SC	28.19	33.59	75.2	93.8	70.6	23.71	1.189
21	SC	28.19	23.02	118.0	104.6	123.4	28.41	.992
22	B	12.48	10.56	52.5	129.1	67.8	7.16	1.743
23	B	12.48	10.05	57.2	161.8	92.5	9.30	1.342
24	B	12.48	19.65	59.8	152.7	91.3	17.94	.696
25	B	12.48	14.24	51.2	150.9	77.3	11.01	1.134
26	B	12.48	15.02	52.5	132.7	69.7	10.47	1.192
27	B	12.48	19.36	55.0	114.5	63.0	12.20	1.023

[1] SC, saltcedar; C, cottonwood; B, baccharis.
[2] Areal density times vertical density.

tank. The figures obtained for water used in the tanks, by months, were multiplied by the ratio of tank area to area of 100-percent volume density to obtain figures for water used at 100-percent volume density. The results are given in the last column of table 26.

APPLICATION TO FIELD

The amount of water used, not including rainfall, during the period October 1, 1943, to September 22, 1944, was totaled for each tank of saltcedar and of baccharis. The average depth to water in each tank was calculated for the same period. Using these data, two curves were then drawn (see fig. 39) to show the relation between rate of use and depth to water for the period—one curve for the nine saltcedar tanks and one for the six baccharis tanks.

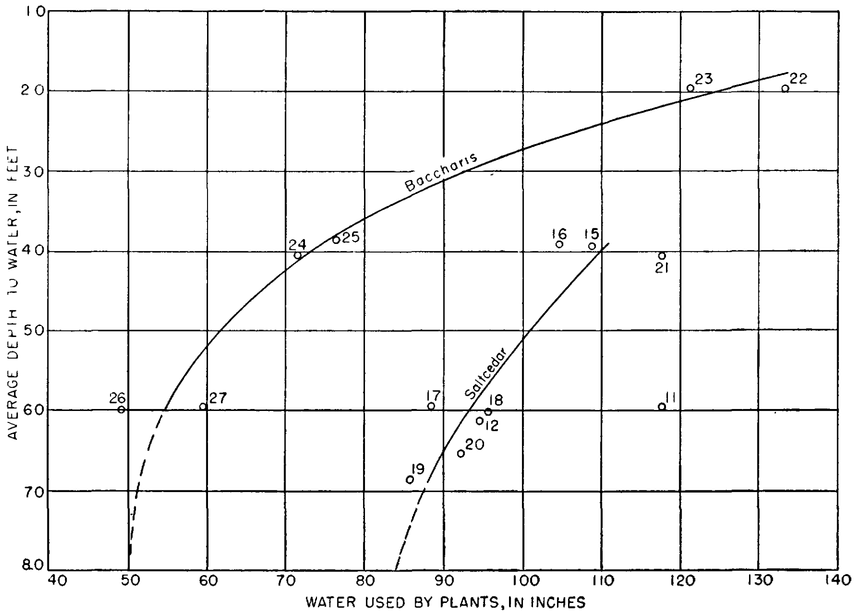

Figure 39.—Relation between depth to water and water used by plants in tanks, October 1, 1943, to September 22, 1944.

Use of water in the field for the period October 1, 1943, to September 22, 1944, was determined for each of the four reaches. Table 29 gives the results in acre-feet. The average depth to ground water in a reach (see table 29) was applied to figure 39, and the corresponding annual rates of transpiration by saltcedar and baccharis were read from the corresponding curves. These rates were multiplied by the respective areas of saltcedar and baccharis at 100-percent volume density to obtain the total acre-feet of ground water used by those phreatophytes in the reach. All the steps used in computing use of water by saltcedar and baccharis, except the correction for depth to ground water, were applied in determining use of water by cottonwoods. Data were not available for determining the effect of depth to water on rate of water use by cottonwoods. A correction for depth to ground water in the areas occupied by cottonwoods would lower the indicated totals in table 29 by a small amount.

The use of water by mesquite, given in table 29, was determined by the transpiration-well method, as no mesquite plants were grown in tanks. The plants included as "brush" in table 29 are not all phreatophytes, and no studies were made during the investigation to determine the use of ground water by the group. It is believed from field observations that the draft on ground water by miscellaneous brush does not exceed 1 foot per year, and that figure has been adopted for this report.

TABLE 29.—*Use of water by bottom-land vegetation, based on experiments with tanks, October 1, 1943, to September 22, 1944*

Reach	Saltcedar				Baccharis				Cottonwood and willow			
	Area of 100-percent volume density (acres)	Average depth to water (feet)	Use		Area of 100-percent volume density (acres)	Average depth to water (feet)	Use		Area of 100-percent volume density (acres)	Average depth to water (feet)	Use	
			Feet	Acre-feet			Feet	Acre-feet			Feet	Acre-feet
Thatcher to Glenbar..	940	6.53	7.49	7,041	128	5.87	4.57	585	131	[1]7.0	7.64	1,001
Glenbar to Fort Thomas..	908	6.91	7.33	6,656	65	6.31	4.40	286	16	[1]7.0	7.64	122
Fort Thomas to Black Point....	469	6.75	7.39	3,466	78	5.83	4.58	357	60	[1]7.0	7.64	458
Black Point to Calva..	469	7.70	7.06	3,311	198	[1]6.0	4.51	893	73	[1]7.0	7.64	558
Thatcher to Calva.	2,786	......	.....	20,474	469	......	.....	2,121	280	......	.....	2,139

Reach	Mesquite				Brush				Total	
	Area of 100-percent volume density (acres)	Average depth to water (feet)	Use		Area of 100-percent volume density (acres)	Average depth to water (feet)	Use		Not including precipitation (acre-feet)	Including precipitation (acre-feet)
			Feet	Acre-feet			Feet	Acre-feet		
Thatcher to Glenbar........	27	[2]10.0	[2]2.71	73	98	[1]5.0	[1]1.0	98	8,800	9,990
Glenbar to Fort Thomas........	25	[2]10.0	[2]2.71	68	64	[1]5.0	[1]1.0	64	7,200	8,160
Fort Thomas to Black Point.....	161	[2]10.0	[2]2.71	436	189	[1]5.0	[1]1.0	189	4,910	5,930
Black Point to Calva..........	255	[2]10.0	[2]2.71	691	366	[1]5.0	[1]1.0	366	5,820	8,040
Thatcher to Calva......	468	....	......	1,268	717	....	......	717	26,730	32,120

[1] Estimated.
[2] Based on transpiration wells.

On the basis of field observations, it was assumed that all the rainfall in the bottom land was returned to the atmosphere in one of the following ways: By evaporation, by entering the topsoil and being transpired from there by phreatophytes and other plants, or possibly by entering the zone of saturation and being transpired from there by phreatophytes. Therefore, the rainfall on the gross area of phreatophytes and barren land in each reach was added to the use of ground water by phreatophytes in the reach to obtain the total use of water. Evaporation from wet sand bars along the river and from the surface of the river was not included in the computations; hence precipitation on these areas was not included.

In order to place the results by the tank method on a comparable basis with results by the other methods, the amount of ground water used during the period September 23-30, 1944, was estimated. The estimate of use during this 8-day period was based on the mean of the use during the periods September 1-22, 1944, and October 1-22, 1943. No records were available for October 1944. The adjustment added was 3.1 percent of the use during the 358 days. The following table gives draft on ground water and total use of water, including rainfall, by the tank method for the 366-day period ending September 30, 1944.

TABLE 30.—*Annual use of water by bottom-land vegetation in 1943-44, in acre-feet, based on tank experiments*

Reach	*Draft on ground water*	*Total use of water*
Thatcher–Glenbar	9,070	10,260
Glenbar–Fort Thomas	7,420	8,380
Fort Thomas–Black Point	5,060	6,080
Black Point–Calva	6,000	8,220
Thatcher–Calva	27,550	32,940

TRANSPIRATION-WELL METHOD

It has been demonstrated by White[49] that diurnal fluctuations of the water table can be caused by vegetation that draws its water supply from shallow ground water. White obtained continuous records of water-level fluctuations in shallow wells located in areas of phreatophytes. After an analysis of the daily graphs, he developed a method for measuring the draft on ground water by the plants. The method developed by White was modified and applied in the present investigation as one of the methods for determining the use of water by phreatophytes in the bottom land. The method as applied involves first, obtaining continuous records of the daily water-table fluctuations from shallow

[49] White, W. N., A method of estimating ground-water supplies based on discharge by plants and evaporation from soil—results of investigations in Escalante Valley, Utah: U. S. Geol. Survey Water-Supply Paper 659-A, 105 pp., 1932.

wells in areas of phreatophytes, and second, determining the coefficient of drainage of the material in which the daily fluctuations of the water table occur. The results are then adjusted for volume density of growth at the individual wells and applied to the field.

The location and installation of the wells bored to determine water-level fluctuations caused by transpiration have been described in part 2 of this report. The method of determination of the coefficient of drainage has also been described. The discussion that follows presents analyses of the theory of the method, the factors that may have affected the accuracy of the method, and the computations of results.

THEORY

The theory of the occurrence of diurnal fluctuations has been described by White:[50]

During the day the capillary fringe is depleted by the plants, and the movement of ground water by capillary action to meet the depletion is more rapid than recharge by hydrostatic or artesian pressure. Therefore the water table declines and the head increases. During the night transpiration and evaporation losses are small, the water table moves upward, and the pressure head declines.

From about 6 to 10 in the evening and again from about 6 to 10 in the morning recharge approximately balances discharge, and for a few hours the water table is nearly at a standstill. This state of equilibrium would be reached earlier both in the evening and in the morning if it were not for a lag in some of the operations. At or soon after sunset the rate of transpiration and evaporation declines to a small fraction of the rate that prevails during the day, but for a time the plants continue to draw some water to fill their circulatory systems, which have become somewhat depleted. (Nearly all plants become slightly wilted during the day, particularly on hot days, and tend to have a drooping appearance at night, quite in contrast with their fresh, turgid appearance in the morning.) Moreover, during the day the recharge of the capillary fringe from the zone of saturation lags somewhat behind the discharge by plant action. By midnight, or slightly before, the veins of the plants have become filled with water. Meanwhile capillary equilibrium has been nearly established in the capillary fringe, and during the hours from midnight to morning there is little movement of water to the fringe from the zone of saturation.

Between midnight and 4 a. m. the water table is approximately at a mean elevation for the 24-hour period, and therefore the head is also approximately at a mean, provided there is no net gain or loss in water-table elevation during the 24-hour period. If the water table has a net fall during the 24 hours, the head in the early morning hours mentioned is slightly above the noon to noon mean; and if it has a net rise, the head is slightly below the mean but the difference is generally not great. The velocity of water moving through a rock or soil varies approximately as the hydraulic gradient. Therefore if the slight losses by transpiration and evaporation between midnight and 4 a. m. are neglected, as well as the slight difference between the hydraulic head at this time and the true mean for the day, the hourly rate of recharge from midnight to 4 a. m. may be accepted as the average rate for the 24-hour period. The total quantity of ground water withdrawn by transpiration and evaporation during the 24-hour period can then be determined by the formula $q=y(24r \pm s)$, in which q is the

[50] White, W. N., op. cit., pp. 60-61.

depth of water withdrawn in inches, y is the specific yield of the soil in which the daily fluctuation of the water table takes place, r is the hourly rate of rise of the water table from midnight to 4 a. m. in inches, and s is the net fall or rise of the water table during the 24-hour period in inches. In field experiments the quantities on the right-hand side of the formula except the specific yield can be readily determined from the automatic records of water-table fluctuation.

Figure 40 illustrates the theoretical position of the water table in the bottom land at the times of daily maximum recovery and of daily maximum drawdown. In figure 40, *A*, the total water recharged in a 24-hour period is equal to the total water discharged. At the position representing daily maximum recovery the water table slopes uniformly toward the river, and ground water enters the stream at the maximum rate. Soon after transpiration begins water is withdrawn from the aquifer faster than it can be replenished. Therefore, the water table declines and water enters the stream at a lower rate, but the hydraulic gradient into the area becomes steeper. At the time of daily maximum drawdown the water table has been depressed and has a concave shape. The rate at which water enters the area has increased, but most of the water is being withdrawn by phreatophytes before it reaches the river. A well in the bottom land would exhibit daily fluctuations of the water table as shown in the insert graph, figure 40, *A*.

The conditions that exist when the movement of ground water into the area is not sufficient to return the water table to its original position each day are shown in figure 40, *B*. The daily graph of water-level fluctuations resembles the graph of *A* except that each succeeding daily peak is lower than that of the previous day. Figure 40, *C*, shows the conditions that exist where there is no recharge at all and shows the daily graph of water-level fluctuations that would be obtained. Graphs similar to *C* have been obtained in tanks at the Glenbar experiment station.

FACTORS THAT AFFECT COMPUTED USE OF WATER

The computed results may be affected by variations in natural phenomena. Variations that act directly on the plants (relative humidity, for example) will cause fluctuations in the rate of transpiration but will cause no error in the computed results. Variations in factors that act on the water table through the capillary fringe (barometric pressure, for example) will cause errors in the computed use of water.

TEMPERATURE

The effect of temperature upon transpiration rates and on the position of the water table has been discussed in the description of the tank method. The cold front of April 9, 1944, was reflected by a decline in water level in some of the transpiration wells (see fig. 33), although to a lesser degree than in the tanks. Figure 41 shows the

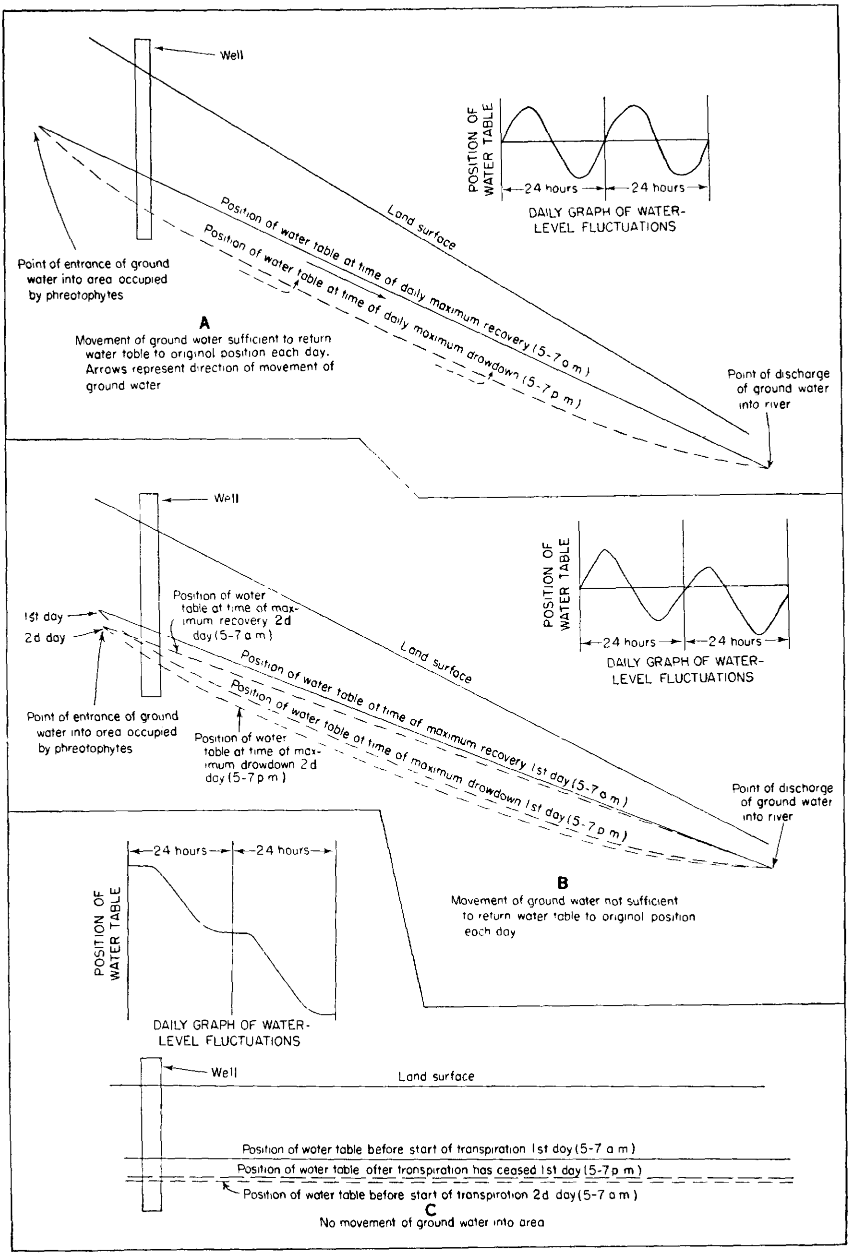

FIGURE 40.—Idealized sketch of section perpendicular to river channel, showing changes in position of water table as a result of daily transpiration.

daily cycle of fluctuations in air temperature compared with fluctuations of the water table in a typical well. The graphs of temperature and position of the water table indicate that the two are rather closely related.

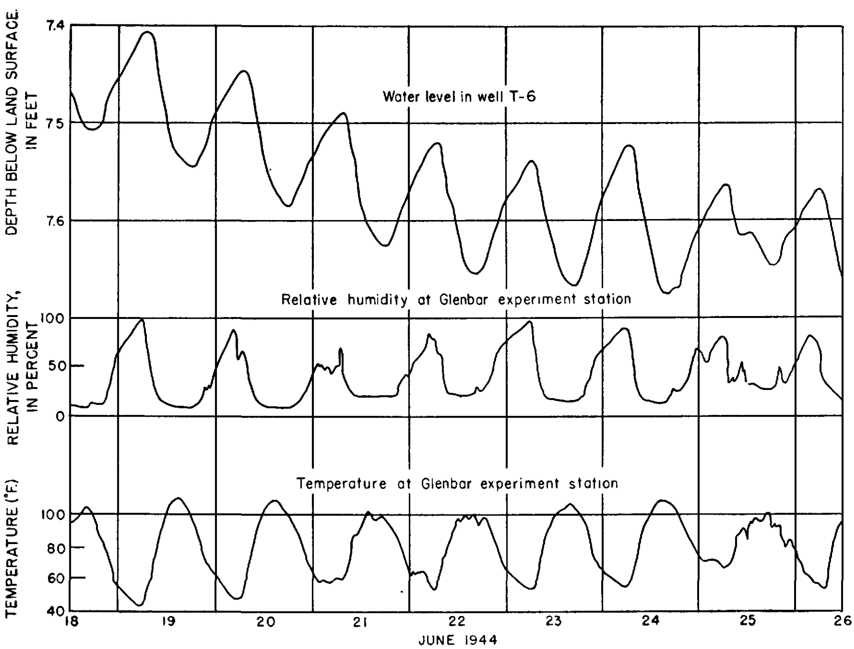

FIGURE 41.—Relation of fluctuation of the water table due to transpiration by saltcedar to fluctuation of relative humidity and temperature.

RELATIVE HUMIDITY

Figure 41 also shows the relation between fluctuations of relative humidity and fluctuations of the ground-water level caused by transpiration. The time of greatest relative humidity is approximately the time of least transpiration, and the time of least relative humidity is approximately the time of greatest transpiration. No experiments were made to determine quantitatively the effect of changes in relative humidity on rate of water use apart from that of temperature.

PRECIPITATION

The graphs of water-level fluctuations, on which the transpiration-well method is based, indicate the rate of withdrawal of ground water from storage without regard to precipitation. In a rainy period the plants utilize the increased soil moisture available and withdraw less ground water than during a dry period. Therefore, the hydrograph from a well for a day when the soil moisture is plentiful will show a low use of water. In making the computations, therefore, it was assumed that the figure for use of ground water for any given period did not include the amount of precipitation on the area involved during the period. A possible error in making this assumption lies in the fact that some of the precipitation during periods of long, slow rains may possibly percolate to the water table. However, the amount that may have reached the water table during the investigation was undoubtedly extremely small, as there were few periods during the growing season when storms lasted more than 5 hours. Observations made on the tanks at the Glenbar experiment station indicated that even after heavy rains the amount of penetration of rain water was small. In the rainfall-penetration experiment previously described under the heading "Tank method," a rain of 0.66 inch caused an average penetration to a depth of 4.6 inches.

BAROMETRIC PRESSURE

Generally speaking, the effect of changes in barometric pressure on the position of the water table was not noticeable in the transpiration wells during the growing season. The results from those wells that were affected by changes in barometric pressure were not used in the final computations.

QUALITY OF WATER

During the investigation it was found that some species of plants tend to use more water when the water available is low in dissolved solids than when the water is highly mineralized (see fig. 24). Some of the transpiration wells were located in areas where ground water was highly mineralized, and others were located where the ground water was low in dissolved solids. Averaging the results in computing water use tended to eliminate the errors introduced by variations in quality of water at individual wells.

DEPTH TO WATER

Table 31 shows the depth to water at each of the wells used in the computations. The mean depth to water in all the wells in saltcedar was 6.4 feet; in the wells in baccharis, 6.1 feet; in the wells in cottonwood, 7.8 feet; and in the well in mesquite, 10.0 feet. These figures are based on the range of fluctuation at the wells and are not weighted according to the length of time the water table was at a given depth. The mean depth to the water table in the bottom land, by species of phreatophyte, is given in table 29. For saltcedar, baccharis, and mesquite the depth to water at the transpiration wells was nearly the same as the average in the field; for cottonwood the water table at the wells was an average of 0.8 foot deeper than in the field. Therefore, the computed use of water by saltcedar, baccharis, and mesquite need not be adjusted for depth to the water table. The computed use of water by

TABLE 31.—*Records of transpiration wells used to determine use of water by bottom-land vegetation*

Well no.	Type of vegetation	Location	Range of depth to water (feet below land surface)	Coefficient of drainage (percent)	Areal density (percent)	Vertical density (percent)	Volume density (percent)	Correction factor for night transpiration	Transpiration factor[1]
T-4	Saltcedar	NW¼SW¼ sec. 21, T. 6 S., R. 25 E.	4.6-6.8	15	97	77	74.7	1.25	0.251
T-6	do	do	6.2-8.1	15	70	100	70.0	1.25	.268
T-7	do	NW¼NW¼ sec. 35, T. 6 S., R. 25 E.	7.5-8.5	18	98	100	98.0	1.25	.230
T-9	Cottonwood	NW¼NE¼ sec. 18, T. 6 S., R. 25 E.	6.1-8.6	13	100	100	100.0	1.00	.130
T-19	Saltcedar	NW¼NW¼ sec. 29, T. 5 S., R. 24 E.	3.8-5.3	17	50	100	50.0	1.25	.425
T-24	Mesquite	SW¼NE¼ sec. 18, T. 4 S., R. 23 E.	8.7-11.3	18	100	100	100.0	1.00	.180
T-25	Baccharis and saltcedar.	SW¼SW¼ sec. 7, T. 4 S., R. 23 E.	2.5-4.4	10	65	100	65.0	1.10	.169
T-26	Cottonwood	NE¼NW¼ sec. 18, T. 4 S., R. 23 E.	7.4-8.9	16	100	100	100.0	1.00	.160
T-29	Baccharis	SE¼SW¼ sec. 7, T. 4 S., R. 23 E.	2.6-4.1	16	80	73	58.4	1.07	.293
T-30	do	SW¼SW¼ sec. 7, T. 4 S., R. 23 E.	2.4-4.4	20	75	100	75.0	1.07	.285
T-33	Saltcedar	NW¼NW¼ sec. 7, T. 5 S., R. 24 E.	6.7-8.0	20	65	96	62.4	1.25	.401
T-34	Baccharis	SW¼SW¼ sec. 26, T. 4 S., R. 23 E.	9.0-9.8	17	100	100	100.0	1.07	.182
T-35	do	San Carlos Indian Reservation	7.7-8.5	23	75	100	75.0	1.07	.328
T-37	Saltcedar	NE¼NW¼ sec. 7, T. 5 S., R. 24 E.	5.0-6.4	15	85	77	65.4	1.25	.287
T-38	do	SW¼NW¼ sec. 36, T. 4 S., R. 23 E.	5.4-7.2	13	90	98	88.2	1.25	.184
T-40	do	SE¼SE¼ sec. 27, T. 4 S., R. 23 E.	5.0-6.7	18	95	92	87.4	1.25	.257
T-41	Baccharis	SW¼SE¼ sec. 7, T. 4 S., R. 23 E.	5.3-6.0	18	95	109	103.6	1.07	.186
T-42	do	do	6.3-6.8	12	90	109	98.1	1.07	.131

[1] Transpiration factor $= \dfrac{\text{coefficient of drainage} \times \text{factor for night transpiration}}{\text{Volume density}}$

cottonwood is slightly lower than the actual field use, but no correction was attempted.

COEFFICIENT OF DRAINAGE

The coefficient of drainage was determined in the laboratory for each of the samples of water-bearing material collected from the transpiration wells within the zone of fluctuation of the water table. The mean of the determinations for any one well was used as the coefficient of drainage for that well.

DETERMINATION OF VOLUME DENSITY AT TRANSPIRATION WELLS

An effort was made to install the wells where the vegetation was of 100-percent volume density. However, not all the sites selected were in areas of extremely dense growth because other factors sometimes controlled the selection of sites. In determining the actual field density of the vegetation surrounding each well a circle having a radius of 50 feet with its center at the well was arbitrarily taken as representing the growth conditions that would affect the fluctuations of the water table in the well. The areal density and vertical density in the circle were determined, and from these figures the volume density for the well was computed. The depth of frondage on the plants surrounding transpiration wells T-41 and T-42 exceeded 5.5 feet, the average maximum depth of frondage for baccharis, and therefore the figures for vertical density used for these wells exceeded 100 percent.

TRANSPIRATION AT NIGHT

Most of the information contained herein is based on work by Robinson,[51] who makes the following statement:

> That the formula developed by White could not be applied with confidence when dealing with saltcedar was first suspected by S. F. Turner during his investigation of the water resources of the Safford and Duncan-Virden Valleys, Arizona and New Mexico, in 1940 and 1941. He was not entirely satisfied with the results obtained by the application of the formula developed by White, because the draft on ground water by saltcedar, when compared with the results obtained by other methods always seemed too low. During the course of the investigation in the lower Safford Valley in 1943 and 1944, the writer noticed that the shape of the diurnal fluctuation curves, obtained by water-stage recorders on wells located in saltcedar thickets, did not follow the usual shape and differed in detail from those obtained by White in Escalante Valley. This difference lay in the decreased rate of rise or flattening of the curves from about 10 p. m. to about 4 a. m.

The basic assumption of the White formula is that the hourly rate of rise of the water table, r, from midnight to 4 a. m. may be accepted as the average rate of recharge for 24 hours, provided specifically that there are no losses by evaporation or transpiration during the period from midnight to 4 a. m. and provided further that the hydraulic head during the period is at the mean for the day. If transpira-

[51] Robinson, T. W., personal communication.

tion is causing withdrawal of water during the period from midnight to 4 a. m., the indicated rate of rise, r, will be less than the true rate of rise. The difference between the indicated rate of rise, r, and the true rate of rise will be the mean rate of transpiration during the period from midnight to 4 a. m. If the factor of night transpiration is not considered, the quantity $(24r \pm s)$ in White's formula will therefore be low by 24 times the hourly rate of night transpiration.

As it was impossible to determine quantitatively from a field curve the effect of transpiration at night, experiments were made at the Glenbar experiment station by Robinson. Tanks containing saltcedar, baccharis, and cottonwood, in which recharge could be controlled and measured volumetrically, were used. Water-stage recorders were installed on each of the tanks selected for testing, and the floats in the recharge wells were adjusted for several days prior to the tests to insure that accurate graphs of the water level would be obtained. Sufficient water was then added to each of these tanks to supply the needs of the plants for 48 hours or more. At the end of 24 hours the residual head in the recharge well was considered sufficiently reduced to proceed with measurements, so that for the ensuing 24 hours the water level in the recharge well would approximate the water level in the tank. The rate of lowering of the water level in the tank is a function of the rate of transpiration.

The tests showed that the water level in tanks containing saltcedar and baccharis continued to decline throughout the night, but at a lesser rate than during the day. This decline indicated that there was transpiration all night, including the period from midnight to 4 a. m. In the tank containing cottonwood there was essentially no change in water level from midnight to 4 a. m., indicating little, if any, transpiration during this period and also indicating that the continued decline in water level in the tanks containing saltcedar and baccharis probably was not a function of soil-moisture depletion.

Figure 42 contains typical curves, obtained during the experiments, showing water-level fluctuations in tanks of saltcedar, baccharis, and cottonwood. The curves show that the rate of decline of the water table at night is different for each of the three species, being greatest for saltcedar and essentially zero for cottonwood. The water level in the tank of saltcedar is analogous to the water level in a transpiration well. If it were assumed that the rate of night transpiration was zero, inspection of the curve alone would indicate that the water level was declining at a constant rate (rate from midnight to 4 a. .m) of 0.00525 foot per hour. Applying the White formula to the curve, $24r$ is equal to -0.126 foot, and s is equal to a net fall of 0.50 foot, so that the parenthetical term $(24r+s)$ becomes $-0.126 + 0.50 = 0.374$ foot, which is the indicated total daily use resulting from such an application of the formula. However, it is known that the true total daily use as shown by the curve is 0.50 foot and that the true daytime use is the sum of the decline in water level between noon and 5 p.m. the first day and the decline in water level between 7 a. m. and noon the second day, or 0.425 foot. Thus, the assumption that the rate of night transpiration for saltcedar is zero leads to a result, as computed by the White formula, that is erroneous and, where the recharge is zero as in the present case, one that is even lower than the true daytime use.

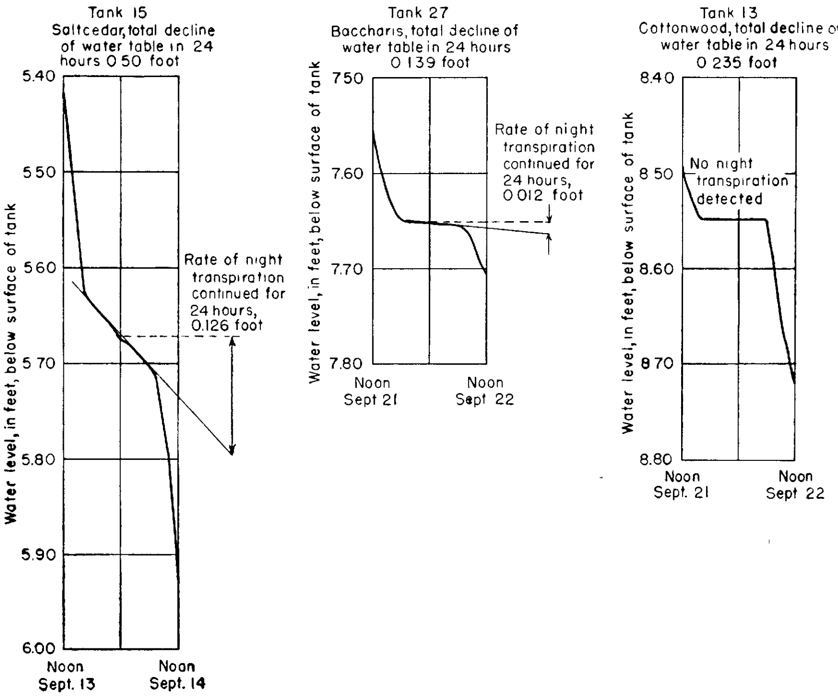

FIGURE 42.—Typical water-level fluctuations in tanks at Glenbar experiment station, showing effect of night transpiration upon position of the water table.

Figure 43 further illustrates the effect of night transpiration by saltcedar on fluctuations of the water table. Figure 43, *A*, is based on the graph obtained from tank 15 on September 13-14, 1944. (See fig. 42.) An assumed rate of recharge was plotted, equal to the total decline of the water table during 24 hours. The recharge curve was added graphically to the curve obtained from the tank, producing a "field curve" similar in general form to curves obtained from transpiration wells. Next, the graph obtained from tank 15 on September 13-14, 1944, was redrawn (fig. 43, *B*) to show all of the decline of the water table occurring during daylight hours. The total decline of the water table was the same as that shown in the original graph, but the effect of transpiration at night was thus eliminated. An assumed rate of recharge was plotted, equal to the total decline, and added graphically to the adjusted tank curve. This produced a field curve similar in shape but greater in amplitude than the field curve from the original data.

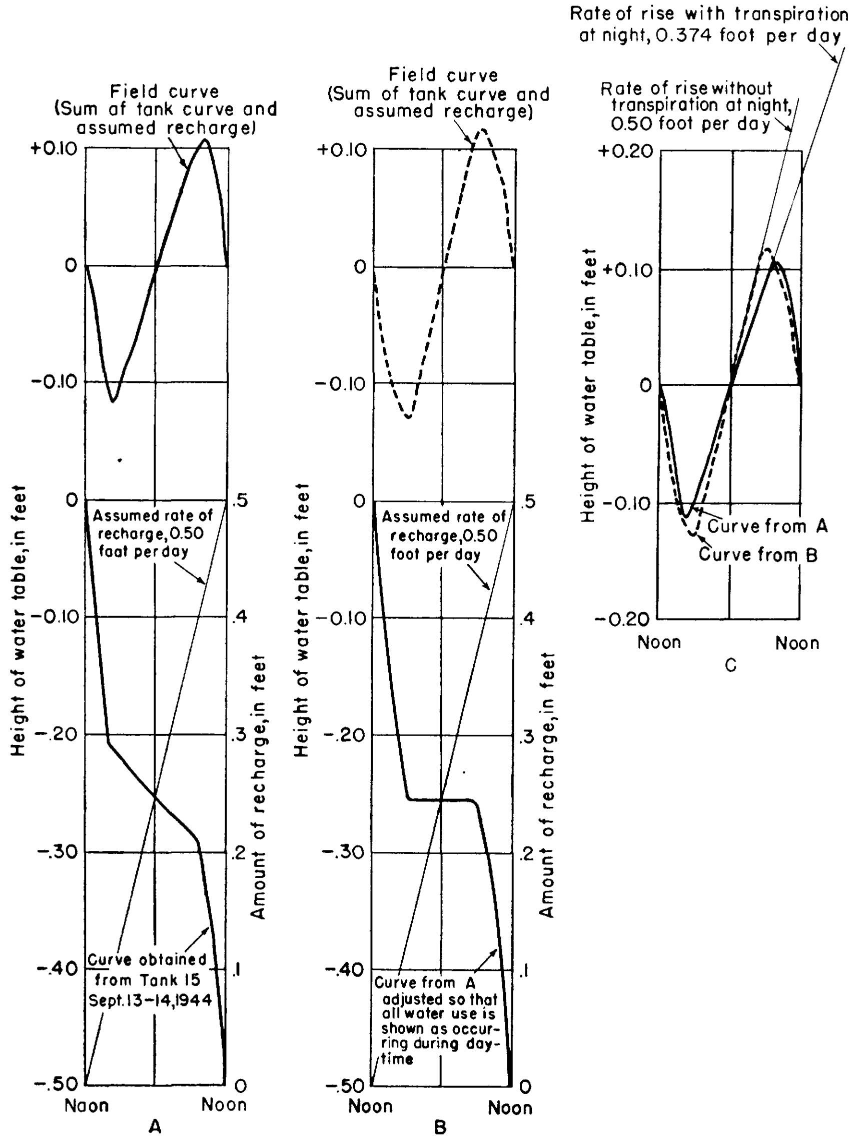

FIGURE 43.—Effect of transpiration at night upon rate of fluctuation of the water table. *A*, Graph from tank 15, with recharge assumed equal to total water used; *B*, Graph from tank 15 adjusted so that all water use occurs during daytime, with recharge assumed equal to total water used; and *C*, Resultant curves of *A* and *B* superposed.

The two field curves were superposed (fig. 43, *C*), and the hourly rate of rise of each curve between midnight and 4 a. m. was measured. Applying the White formula to the field curve based on the occurrence of transpiration at night (from fig. 43, *A*), $24r$ equals 0.374 foot, and s equals zero, so that

$$24r \pm s = 0.374 \text{ foot}$$

Applying the formula to the field curve based on no transpiration at night (from fig. 43, *B*) $24r$ equals 0.50 foot, and s equals zero, so that

$$24r \pm s = 0.50 \text{ foot}$$

According to the base curve from which figure 43 was derived, the total transpiration in 24 hours was known to be 0.50 foot. Although the two field curves were similar in general form, the curve that contained elements of transpiration at night gave results that were 0.126 foot too low when the use of water was computed by the White formula.

There appears to be no sure method of analyzing quantitatively a field curve obtained from a transpiration well that will indicate the effect of transpiration at night. Therefore, correction factors were derived on the basis of the tank experiments, where the effect of transpiration at night could be analyzed. The correction factor for the example cited is the ratio of true use to indicated use, or 0.50 foot divided by 0.374 foot, which equals 1.34. The mean correction factor for saltcedar, based on 12 determinations, was 1.25; the mean correction factor for baccharis, based on 4 determinations, was 1.07; and the mean correction factor for cottonwood, based on 4 determinations, was 1.00 (no discernible transpiration at night). The relative magnitude of the 3 correction factors was also indicated by at least 25 additional graphs of daily fluctuations in tanks. No data were available on mesquite, as no mesquite plants were grown in the tanks, and the correction factor for this species was assumed to be 1.00.

POSSIBLE ERRORS

Number of determinations.—The experiments for determination of the effect of transpiration at night were of necessity terminated by the flood of September 25, 1944, which inundated the Glenbar experiment station. Many more determinations are needed, in different localities, with different types of plants, and at different times of the year, before better results can be accumulated. The studies at the Glenbar experiment station indicated that there is transpiration at night, the probable magnitude of the correction factors, and, more praticularly, the relative magnitude of the factors for the three species of plants studied.

Effect of residual head.—If, during the tests on a given tank, the water level in the recharge well were higher than the water level in the soil-filled part of the tank, the results would be in error. Water that has been poured into the recharge well enters the gravel layer at the bottom of the tank through the perforations in the well. The water percolates upward uniformly over the area of the tank, raising the water level in the tank. However, water enters the soil from the gravel layer more slowly than water can be poured into the top of the recharge well. Therefore, when adding water to a tank the water level in the recharge well rises temporarily above the water level in the soil-filled part of the tank, sometimes as much as several feet. This difference in the position of the water level is called residual head, and sometimes a period of several hours was required before this head was dissipated. As an extreme case, if the residual head in the recharge well of tank 15 had been declining at the rate of 0.00525 foot an hour the night of September 13-14 the decline in head would have been sufficient to account for the observed decline in water level. Under these circumstances the assumption that transpiration occurred at night would have been erroneous. However, the materials in all the tanks were similar in composition, permeability, coefficient of drainage, and degree of compaction. Hence, if the observed decline of the water level in the tank containing saltcedar had been caused solely by a decline in residual head in the recharge well the effect should have occurred in about the same amount in the tanks containing baccharis and cottonwood. As the decline in water level in the recharge wells was practically the same in those tanks containing plants of a given species, but different in the tanks containing plants of other species, it was concluded that the possible error caused by residual head in the recharge well was small with respect to the amount of transpiration at night.

TRANSPIRATION FACTOR

In applying the transpiration-well method in computing the amount of water used by bottom-land vegetation, a transpiration factor was determined for each well. This factor is the product of the coefficient of drainage and the factor for night transpiration, divided by the volume density of the vegetation in the vicinity of the well. The water used was computed by multiplying the transpiration factor by the indicated use, in inches, obtained from the graphs of water-table fluctuations. Thus the transpiration factor corresponds to the specific yield y in the White equation (see p. 140) combined with factors to adjust for night transpiration and to 100-percent volume density.

COMPUTATION OF RESULTS

The first step in the computations was to determine the indicated daily use of water ($24r \pm s$) for each transpiration well. It was not possible to obtain an unbroken record of water-table fluctuations for any of the transpiration wells for a full growing season. The records

TABLE 32.—*Monthly use of ground water, in inches, by bottom-land vegetation at transpiration wells, 1943 and 1944*

[Indicated use is monthly sum of daily figures of use computed from formula (24r ±s); adjusted use is indicated use multiplied by transpiration factor]

	Saltcedar								Baccharis						Cottonwood		Mesquite	Mixed baccharis and saltcedar[1]
	T-4	T-6	T-7	T-19	T-33	T-37	T-38	T-40	T-29	T-30	T-34	T-35	T-41	T-42	T-9	T-26	T-24	T-25
1943																		
July, indicated use	68.6	74.9	36.5	32.3	19.5	...	...	...	42.6	53.6	...	...	...	...	32.8	53.5	64.2	60.6
adjusted use	17.2	20.1	8.4	13.7	7.8	...	...	...	12.5	15.3	...	...	...	...	4.3	8.6	11.6	10.2
Aug., indicated use	63.2	63.8	35.3	22.4	17.2	...	...	...	33.3	33.8	9.3	25.7	...	...	43.0	44.1	55.8	41.8
adjusted use	15.9	17.1	8.1	9.5	6.9	...	...	...	9.8	9.6	1.7	8.4	...	...	5.6	7.1	10.0	7.1
Sept. indicated use	...	68.6	14.9	23.3	7.5	...	...	...	16.6	22.9	7.4	14.2	...	...	17.5	22.5	27.0	35.6
adjusted use	...	18.4	3.4	9.9	3.0	...	...	...	4.9	6.5	1.3	4.7	...	...	2.3	3.6	4.9	6.0
Oct., indicated use	37.8	29.6	17.6	7.0	3.3	...	...	...	16.3	11.4	.9	6.9	...	...	3.7	8.6	8.0	21.5
adjusted use	9.5	7.9	4.0	3.0	1.3	...	...	...	4.8	3.2	.2	2.3	...	...	.5	1.4	1.4	3.6
Nov., indicated use	3.7	0	1.4	0	0	...	...	...	.8	1.1	0	0	...	...	0	3.9	0	.7
adjusted use	.9	0	.3	0	0	...	...	...	.2	.3	0	0	...	...	0	.6	0	.1
Dec., indicated use	0	0	0	0	0	...	...	...	0	0	0	0	...	...	0	0	0	0
adjusted use	0	0	0	0	0	...	...	...	0	0	0	0	...	...	0	0	0	0
1944																		
Jan., indicated use	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
adjusted use	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Feb., indicated use	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
adjusted use	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mar., indicated use	.5	.1	...	...	...	0	0	0	.4	.9	...	...	0	0	...	0	0	.9
adjusted use	.1	0	...	...	...	0	0	0	.1	.3	...	...	0	0	...	0	0	.2
Apr., indicated use	9.5	7.7	...	...	.6	3.7	2.5	4.2	12.5	7.0	...	...	3.5	0	...	15.8	0	12.7
adjusted use	2.4	2.1	...	...	.2	1.1	.5	1.1	3.7	2.0	...	...	.7	0	...	2.5	0	2.1
May, indicated use	41.3	48.2	...	...	21.9	44.6	44.6	50.6	44.3	44.5	...	...	26.3	8.1	...	55.8	16.6	53.9
adjusted use	10.4	12.9	...	...	8.8	12.8	8.2	13.0	13.0	12.7	...	...	4.9	1.1	...	8.9	3.0	9.1
June, indicated use	60.6	84.7	...	...	43.2	63.1	65.8	63.3	61.2	51.0	...	...	27.8	43.5	...	57.6	44.0	65.1
adjusted use	15.2	22.7	...	...	17.3	18.1	12.1	16.3	17.9	14.5	...	...	5.2	5.7	...	9.2	7.9	11.0
July, indicated use	65.8	78.4	...	...	40.0	56.1	...	42.3	45.2	41.7	...	15.3	25.0	40.5	...	54.1	34.1	53.9
adjusted use	16.5	21.0	...	...	16.0	16.1	...	10.9	13.2	11.9	...	5.0	4.6	5.3	...	8.7	6.1	9.1
Aug., indicated use	65.3	82.4	...	...	37.8	54.6	63.4	40.7	40.6	28.3	...	21.8	15.5	25.5	...	42.8	28.9	47.6
adjusted use	16.4	22.1	...	...	15.2	15.7	11.7	10.5	11.9	8.1	...	7.1	2.9	3.3	...	6.8	5.2	8.0
Sept., indicated use	62.0	66.6	...	...	32.7	51.6	55.1	38.3	32.9	37.1	...	16.2	16.8	28.2	...	32.8	19.5	46.0
adjusted use	15.6	17.8	...	...	13.1	14.8	10.1	9.8	9.6	10.6	...	5.3	3.1	3.7	...	5.2	3.5	7.8
Oct., indicated use	...	0	...	...	3.9	0	1.7	...	0	...	...	0	0	0	...	9.2	3.5	0
adjusted use	...	0	...	...	1.6	0	.3	...	0	...	...	0	0	0	...	1.5	.6	0
Nov., indicated use	...	0	...	...	1.6	0	0	...	0	...	...	0	0	0	...	4.3	0	0
adjusted use	...	0	...	...	.6	0	0	...	0	...	...	0	0	0	...	.7	0	0
Dec., indicated use	...	0	...	...	0	0	0	...	0	...	...	0	0	0	...	0	0	0
adjusted use	...	0	...	...	0	0	0	...	0	...	...	0	0	0	...	0	0	0

[1] Not used in final computations.

were interrupted for short periods by mechanical failure of the recorders or were made worthless by floods in the Gila River or by a large rise of the water table as the result of irrigation. The daily use was computed for all wells, and after comparative studies the poor and incomplete records were discarded. Most of the remaining records were complete for a month or longer, although where only a day or two of record in a month was missing the record was completed by interpolation. Table 32 gives the indicated use and adjusted use for each month, by wells. The indicated monthly use of ground water is the monthly sum of the daily figures of use computed from the term $(24r \pm s)$ of White's formula. The adjusted use is the product of the indicated use, and the transpiration factor, which gives the use of water, in inches by bottom-land vegetation at 100-percent volume density.

The mean monthly use of water by each species was computed from data collected in 1943 and 1944. (See table 33.) Because few of the computed records from any well were continuous for a period of a year, the available results were combined to give the use of ground water for a 12-month period beginning October 1 and ending September 30. The monthly use by saltcedar in July, for instance, was obtained by computing the mean of all determinations for saltcedar in both July 1943 and July 1944. For the months prior to July the 1944 records were used. The sum of the 12 monthly figures for each species was considered to be the amount of ground water used by that type of plant in a year. This sum was multiplied by the area of 100-percent volume density in each reach of the bottom-land to obtain the annual use of ground water.

TABLE 33.—*Mean monthly use of ground water by bottom-land vegetation, in inches, based on an average of records from transpiration wells for the 1943 and 1944 seasons*

	Jan.	Feb.	Mar.	Apr.	May	June	July
Saltcedar	0	0	0	1.2	11.0	17.0	14.8
Baccharis	0	0	.1	1.6	7.9	10.8	9.7
Cottonwood	0	0	0	2.5	8.9	9.2	7.2
Mesquite	0	0	0	0	3.0	7.9	8.8

	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Saltcedar	13.5	11.6	3.1	0.2	0	72.4
Baccharis	7.0	5.5	1.3	.1	0	44.0
Cottonwood	6.5	3.7	1.1	.4	0	39.5
Mesquite	7.6	4.2	1.0	0	0	32.5

Table 34 lists for each species, by reaches, the acreage of growth at 100-percent volume density, the annual draft on ground water in feet, and the annual use of ground water in acre-feet. The same figures are given for use of water by brush as were given in table 29 because no transpiration wells were operated in thickets of brush. Precipitation in acre-feet for the gross area of phreatophytes and barren land in each reach was obtained from table 10. The precipitation in a reach was added to the draft on ground water in the reach to obtain the total use of water. Rainfall on and evaporation from the surface of the river and wet sand bars along the river were not included.

TABLE 34.—*Annual use of water by bottom-land vegetation, based on an average of records from transpiration wells for the 1943 and 1944 seasons*

Reach	Saltcedar			Baccharis			Cottonwood		
	Area of 100-percent volume density (acres)	Draft on ground water		Area of 100-percent volume density (acres)	Draft on ground water		Area of 100-percent volume density (acres)	Draft on ground water	
		Feet	Acre-feet		Feet	Acre-feet		Feet	Acre-feet
Thatcher to Glenbar	940	6.03	5,668	128	3.67	470	131	3.29	431
Glenbar to Fort Thomas	908	6.03	5,475	65	3.67	238	16	3.29	53
Fort Thomas to Black Point	469	6.03	2,828	78	3.67	286	60	3.29	197
Black Point to Calva	469	6.03	2,828	198	3.67	727	73	3.29	240
Thatcher to Calva	2,786	......	16,799	469	......	1,721	280	......	921

Reach	Mesquite			Brush			Total	
	Area of 100-percent volume density (acres)	Draft on ground water		Area of 100-percent volume density (acres)	Draft on ground water		Not including precipitation (acre-feet)	Including precipitation (acre-feet)
		Feet	Acre-feet		Feet	Acre-feet		
Thatcher to Glenbar	27	2.71	73	98	[1]1.0	98	6,740	7,930
Glenbar to Fort Thomas	25	2.71	68	64	[1]1.0	64	5,900	6,860
Fort Thomas to Black Point	161	2.71	436	189	[1]1.0	189	3,940	4,960
Black Point to Calva	255	2.71	691	366	[1]1.0	366	4,850	7,070
Thatcher to Calva	468	......	1,268	717	......	717	21,430	26,820

[1] Estimated.

SEEPAGE-RUN METHOD

THEORY

For any seepage run in any reach a figure of gain or loss in the river can be computed on the basis of discharge measurements at the beginning and end of the reach. The water passing through a reach is depleted by evaporation from the surface of the river and wet sand bars in the reach. Therefore, the figure of gain or loss is too small by the amount of this evaporation. A figure of actual inflow to or outflow from the river in the reach can be computed by adding algebraically the gain or loss and the evaporation in the reach. If precipitation had occurred during a seepage run an adjustment for precipitation could be made in a similar manner.

The actual inflow of ground water to the river is equal to the net underground inflow moving toward the river across the outer edges of the bottom land, if adjustment is made for three factors: The rate of change in ground-water storage beneath the bottom land, the rate of withdrawal of ground water in the phreatophyte-covered part of the bottom land, and the rate of percolation to the water table from surface water within the bottom-land area. The last factor was considered negligible for the period of the investigation.

The adjustment for changes in ground-water storage can be computed from the records for observation wells. The effect of changes in ground-water storage is such that, when the storage is increasing, the inflow to the river is less than the net underground inflow to the bottom land by the rate of change of the contents of the ground-water reservoir in the bottom land. Thus for each seepage run a figure of inflow to the river, adjusted for rate of change in ground-water storage in the bottom land can be computed.

In winter, when the draft on ground water is zero or nearly so, the figure of inflow to the river, adjusted for changes in ground-water storage in the bottom land, is equal to the net underground inflow at the outer edges of the bottom land. As the rate of net underground inflow to the bottom land during the year has been considered to be practically constant, the mean of the adjusted results from the seepage runs made in the winter gives a figure of net underground inflow that is considered to represent the inflow throughout the year.

In a given reach the actual inflow to the river after adjustment for rate of change in ground-water storage is less during the growing season than the net underground inflow across the outer edges of the bottom land, and the difference is the amount of ground water used in the phreatophyte-covered part of the bottom land. Therefore this difference, for each seepage run made during the growing season, represents draft on ground water in the reach. These computations thus provide a measure of the draft on ground water in a reach for the days of the seepage runs. Also, the figures are fairly representative of the use of ground water during a period of a week or two before and after each seepage run. The mean use of ground water computed from two successive seepage runs can be considered to apply to the period between those runs. On this basis, use of ground water for the entire year can be computed.

COMPUTATION OF INFLOW TO RIVER ADJUSTED FOR RATE OF CHANGE IN GROUND-WATER STORAGE

Tables 35-38 show the figures needed for the computations for each of the seepage runs for the four reaches. The figures of adjusted gain are a summation of the appropriate figures of gain or loss from table

22, and the rate of evaporation was computed from table 11. The algebraic sum of the adjusted gain and the rate of evaporation is the net underground inflow to the river.

TABLE 35.—*Adjustment of seepage runs, in second-feet, to obtain net underground inflow to bottom land minus use by phreatophytes, Thatcher-Glenbar reach, 1943-44*

Date of seepage run	Adjustment for evaporation from river surface and wet sand bars			Adjustment for changes in ground-water storage	
	Adjusted gain in reach	Rate of evaporation from river surface and sand bars	Net underground inflow to river	Rate of change in contents of ground-water reservoir	Inflow to river, adjusted for rate of change in ground-water storage[1]
1943					
June 24	2.7	0.9	3.6	−3.4	0.2
Sept. 16, 17	7.9	.9	8.8	−4.4	4.4
Nov. 4	13.9	.6	14.5	+5.3	19.8
Nov. 25	19.9	.5	20.4	+1.5	21.9
Dec. 13	23.0	.3	23.3	+3.2	26.5
1944					
Jan. 13	22.2	.5	22.7	+1.1	23.8
Feb. 14	35.8	.6	36.4	0	36.4
Mar. 15	24.6	.6	25.2	−.8	24.4
Apr. 12	17.2	.8	18.0	−3.0	15.0
May 3	18.3	1.2	19.5	−4.2	15.3
May 24	9.9	.9	10.8	−5.1	5.7
June 21	4.4	1.0	5.4	−3.8	1.6
Oct. 28, 30	12.8	.6	13.4	−3.2	10.2

[1] Equivalent to that part of the net underground inflow to the bottom land that is not used in the phreatophyte-covered part.

TABLE 36.—*Adjustment of seepage runs, in second-feet, to obtain net underground inflow to bottom land minus use by phreatophytes, Glenbar-Fort Thomas reach, 1943-44*

Date of seepage run	Adjustment for evaporation from river surface and wet sand bars			Adjustment for changes in ground-water storage	
	Adjusted gain in reach	Rate of evaporation from river surface and sand bars	Net underground inflow to river	Rate of change in contents of ground-water reservoir	Inflow to river, adjusted for rate of change in ground-water storage[1]
1943					
June 24	−0.2	1.0	0.8	−3.1	−2.3
Sept. 17	.3	.9	1.2	−2.7	−1.5
Nov. 5	3.4	.8	4.2	+3.1	7.3
Nov. 26	4.7	.4	5.1	+.2	5.3
Dec. 16	8.4	.6	9.0	+1.3	10.3
1944					
Jan. 14	14.4	.4	14.8	+2.6	17.4
Feb. 15	15.8	.5	16.3	−1.5	14.8
Mar. 16	15.1	.7	15.8	−2.4	13.4
Apr. 13	9.7	.9	10.6	−1.1	9.5
May 4	6.1	1.0	7.1	−2.7	4.4
May 25	2.2	.9	3.1	−4.2	−1.1
June 22	.2	1.0	1.2	−3.7	−2.5
July 17	−1.0	1.0	0	−2.0	−2.0
Aug. 7	−.4	.8	.4	−1.5	−1.1
Oct. 26	5.9	.5	6.4	−4.2	2.2

[1] Equivalent to that part of the net underground inflow to the bottom land that is not used in the phreatophyte-covered part.

TABLE 37.—*Adjustment of seepage runs, in second-feet, to obtain net underground inflow to bottom land minus use by phreatophytes, Fort Thomas-Black Point reach, 1943-44*

Date of seepage run	Adjustment for evaporation from river surface and wet sand bars			Adjustment for changes in ground-water storage	
	Adjusted gain in reach	Rate of evaporation from river surface and sand bars	Net underground inflow to river	Rate of change in contents of ground-water reservoir	Inflow to river, adjusted for rate of change in ground-water storage[1]
1943					
June 24, 25	1.4	1.1	2.5	−1.8	0.7
Sept. 17, 18	5.8	.9	6.7	−2.9	3.8
Nov. 9	13.5	.8	14.3	+4.1	18.4
Nov. 23	9.8	.5	10.3	+1.3	11.6
Dec. 14	16.7	.4	17.1	+2.9	20.0
1944					
Jan. 15	17.6	.4	18.0	+1.6	19.6
Feb. 18	21.7	.6	22.3	−1.4	20.9
Mar. 17	15.9	.5	16.4	−1.3	15.1
Apr. 14	12.6	1.0	13.6	−1.4	12.2
May 5	10.7	1.1	11.8	−2.3	9.5
May 26	7.3	1.1	8.4	−3.6	4.8
June 23	1.9	1.1	3.0	−2.7	.3
July 18	2.6	1.0	3.6	−2.0	1.6
Aug. 8	2.3	.5	2.8	−2.5	.3
Oct. 27	6.2	.7	6.9	−2.9	4.0

[1] Equivalent to that part of the net underground inflow to the bottom land that is not used in the phreatophyte-covered part.

TABLE 38.—*Adjustment of seepage runs, in second-feet, to obtain net underground inflow to bottom land minus use by phreatophytes, Black Point-Calva reach, 1943-44*

Date of seepage run	Adjustment for evaporation from river surface and wet sand bars			Adjustment for changes in ground-water storage	
	Adjusted gain in reach	Rate of evaporation from river surface and sand bars	Net underground inflow to river	Rate of change in contents of ground-water reservoir	Inflow to river, adjusted for rate of change in ground-water storage[1]
1943					
June 25	−2.0	1.3	−0.7	−5.0	−5.7
Sept. 18	−4.4	1.1	−3.3	−9.3	−12.6
Nov. 9	−5.1	1.1	−4.0	+4.3	.3
Nov. 23	−.2	.7	.5	+3.7	4.2
Dec. 14	.1	.6	.7	+4.1	4.8
1944					
Jan. 15	2.3	.5	2.8	+1.4	4.2
Feb. 18	6.7	.8	7.5	−1.7	5.8
Mar. 17	5.3	.8	6.1	−1.8	4.3
Apr. 14	2.7	1.4	4.1	−3.9	.2
May 5	−1.1	1.5	.4	−4.4	−4.0
May 26	−2.9	1.4	−1.5	−7.9	−9.4
June 23	−2.7	1.3	−1.4	−12.1	−13.5
July 18	−5.9	1.0	−4.9	−6.1	−11.0
Aug. 8	−2.7	.7	−2.0	−7.4	−9.4
Oct. 27	−1.4	.8	−.6	−3.7	−4.3

[1] Equivalent to that part of the net underground inflow to the bottom land that is not used in the phreatophyte-covered part.

The figures in the last column in each of tables 35-38 are the algebraic sum of the figures for net underground inflow to the river and for rate of change in contents of the ground-water reservoir. The method of computing the rate of change of contents of the ground-water reservoir was described in part 2. The figures in the last column in each of the tables represent inflow to the river, adjusted for rate of change in ground-water storage, which is equivalent to that part of the net underground inflow to the bottom land that is not used in the phreatophyte-covered part.

COMPUTATION OF NET UNDERGROUND INFLOW TO BOTTOM LAND

The figures for the winter months in the last column of tables 35-38 are equal to the net underground inflow entering each reach across the outer edges of the bottom land. As the draft on ground water was zero, or nearly so, when the seepage runs in December, January, February, and March were made, the mean results from those runs have been accepted as the mean net underground inflow for the year as computed by the seepage-run method. The figures for net underground inflow computed by this method are given in table 39.

TABLE 39.—*Net underground inflow to bottom land, in second-feet, computed by the seepage-run method*

Reach	*Net underground inflow*
Thatcher–Glenbar	27.8
Glenbar–Fort Thomas	14.0
Fort Thomas–Black Point	18.9
Black Point–Calva	4.8
Total	65.5

Net underground inflow to the bottom land was also computed by the independent inflow-outflow method. The accuracy of the figures for net underground inflow is believed to be about the same by both methods. Therefore, the results by the two methods were averaged to give figures which are probably more accurate than those derived by either method alone. The averaged figures are repeated from part 2 in table 40.

TABLE 40.—*Net underground inflow to bottom land, in second-feet, computed as the mean of results obtained by the inflow-outflow and seepage-run methods*

Reach	*Net underground inflow*
Thatcher–Glenbar	27.8
Glenbar–Fort Thomas	15.5
Fort Thomas–Black Point	18.8
Black Point–Calva	4.0
Total	66.1

COMPUTATION OF RESULTS

Tables 41-44 show, for each seepage run, the net underground inflow to the bottom land minus use by phreatophytes. These figures are equal to the actual inflow to the river, adjusted for rate of change in ground-water storage (tables 35-38). Therefore, for each reach, if the figures for net underground inflow to the bottom land minus use by phreatophytes are subtracted from the figure of net underground inflow for the reach (shown at head of tables 41-44), the result is the rate of use of ground water by the phreatophytes. No figures for rate of use have been shown for the seepage runs made in December, January, February, or March, because the net underground inflow was considered equal to the actual inflow to the river during those months. The small

TABLE 41.—*Use of ground water by bottom-land vegetation, Thatcher-Glenbar reach, based on seepage-run method*

[Mean net underground inflow to reach, 27.8 second-feet]

	Seepage runs		Period between runs		
	Inflow to bottom land minus use by phreatophytes (second-feet)	Rate of use by phreatophytes (second-feet)	Mean use by phreatophytes per day (acre-feet)	Length of period (days)	Use by phreatophytes (acre-feet)
1943					
June 24	0.2	27.6			
Sept. 16, 17	4.4	23.4			
Sept. 16-30			31.1	15	466
Oct. 1 to Nov. 3			31.1	34	1,057
Nov. 4	19.8	8.0			
Nov. 4-24			13.8	21	290
Nov. 25	21.9	5.9			
Nov. 25-30			5.9	6	35
Dec. 1-12			0	12	0
Dec. 13	26.5				
Dec. 13 to Jan. 12			0	31	0
1944					
Jan. 13	23.8				
Jan. 13 to Feb. 13			0	32	0
Feb. 14	36.4				
Feb. 14 to Mar. 14			0	30	0
Mar. 15	24.4				
Mar. 15-31			0	17	0
Apr. 1-11			12.7	11	140
Apr. 12	15.0	12.8			
Apr. 12 to May 2			25.1	21	527
May 3	15.3	12.5			
May 3-23			34.3	21	720
May 24	5.7	22.1			
May 24 to June 20			47.9	28	1,341
June 21	1.6	26.2			
June 21 to July 16			49.9	26	1,297
July 17		[1] 24.1			
July 17 to Aug. 6			46.5	21	976
Aug. 7		[1] 22.8			
Aug. 7 to Sept. 30			40.1	55	2,206
Oct. 1-28			40.1	28	1,123
Oct. 28, 30	10.2	17.6			
Total Oct. 1, 1943, to Sept. 30, 1944					8,590

[1] Computed on basis of ratio of rate of use by phreatophytes in this reach to rate of use by phreatophytes n Glenbar-Fort Thomas reach for runs of May 25, June 22, and Oct. 26, 1944.

negative figures that can be computed for seepage runs made in the winter are a result of using a figure for net underground inflow that is the mean of calculations by two different methods.

TABLE 42.—*Use of ground water by bottom-land vegetation, Glenbar-Fort Thomas reach, based on seepage-run method*

[Mean net underground inflow to reach, 15.5 second-feet]

	Seepage runs		Period between runs		
	Inflow to bottom land minus use by phreatophytes (second-feet)	Rate of use by phreatophytes (second-feet)	Mean use by phreatophytes per day (acre-feet)	Length of period (days)	Use by phreatophytes (acre-feet)
1943					
June 24	−2.3	17.8			
Sept. 17	−1.5	17.0			
Sept. 17-30			25.0	14	350
Oct. 1 to Nov. 4			25.0	35	875
Nov. 5	7.3	8.2			
Nov. 5-25			18.2	21	382
Nov. 26	5.3	10.2			
Nov. 26-30			10.1	5	50
Dec. 1-15			0	15	0
Dec. 16	10.3				
Dec. 16 to Jan. 13			0	29	0
1944					
Jan. 14	17.4				
Jan. 14 to Feb. 14			0	32	0
Feb. 15	14.8				
Feb. 15 to Mar. 15			0	30	0
Mar. 16	13.4				
Mar. 16-31			0	16	0
Apr. 1-12			6.0	12	72
Apr. 13	9.5	6.0			
Apr. 13 to May 3			17.0	21	357
May 4	4.4	11.1			
May 4-24			27.5	21	578
May 25	−1.1	16.6			
May 25 to June 21			34.3	28	960
June 22	−2.5	18.0			
June 22 to July 16			35.2	25	880
July 17	−2.0	17.5			
July 17 to Aug. 6			33.8	21	710
Aug. 7	−1.1	16.6			
Aug. 7 to Sept. 30			29.7	55	1,634
Oct. 1-25			29.7	25	742
Oct. 26	2.2	13.3			
Total Oct. 1, 1943, to Sept. 30, 1944					6,500

The mean use of ground water by the phreatophytes per day, in acre-feet, for the periods between successive seepage runs was computed from the appropriate figures for rate of use, in second-feet. The last column in tables 41-44 is the product of the mean use of ground water per day and the number of days in each period and shows the use of ground water for each period. Use of ground water was arbitrarily assumed to stop on November 30 and to begin on April 1. Use of water was not computed for the period between the seepage runs of June and September 1943 because the period was believed to be too long for the computed mean rate of use of ground water to be representative of field conditions. Use of ground water for the year ending September 30, 1944, was computed by a summation of the appropriate items in the last column of tables 41-44.

The use of water thus computed represents draft on ground water and does not include use of precipitation. Table 45 gives results, in acre-feet, for the year ending September 30, 1944, in terms of draft on ground water and total use including precipitation.

TABLE 43.—*Use of ground water by bottom-land vegetation, Fort Thomas-Black Point reach, based on seepage-run method*

[Mean net underground inflow to reach, 18.8 second-feet]

	Seepage runs		Period between runs		
	Inflow to bottom land minus use by phreatophytes (second-feet)	Rate of use by phreatophytes (second-feet)	Mean use by phreatophytes per day (acre-feet)	Length of period (days)	Use by phreatophytes (acre-feet)
1943					
June 24, 25	0.7	18.1			
Sept. 17, 18	3.8	15.0			
Sept. 17-30			15.3	14	214
Oct. 1 to Nov. 8			15.3	39	597
Nov. 9	18.4	.4			
Nov. 9-22			7.5	14	105
Nov. 23	11.6	7.2			
Nov. 23-30			7.1	8	57
Dec. 1-13			0	13	0
Dec. 14	20.0				
Dec. 14 to Jan. 14			0	32	0
1944					
Jan. 15	19.6				
Jan. 15 to Feb. 17			0	34	0
Feb. 18	20.9				
Feb. 18 to Mar. 16			0	28	0
Mar. 17	15.1				
Mar. 17-31			0	15	0
Apr. 1-13			6.5	13	84
Apr. 14	12.2	6.6			
Apr. 14 to May 4			15.8	21	332
May 5	9.5	9.3			
May 5-25			23.1	21	485
May 26	4.8	14.0			
May 26 to June 22			32.2	28	902
June 23	.3	18.5			
June 23 to July 17			35.4	25	885
July 18	1.6	17.2			
July 18 to Aug. 7			35.4	21	743
Aug. 8	.3	18.5			
Aug. 8 to Sept. 30			33.0	54	1,782
Oct. 1-26			33.0	26	858
Oct. 27	4.0	14.8			
Total Oct. 1, 1943, to Sept. 30, 1944					5,970

TABLE 44.—*Use of ground water by bottom-land vegetation, Black Point-Calva reach, based on seepage-run method*

[Mean net underground inflow to reach, 4.0 second-feet]

	Seepage runs		Period between runs		
	Inflow to bottom land minus use by phreatophytes (second-feet)	Rate of use by phreatophytes (second-feet)	Mean use by phreatophytes per day (acre-feet)	Length of period (days)	Use by phreatophytes (acre-feet)
1943					
June 25	−5.7	9.7			
Sept. 18	−12.6	16.6			
Sept. 18-30			20.1	13	261
Oct. 1 to Nov. 8			20.1	39	784
Nov. 9	.3	3.7			
Nov. 9-22			3.7	14	52
Nov. 23	4.2	0			
Nov. 23-30			0	8	0
Dec. 1-13			0	13	0
Dec. 14	4.8				
Dec. 14 to Jan. 14			0	32	0
1944					
Jan. 15	4.2				
Jan. 15 to Feb. 17			0	34	0
Feb. 18	5.8				
Feb. 18 to Mar. 16			0	28	0
Mar. 17	4.3				
Mar. 17-31			0	15	0
Apr. 1-13			3.8	13	49
Apr. 14	.2	3.8			
Apr. 14 to May 4			11.7	21	246
May 5	−4.0	8.0			
May 5-25			21.2	21	445
May 26	−9.4	13.4			
May 26 to June 22			30.6	28	857
June 23	−13.5	17.5			
June 23 to July 17			32.2	25	805
July 18	−11.0	15.0			
July 18 to Aug. 7			28.2	21	592
Aug. 8	−9.4	13.4			
Aug. 8 to Sept. 30			21.5	54	1,161
Oct. 1-26			21.5	26	559
Oct. 27	−4.3	8.3			
Total Oct. 1, 1943, to Sept. 30, 1944					4,990

TABLE 45.—*Annual use of water by bottom-land vegetation, in acre-feet, based on seepage runs made in 1943-44*

Reach	*Draft on ground water*	*Total use of water*
Thatcher–Glenbar	8,590	9,780
Glenbar–Fort Thomas	6,500	7,460
Fort Thomas–Black Point	5,970	6,990
Black Point–Calva	4,990	7,210
Total	26,050	31,440

INFLOW-OUTFLOW METHOD

THEORY

The inflow-outflow method of determining use of water by bottom-land vegetation is sometimes called the water-inventory method. For a given time period and a given area, the method consists of measuring all the water that enters, all that leaves, and the increase or decrease of the quantity of water stored in the area. It may be stated as an equation as follows:

$$\text{Inflow} - \text{outflow} - \text{change in storage} = 0$$

In this investigation all the factors that make up each part of the equation were measured or determined except two: For the winter months, net underground inflow and for the growing season, use of ground water in the phreatophyte-covered part of the bottom land. In applying the inflow-outflow equation to lower Safford Valley, only those factors were considered that bear on the use of ground water, and the computed result does not include use of precipitation, which was added later.

The three parts of the inflow-outflow equation as applied to any reach in lower Safford Valley are made up of the following factors, all of which must be considered, even though some may be zero for a particular reach or period of time:

Inflow to reach:
1. Surface flow of river.
2. Underflow of river.
3. Surface flow of canals.
4. Surface flow of canal spills and canal and field wastes.
5. Surface flow of washes.
6. Precipitation on river surface and wet sand bars.
7. Net underground inflow.

Outflow from reach:
1. Surface flow of river.
2. Underflow of river.
3. Surface flow of canals.
4. Surface flow of canal spills and canal and field wastes.
5. Evaporation from river surface and wet sand bars.
6. Draft on ground water in phreatophyte-covered area.
7. Evapotranspiration of water, other than precipitation, from farm land and associated waste land. (Applies only to computations for entire inner valley.)

Changes in storage:
1. Channel storage in river, canals, and washes.
2. Ground-water reservoir.
3. Soil moisture.

Of all these factors, direct measurement was made only of the surface flow of the river and canals. All other factors, except draft on ground water in the phreatophyte-covered area, were evaluated on the basis of indirect measurements.

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The effect of pumping ground water for irrigation does not have to be considered in the inflow-outflow equation except under special conditions. Generally, pumping circulates water within the reach without changing the net total of inflow, outflow, and storage. Pumping withdraws water from the ground-water reservoir, causing a reduction in storage. The pumped water appears as evapotranspiration, as an increase in the net underground inflow to the bottom-land area, or in other ways. The quantity thus measured as outflow is equal to the reduction in storage in the ground-water reservoir. A lag existed between the time of drawdown of the ground-water reservoir and the time of appearance of the pumped water as a measurable outflow quantity, and the effect of this lag had to be considered. The effect was negligible for all but one short period.

The first step in applying the inflow-outflow method is to determine the net underground inflow for the winter months, when use of ground water by phreatophytes is zero, or nearly so. The second step is to determine the use of ground water in the phreatophyte-covered part of the bottom land for the growing season, assuming that the rate of net underground inflow to the bottom land is constant for a year. Thus, of the factors that enter into the inflow-outflow equation, the equation is solved for these two unknowns, one for the winter months and one for the growing season.

BASIS OF COMPUTATIONS

AREAS

If sufficient field data were available, an inflow-outflow equation could be applied to any area for any period of time. For lower Safford Valley data were available to apply the equation to the bottom-land area in each of the three reaches from Glenbar to Calva. Data were also available to apply the equation to the entire inner valley, between the edges of the mesas, in the reach from Fort Thomas to Black Point.

The inflow-outflow method was not applied to the Thatcher-Glenbar reach because no stream-flow records were available after February 1944 and because the network of canals and surface-water wastes complicated determination of the surface-water inflow to the river. The method was not applied to the entire inner valley in the Glenbar-Fort Thomas reach because of the evapotranspiration from the large acreage of farm land. Only the bottom land was studied in the Black Point-Calva reach, but in this reach the bottom land covered nearly the entire inner valley.

TIME PERIODS

In general stream-flow records were collected and other necessary data were available for the period July 1, 1943, to October 31, 1944. Hence, equations were applied to the bottom land for that period, except for the following five short flood periods for which there were no stream-flow records: August 1-17 and 24-31 and September 26-30, 1943, and August 16-21 and September 23-30, 1944. The equations were applied for periods of a month or less in order to determine the change in rate of use of ground water from one month to another, even though the results for individual periods as short as a month were far less accurate than for a year.

Equations were applied to the entire inner valley for the Fort Thomas-Black Point reach for the two periods October 1, 1943, to August 15, 1944, and August 22 to September 22, 1944. One factor in these equations was the use of water by farm crops. As figures for this use are available only on an annual basis, equations could not be applied for periods as short as a month.

METHOD OF COMPUTING FIGURES FOR INFLOW TO BOTTOM LAND

Surface flow of river.—Figures for the flow of the Gila River into any reach were obtained from the gaging-station records of stream flow as described in part 2. A gaging station was located at the upper end of each reach.

Underflow of river.—This factor was not determined, and no figure for underflow is included in the inflow-outflow equation. For the equation, it is sufficient that the difference between the underflow into and out of a reach be known, and this difference is included as part of the net underground inflow.

Surface flow of canals.—A gaging station was maintained on each canal at the point at which the canal entered each reach. The records of flow for each canal were collected as described in part 2.

Surface flow of canal spills and canal and field wastes.—No gaging stations were maintained on spills or wastes, but the amount of inflow to the river was determined in two ways. First, all spills and wastes were measured at the time of seepage runs. Second, a comparison of the record of gage height at each river gaging station was made with the record at the next station upstream, and any small sharp change in gage height at the downstream station, not showing at the upstream station and not explainable otherwise, was considered as caused by a spill or waste. Such changes usually were only a few hundredths of a foot. The amount of the change, in second-feet, was computed on the basis of the change in gage height at the downstream station. As the river discharge was usually very low during the period of the investigation, the discharge of canal spills and canal and field wastes was computed with reasonable accuracy by these methods.

The spill from the Fort Thomas Canal in the Glenbar-Fort Thomas reach was large and almost continuous. The quantity of this spill was computed as the difference between the measured flow of the canal at the gaging station at the upper end of the reach, near Glenbar, and the measured flow at the canal-gaging station immediately downstream from the spill, 1½ miles downstream from the first gage. The downstream gaging station was a recording station operated by the Gila Water Commissioner.

Surface flow of washes.—The gaging stations operated on the five largest washes in lower Safford Valley recorded only those flows greater than about 100 to 200 second-feet. During the period the stations were operated, from early August 1943 to October 1944, no flow greater than this occurred, except during the five flood periods for which the inflow-outflow equation was not applied.

The low-water flow of these washes and of all other smaller washes from July 1, 1943, to October 31, 1944, except for the five flood periods, was computed by the same methods used for computing the flow of canal spills and canal and field wastes. More data were available regarding the flow of the washes than regarding the flow of canal spills and wastes, because each gaging station on a wash was visited each week and an estimate of the flow, if any, was made.

Precipitation on river surface and wet sand bars.—Precipitation, except for that on the river surface and wet sand bars, was not a factor in the inflow-outflow equation. On the basis of field observations, it was assumed that precipitation on the phreatophyte-covered part of the bottom land was returned to the air by evaporation or transpiration. Precipitation on the phreatophyte-covered area during the periods for which inflow-outflow equations were applied did not occur for a long enough time nor with great enough intensity to cause surface runoff or to infiltrate to the water table. On the basis of data given in part 2, the precipitation on the river surface and wet sand bars was computed for the inflow-outflow equations.

Net underground inflow.—In part 2 the rate of net underground inflow to each of the four reaches was derived, partly on the basis of the results of the inflow-outflow method. Net underground inflow, considered constant throughout the year, was computed from the inflow-outflow equations for the winter, when the draft on ground water in the phreatophyte-covered area was nearly zero. Net underground inflow was the only unknown in the equation.

METHOD OF COMPUTING FIGURES FOR OUTFLOW FROM BOTTOM LAND

Surface flow of river.—This factor was computed from stream-flow records in the same manner as the surface-water inflow of the river was computed. There was a gaging station at the downstream end of each reach.

Underflow of river.—This factor was not determined and need not be computed separately. Net underflow in a reach was a component part of the net underground inflow.

Surface flow of canals.—This factor was computed from stream-flow records. A gaging station was located on each canal at the downstream end of each reach.

Surface flow of canal spills and canal and field wastes.—As there were no known spills or wastes flowing out of any reach during the investigation, the factor is not included in the inflow-outflow equation.

Evaporation from river surface and wet sand bars.—Evaporation data were based on figures given in tables 3 and 12, and the methods of computing evaporation are given in part 2.

Draft on ground water in phreatophyte-covered area.—This factor was almost zero in the nongrowing season and was computed as the unknown in the inflow-outflow equations for the growing season. In the winter little evaporation of ground water occurs from the phreatophyte-covered area, as shown by the results from the bare soil tanks and the tanks containing vegetation at the Glenbar experiment station. Most of the evaporation in the winter from the phreatophyte-covered area was evaporation of precipitation, a factor not required in the inflow-outflow equations as applied. According to the results from the tanks containing vegetation at the Glenbar experiment station, a small amount of water is used in the winter, particularly by baccharis. Use of water by baccharis during the winter months was far greater than use of water by saltcedar (see table 26). None of the species retain leaves or fronds in the winter, but baccharis keeps its leaves into early winter and puts out new leaves as early as February. For the winter periods between December 14, 1943 and March 15, 1944, figures are included for the small amount of ground water evaporated and for transpiration by baccharis.

METHOD OF COMPUTING FIGURES FOR CHANGES IN STORAGE IN BOTTOM LAND

Channel storage in river, canals, and washes.—The quantity of water in transit in the river, canals, and washes was greater or less at the end of a given period than at the beginning, and the change in channel storage was computed as the difference between the quantity of water in transit in a reach at the start of the period and at the end of the period. This change in channel storage was computed on the basis of the time of travel through a reach, in the same general manner that was used to adjust the seepage runs.

Ground-water reservoir.—The quantity of water stored in the ground-water reservoir of a reach changed during each period for which an equation was established. The volume of the change was computed according to the methods given in part 2.

Soil moisture.—In the bottom land soil moisture could be supplied from three possible sources: irrigation, precipitation, and flooding by the river or by washes. In the bottom land there is no irrigation water except field waste, which is a negligible factor. Precipitation in 1943-44 was light, so that changes in soil moisture from this source were negligible, except for the effects of the heavy rains of September 25-26, 1943, and September 23-25, 1944. Soil moisture was probably high for several weeks following both of these storms, as use of ground water was low during those weeks. However, no field determinations of soil moisture were made during the investigation, and thus some error may have been introduced into the inflow-outflow equations, particularly for individual months and other short periods.

The soil of the bottom land is estimated to have contained more soil moisture on October 1, 1943, than on September 22, 1944, by an amount equivalent to 1 inch of water. Therefore, a figure representing a decrease of 1 inch of soil moisture was introduced into the inflow-outflow equations for the 352-day period between October 1, 1943, and September 22, 1944. Because of the difficulty in making reliable estimates, no attempt was made to introduce the factor of change of soil moisture in the equations for individual months or shorter periods. The bottom lands were flooded by the river on September 25, 1944. No adjustment for change in soil moisture was made for the following month, and as a result the computed use of water for October 1944 is believed to be low.

METHOD OF COMPUTING FIGURES FOR APPLICATION TO ENTIRE INNER VALLEY

The same factors of inflow, outflow, and changes in storage considered for the bottom land must be considered for the area of the inner valley.

Inflow.—Figures for the three inflow factors, surface flow of river, surface flow of washes, and precipitation on river surface and wet sand bars, are the same in the equations for the inner valley as for the bottom land. Figures for the other four inflow factors were different from those for the bottom land but were computed by the same procedures.

Outflow.—Figures for two of the outflow factors, surface flow of river and evaporation from river surface and wet sand bars, are the same in the equations for the inner valley as for the bottom land. Surface flow of canals and of canal spills and canal and field wastes in the inner valley was zero for the Fort Thomas-Black Point reach. Evapotranspiration of water other than precipitation from farm lands and associated waste lands must be considered for the inner valley but is zero for the bottom lands. Draft on ground water in the phreatophyte-covered area was computed by the same procedure as for the bottom land.

Evapotranspiration of water, other than precipitation, from farm lands and associated waste lands was computed for three periods: The nongrowing season, March 1 to August 15, and August 22 to September 22. The periods August 16-21 and September 23-30 were omitted, as inflow-outflow equations could not be set up for those periods. Evapotranspiration of water from precipitation need not be included as an outflow factor because precipitation on the farm land and associated waste land was not included as an inflow factor.

In the Fort Thomas-Black Point reach evaporation from farm land and associated waste land during the period October 1, 1943, to February 29, 1944, was computed on the basis of the following assumptions: (1) That no irrigation water was applied to mesquite-covered land, uncultivated land served by the Colvin-Jones Canal (which had no flow during the period), or to 50 percent of the fallow land; (2) that at any given time only half the irrigated land was so wet that evaporation was appreciable; (3) that evaporation from a fully saturated land surface was 70 percent of the evaporation from the Weather Bureau pan at the Glenbar experiment station; and (4) that only half the evaporation rate as determined in (3) should be used in the computation because each field was fully saturated for only a short time. On these bases the following figures of evaporation from farm lands and associated waste lands in the Fort Thomas-Black Point reach were computed for the periods indicated: December 14, 1943, to January 13, 1944, 46 acre-feet; January 14 to February 15, 1944, 67 acre-feet; February 16 to March 15, 1944, 91 acre-feet; October 1, 1943, to February 29, 1944, 361 acre-feet.

Evapotranspiration of water, other than precipitation, by crops during the periods March 1 to August 15 and August 22 to September 22, 1944, is given in table 46. The area occupied by each crop was determined on the basis of a vegetation survey in August 1944. The estimated annual use of water by each crop was based on figures furnished by H. C. Schwalen, professor of agricultural engineering, University of Arizona. The figures in table 46 are slightly lower than they might be for a year when water was more plentiful. Based on studies of the distribution of use with respect to time for seven tanks of saltcedar at the Glenbar experiment station, the estimated use of water from March 1 to August 15 was 70.5 percent of the annual use. Use of water by crops is assumed to be distributed through the year in the same proportion as the use of water by saltcedar. On the basis of similar studies the estimated use of water from August 22 to September 22 was 21.8 percent of the annual use. Precipitation was 0.32 foot and 0.07 foot, respectively, for the two periods under consideration. Figures for precipitation were subtracted from the estimated use of water to determine the net use, exclusive of precipitation. Net use of water, in acre-feet, by each crop was computed from the net use, in feet, and area, in acres.

The figure of 2,486 acre-feet entered in table 50 as use of water by crops for the period October 1, 1943, to August 15, 1944, was computed as the sum of the use of water by crops March 1 to August 15, 1944 (given in table 46 as 2,125 acre-feet) and loss of water by evaporation from farm lands and associated waste lands October 1, 1943, to February 29, 1944 (given as 361 acre-feet in second paragraph above).

Changes in storage.—The figures for changes in channel storage in river, canals, and washes are the same for the inner valley as for the bottom land. The changes in ground-water storage and soil moisture were computed by the same procedure as described for the bottom land.

TABLE 46.—*Use of water by crops, not including precipitation, for periods in 1944 Fort Thomas-Black Point reach*

Crop	Area of crop (acres)	Estimated annual use (feet)	Mar. 1 to Aug. 15			Aug. 22 to Sept. 22			Total net use in both periods (acre-feet)
			Estimated use[1] (feet)	Net use[2]		Estimated use[3] (feet)	Net use[4]		
				Feet	Acre-feet		Feet	Acre-feet	
Alfalfa	223	2.8	1.97	1.65	368	0.61	0.54	120	488
Cotton	694	2.1	1.48	1.16	805	.46	.39	271	1,076
Grasses	196	1.6	1.13	.81	159	.35	.28	55	214
Grain	227	1.8	[5] 1.80	1.48	336	[5] 0	0	0	336
Vegetables	92	2.5	1.76	1.44	132	.54	.47	43	175
Mesquite	401	1.6	1.13	.81	325	.35	.28	112	437
Total	1,833	....	....	......	2,125	....	......	601	2,726

[1] 70.5 percent of annual use.
[2] Estimated use minus 0.32 foot of precipitation.
[3] 21.8 percent of annual use.
[4] Estimated use minus 0.07 foot of precipitation.
[5] Grain matured and harvested before August 15.

COMPUTATION OF RESULTS

The figures computed for each factor of the inflow-outflow equations for the bottom land are shown in table 47 for the Glenbar-Fort Thomas reach, table 48 for the Fort Thomas-Black Point reach, and table 49 for the Black Point-Calva reach. The figures for the inner valley are shown in table 50 for the Fort Thomas-Black Point reach.

During the winter periods between December 14, 1943, and March 15, 1944, for which equations were set up, draft on ground water in the phreatophyte-covered area was zero, or nearly so, and the unknown for which the inflow-outflow equation was to be solved was net underground inflow. The equation may be written:

Net underground inflow = total outflow − total inflow exclusive of net underground inflow + change in storage.

For the periods between July 1943 and October 1944, when draft on ground water in the phreatophyte-covered area is the unknown, the equation may be written:

Draft on ground water in phreatophyte-covered area = total inflow − total outflow exclusive of draft on ground water − change in storage.

Each line in tables 47-50 may be considered a separate equation. The

TABLE 47.—*Use of ground water, in acre-feet, by bottom-land vegetation in Glenbar-Fort Thomas reach, based on inflow-outflow method applied to bottom land*

Period	Inflow: Gila River near Glenbar	Inflow: Canal spills and canal and irrigation waste water	Inflow: Washes	Inflow: Precipitation on river surface and wet sand bars	Inflow: Net underground inflow	Inflow: Sum of known inflow factors	Outflow: Gila River at Fort Thomas	Outflow: Colvin-Jones Canal at Fort Thomas	Outflow: Evaporation from river surface and wet sand bars	Outflow: Draft on ground water in bottom land	Outflow: Sum of known outflow factors	Change in storage: Channel storage in river, canals, and washes	Change in storage: Ground-water reservoir	Change in storage: Soil moisture	Change in storage: Total change in storage[1]	Computed net underground inflow	Computed draft on ground water in bottom land
Dec. 14, 1943, to Jan. 13, 1944	221	2,906	0	10	(?)	3,137	4,005	0	21	6	4,032	+7	+134	[2]	+141	1,036	....
Jan. 14 to Feb. 15, 1944	270	2,908	0	4	(?)	3,182	4,124	0	30	5	4,159	−21	+47	[2]	+26	1,003	....
Feb. 16 to Mar. 15, 1944	192	877	0	8	(?)	1,077	1,890	0	34	6	1,930	−8	+254	[2]	+246	1,099	....
1943																	
July	764	476	70	21	952	2,283	1,210	56	71	(?)	1,337	−44	+65	[2]	+21	....	925
Aug. 18-23	18	0	0	0	184	202	146	0	10	(?)	156	−29	−114	[2]	−143	....	189
Sept. 1-25	143	5	0	3	768	919	315	0	36	(?)	351	−18	+25	[2]	+7	....	561
October	238	733	0	1	952	1,924	1,577	0	39	(?)	1,616	−64	+94	[2]	+30	....	278
November	110	793	0	0	921	1,824	1,686	0	28	(?)	1,714	+13	+116	[2]	+129	....	−19
December	115	1,640	0	13	952	2,720	2,715	0	18	(?)	2,733	−4	+94	[2]	+90	....	−103
1944																	
January	308	3,806	0	4	952	5,070	4,816	0	24	(?)	4,840	+18	+80	[2]	+98	....	132
February	208	1,620	0	7	890	2,725	2,783	0	27	(?)	2,810	−14	+145	[2]	+131	....	−216
March	187	394	0	5	952	1,538	1,400	0	42	(?)	1,442	−16	−94	[2]	−110	....	206
April	181	106	0	2	921	1,210	712	119	53	(?)	884	−3	−275	[2]	−278	....	604
May	104	52	0	1	952	1,109	356	55	53	(?)	464	−5	−207	[2]	−212	....	857
June	48	5	0	0	921	974	92	0	57	(?)	149	−1	−185	[2]	−186	....	1,011
July	1,261	414	50	13	952	2,690	1,596	21	64	(?)	1,681	0	+11	[2]	+11	....	998
Aug. 1-15	836	321	20	11	460	1,648	1,283	20	47	(?)	1,350	+1	+54	[2]	+55	....	243
Aug. 22-31	1,355	193	10	1	307	1,866	1,737	5	40	(?)	1,782	−98	−271	[2]	−369	....	453
Sept. 1-22	1,833	167	0	4	675	2,679	2,343	14	58	(?)	2,415	−2	+58	[2]	+56	....	208
October	4,875	51	0	10	952	5,888	5,389	0	52	(?)	5,441	−21	+185	[2]	+164	....	283
Oct. 1, 1943, to Aug. 15, 1944, and Aug. 22 to Sept. 22, 1944	6,784	10,244	80	62	10,807	27,977	23,096	234	550	(?)	23,880	−175	−380	−161	−716	....	4,813

[1] Not including changes in soil moisture for periods of a month or less; changes for these periods were considered negligible.

[2] Changes in soil moisture for periods of a month or less not computed; considered negligible.

NOTE.—No figures shown for inflow from canals or for outflow from canal spills and canal and irrigation waste water, because none existed in the bottom land in this reach for the periods covered. (?) Unmeasured; computed values, based on data in other columns, are given in columns at extreme right.

TABLE 48.—*Use of ground water, in acre-feet, by bottom-land vegetation in Fort Thomas-Black Point reach, based on inflow-outflow method applied to bottom land*

Period	Inflow						Outflow				Change in storage				Computed net underground inflow	Computed draft on ground water in bottom land
	Gila River at Fort Thomas	Canal spills and canal and irrigation waste water	Washes	Precipitation on river surface and wet sand bars	Net underground inflow	Sum of known inflow factors	Gila River at Black Point	Evaporation from river surface and wet sand bars	Draft on ground water in bottom land	Sum of known outflow factors	Channel storage in river, canals, and washes	Ground-water reservoir	Soil moisture	Total change in storage[1]		
Dec. 14, 1943, to Jan. 13 1944	4,005	60	35	13	(?)	4,113	5,183	24	6	5,213	+6	+43	(2)	+49	1,149	....
Jan. 14 to Feb. 15, 1944	4,124	30	10	5	(?)	4,169	5,427	33	5	5,465	−13	+39	(2)	+26	1,322	....
Feb. 16 to Mar. 15, 1944	1,890	25	5	8	(?)	1,928	2,882	42	6	2,930	−12	0	(2)	−12	990	....
1943																
July	1,210	0	5	18	1,159	2,392	1,426	85	(?)	1,511	−126	+57	(2)	−69	....	950
Aug. 18-23	146	1	0	0	224	371	298	11	(?)	309	−11	−107	(2)	−118	....	180
Sept. 1-25	315	5	0	4	935	1,259	762	46	(?)	808	−10	+50	(2)	+40	....	411
October	1,577	3	0	1	1,159	2,740	2,192	48	(?)	2,240	−67	−43	(2)	−110	....	610
November	1,686	20	30	0	1,122	2,858	2,586	33	(?)	2,619	+15	+99	(2)	+114	....	125
December	2,715	85	65	15	1,159	4,039	4,151	23	(?)	4,174	−6	+53	(2)	+47	....	−182
1944																
January	4,816	30	10	4	1,159	6,019	5,883	27	(?)	5,910	+20	+39	(2)	+59	....	50
February	2,783	30	10	8	1,085	3,916	3,872	33	(?)	3,905	−12	+21	(2)	+9	....	2
March	1,400	20	0	6	1,159	2,585	2,364	55	(?)	2,419	−17	−60	(2)	−77	....	243
April	712	5	0	5	1,122	1,844	1,472	72	(?)	1,544	−3	−89	(2)	−92	....	392
May	356	5	0	3	1,159	1,523	851	70	(?)	921	−5	−121	(2)	−126	....	728
June	92	5	0	0	1,122	1,219	263	76	(?)	339	−3	−135	(2)	−138	....	1,018
July	1,596	15	20	21	1,159	2,811	1,636	93	(?)	1,729	0	−85	(2)	−85	....	1,167
Aug. 1-15	1,283	5	5	13	561	1,867	1,368	54	(?)	1,422	+6	−18	(2)	−12	....	457
Aug. 22-31	1,737	15	30	8	374	2,164	2,243	44	(?)	2,287	−140	−194	(2)	−334	....	211
Sept. 1-22	2,343	0	10	6	823	3,182	2,520	64	(?)	2,584	−3	+103	(2)	+100	....	498
October	5,389	10	0	9	1,159	6,567	6,504	57	(?)	6,561	−29	+85	(2)	+56	....	−50
Oct. 1, 1943, to Aug. 15, 1944, and Aug. 22 to Sept. 22, 1944	23,096	238	180	90	13,163	36,767	31,401	692	(?)	32,093	−215	−430	−145	−790	....	5,464

[1] Not including change in soil moisture for periods of a month or less; changes for these periods were considered negligible.

[2] Changes in soil moisture for periods of a month or less not computed; considered negligible.

NOTE.—No figures shown for inflow and outflow from canals or for outflow from canal spills and canal and irrigation waste water, because none existed in the bottom land in this reach for the periods covered. (?) Unmeasured; computed values, based on data in other columns, are given in columns at extreme right.

TABLE 49.—*Use of ground water, in acre-feet, by bottom-land vegetation in Black Point-Calva reach, based on inflow-outflow method applied to bottom land* [1]

Period	Inflow					Outflow					Change in storage				Computed net underground inflow	Computed draft on ground water in bottom land
	Gila River at Black Point	Washes	Precipitation on river surface and wet sand bars	Net underground inflow	Sum of known inflow factors	Gila River at Calva	Evaporation from river surface and wet sand bars	Use of water by crops (not including precipitation)	Draft on ground water in bottom land	Sum of known outflow factors	Channel storage in river, canals, and washes	Ground-water reservoir	Soil moisture	Total change in storage[2]		
Dec. 14, 1943, to Jan. 13, 1944	5,183	0	22	(?)	5,205	5,147	30	0	14	5,191	−2	+197	(3)	+195	181	....
Jan 14 to Feb. 15, 1944	5,427	40	8	(?)	5,475	5,589	44	25	13	5,671	−21	+12	(3)	−9	187	....
Feb. 16 to Mar. 15, 1944	2,882	0	8	(?)	2,890	3,172	53	40	14	3,279	−17	−148	(3)	−165	224	....
1943																
July	1,426	6	3	245	1,680	1,234	74	70	(?)	1,378	−120	−283	(3)	−403	....	705
Aug. 18-23	298	20	1	47	366	492	16	10	(?)	518	−62	−185	(3)	−247	....	95
Sept. 1-25	762	0	2	198	962	651	60	20	(?)	731	−78	−345	(3)	−423	....	654
October	2,192	30	6	245	2,473	2,164	60	60	(?)	2,284	−98	+49	(3)	−49	....	238
November	2,586	0	2	237	2,825	2,344	45	70	(?)	2,459	+28	+444	(3)	+472	....	−106
December	4,151	0	21	245	4,417	4,175	29	0	(?)	4,204	−19	+185	(3)	+166	....	47
1944																
January	5,883	40	9	245	6,177	5,796	33	0	(?)	5,829	+49	+74	(3)	+123	....	225
February	3,872	0	11	229	4,112	4,032	42	50	(?)	4,124	−29	−37	(3)	−66	....	54
March	2,364	0	10	245	2,619	2,640	72	40	(?)	2,752	−26	−74	(3)	−100	....	−33
April	1,472	0	7	237	1,716	1,599	88	50	(?)	1,737	−10	−209	(3)	−219	....	198
May	851	0	5	245	1,101	836	88	60	(?)	984	−10	−456	(3)	−466	....	583
June	263	0	1	237	501	79	70	170	(?)	319	−9	−604	(3)	−613	....	795
July	1,636	72	23	245	1,976	1,241	92	190	(?)	1,523	+5	−197	(3)	−192	....	645
Aug. 1-15	1,368	6	11	118	1,503	1,137	55	130	(?)	1,322	+6	−74	(3)	−68	....	249
Aug. 22-31	2,243	150	3	79	2,475	2,404	54	40	(?)	2,498	−232	+12	(3)	−220	....	197
Sept. 1-22	2,520	30	9	174	2,733	2,231	79	40	(?)	2,350	−3	−246	(3)	−249	....	632
October	6,504	20	17	245	6,786	7,113	69	7	(?)	7,189	−148	−604	(3)	−752	....	349
Oct. 1, 1943, to Aug. 15, 1944, and Aug. 22 to Sept. 22, 1944	31,401	328	118	2,781	34,628	30,678	807	900	(?)	32,385	−348	−1,133	−265	−1,746	....	3,989

[1] The bottom-land area and entire inner valley in this reach are the same, for practical purposes.

[2] Not including change in soil moisture for periods of a month or less; changes for these periods were considered negligible.

[3] Changes in soil moisture for periods of a month or less not computed; considered negligible.

NOTE.—No figures shown for inflow or outflow from canals or from canal spills and canal and irrigation waste water, because none existed in the bottom land in this reach for the periods covered. (?) Unmeasured; computed values, based on data in other columns, are given in columns at extreme right.

TABLE 50.—*Use of ground water, in acre-feet, by bottom-land vegetation in Fort Thomas-Black Point reach, based on inflow-outflow method applied to entire inner valley*

Period	Inflow						Outflow					Change in storage				Computed net underground inflow	Computed draft on ground water in bottom land
	Gila River at Fort Thomas	Fort Thomas and Colvin-Jones Canals at Fort Thomas	Washes	Precipitation on river surface and wet sand bars	Net underground inflow	Sum of known inflow factors	Gila River at Black Point	Evaporation from river surface and wet sand bars	Use of water by crops (not including precipitation)	Draft on ground water in bottom land	Sum of known outflow factors	Channel storage in river, canals, and washes	Ground-water reservoir	Soil moisture	Total change in storage[1]		
Dec. 14, 1943, to Jan. 13, 1944	4,005	673	35	13	(?)	4,726	5,183	24	46	6	5,259	+6	+174	(2)	+180	713	....
Jan. 14 to Feb. 15, 1944	4,124	611	10	5	(?)	4,750	5,427	33	67	5	5,532	−13	+48	(2)	+35	817	....
Feb. 16 to Mar. 15, 1944	1,890	150	5	8	(?)	2,053	2,882	42	91	6	3,021	−13	−145	[1]10	−148	820	....
Oct. 1, 1943, to Aug. 15, 1944	19,016	4,631	140	76	8,096	31,959	26,638	584	2,486	(?)	29,708	−71	−590	(2)	−661	....	2,912
Aug. 22 to Sept. 22, 1944	4,080	582	40	14	810	5,526	4,763	108	601	(?)	5,472	−145	−614	(2)	−759	....	813
Oct. 1, 1943, to Aug. 15, 1944, and Aug. 22 to Sept. 22, 1944	23,096	5,213	180	90	8,906	37,485	31,401	692	3,087	(?)	35,180	−216	−1,204	[1]−332	−1,752	....	4,057

[1] Does not include changes in soil moisture except for period Feb. 16 to Mar. 15, 1944, during which a large pumping operation increased soil moisture about 10 acre-feet, and for 352-day period Oct. 1, 1943, to Aug. 15, 1944, and Aug. 22 to Sept. 22, 1944, during which a total decrease of 332 acre-feet is estimated to have occurred.

[2] Changes in soil moisture not computed; considered negligible for period Dec. 14, 1943, to Feb. 15, 1944.

NOTE.—No figures shown for outflow from canals or inflow or outflow from canal spills and canal and irrigation-waste water, because none existed in this reach for the periods covered. (?) Unmeasured; computed values, based on data in other columns, are given in columns at extreme right.

figures for net underground inflow or for draft on ground water in the phreatophyte-covered area, given for each line in the last column of each table, were computed by solving an equation based on the factors given in the line.

The figure of net underground inflow for each reach for the bottom land was computed as the mean of the figures for three periods between December 14, 1943, and March 15, 1944. The figure for each reach was as follows: Glenbar-Fort Thomas reach, 17.0 second-feet; Fort Thomas-Black Point reach, 18.8 second-feet; and Black Point-Calva reach, 3.2 second-feet. The figure for the Fort Thomas-Black Point reach for the entire inner valley was 12.8 second-feet. The figures for net underground inflow to the bottom land, which are entered as an inflow factor in each equation where draft on ground water is the unknown, are the mean of results computed by the inflow-outflow method and the seepage-run method. (See table 23.)

For the Fort Thomas-Black Point reach, the computed figure of net underground inflow to the inner valley was 6.0 second-feet less than the computed figure of net underground inflow to the bottom land. A considerable difference is to be expected, because the net underground inflow to the inner valley does not include seepage from canals and irrigated fields. The water supplied to the reach by the canals is believed to be the source of this difference in net underground inflow. According to the data in table 50, about 78 percent of the water that entered the reach in canals between December 14, 1943, and March 15, 1944, infiltrated to the water table and appeared as part of the net underground inflow. This percentage of infiltration for the winter months, when infiltration is higher than the average, appears reasonable. Turner and others [52] state that, for the year, about half of all water diverted from the river infiltrates to the ground-water reservoir.

For the winter months, when water use should be almost zero, tables 47-49 show some negative and some positive figures of draft on ground water in the phreatophyte-covered area. These figures tend to cancel each other, however.

The figure at the bottom of the last column of tables 47-50 gives draft on ground water in the phreatophyte-covered area for a 352-day period, as no data were available for the other 14 days of the year. In order to compute a figure for a full year, studies were made of the use of water with respect to time in seven of the saltcedar tanks at Glenbar experiment station. These studies showed that 92.9 percent of the annual use occurred in the 352-day period.

All the precipitation on the phreatophyte-covered area in a given reach is assumed to have been evaporated from the area or transpired

[52] Turner, S. F., and others, Water resources of Safford and Duncan-Virden Valleys, Ariz. and N. Mex., p. 28, U. S. Geol. Survey, 1941. (See list of studies, p. 5.)

by phreatophytes. Table 51 that follows is based on figures in tables 47-50 and gives draft on ground water in the phreatophyte-covered area for a full year and total use of water for a full year.

TABLE 51.—*Annual use of water, in acre-feet, by bottom-land vegetation, 1943-44, based on inflow-outflow method*

Reach	Draft on ground water		Total use of water for a year, including precipitation
	From tables 47–50	Adjusted for a full year	
Glenbar–Fort Thomas	4,813	5,180	6,140
Fort Thomas–Black Point[1]	5,464	5,880	6,900
Fort Thomas–Black Point[2]	4,057	4,370	5,390
Black Point–Calva	3,989	4,290	6,510

[1] For bottom land.
[2] For entire inner valley.

DIFFERENCE IN RESULTS FOR FORT THOMAS-BLACK POINT REACH

By the inflow-outflow method the draft on ground water by the bottom-land vegetation in the Fort Thomas-Black Point reach is 1,407 acre-feet more (see tables 48 and 50) as computed on the basis of the bottom-land area than it is for the same vegetation as computed on the basis of the entire inner valley. If there were no errors in the data, basic assumptions, or computations, there should be no difference between the results by the two sets of computations. The reason for the difference is believed to lie in the fact that the net underground inflow to the bottom-land area is not as constant as is the net underground inflow to the entire inner valley.

The net underground inflow to the entire inner valley is supplied mostly by relatively constant artesian seepage and by seepage from washes. The net underground inflow to the bottom-land area is supplied not only from these sources but also by seepage from canals and irrigated fields. This seepage from canals and fields varies throughout the year, being greatest in the winter and spring, when canal flow is high and evapotranspiration low, and least in summer and fall, when canal flow is low and evapotranspiration high.

For the inflow-outflow method as applied to both the entire inner valley and to the bottom-land area, the rate of net underground inflow computed for the period December 14, 1943, to March 15, 1944, was assumed to be the rate for the entire year. For the net underground inflow to the entire inner valley, this assumption was probably more nearly correct than for the more variable net underground inflow to the bottom-land area. The errors involved in these assumptions are not considered excessive for this type of investigation.

CHLORIDE-INCREASE METHOD

THEORY

In the chloride-increase method figures for use of ground water are based on analyses of water samples taken from wells in the bottom land and on the computed mean figures for net underground inflow.

Transpiration and evaporation have a measurable effect on the quality of the ground water in the bottom land. They remove very little dissolved matter from the ground-water reservoir and thus increase the concentration of dissolved matter in the reduced volume of water remaining, much as evaporation increases the concentration of dissolved solids in a body of water standing open to the atmosphere. Under ideal conditions the volume of water in the ground-water reservoir could be definitely determined, and the extent of the increase in concentration would provide an accurate means of determining the amount of ground water removed. Under natural conditions, however, it is difficult to determine all the factors needed to compute water use by this method.

With certain assumptions, the method is applicable to the computation of use of ground water in lower Safford Valley. As an illustration, in a typical reach of the bottom land the ground water is moving slowly toward the river from beneath the cultivated land. In moving across the phreatophyte-covered bottom land, part of the ground water is intercepted and removed by transpiration or evaporation. As the amount of ground water moving through the bottom land is thus reduced, an increase occurs in the concentration of mineral matter in the remaining water. The net underground inflow to the bottom land has been computed from data gathered during the investigation. The chloride ion was selected for the determination as it is easy to measure, and little is removed from the water as it moves through the ground. The increase in concentration of chloride in the ground water between the outer edges of the bottom land and the river can be determined from the analyses of samples of water taken from the many observation wells. Knowing the rate of net underground inflow and the change in concentration of chloride occurring within the bottom land, the amount of water transpired and evaporated in a given period of time can be computed.

BASIS OF COMPUTATION

In order to apply the chloride-increase method to the computation of water use, it is necessary to make the basic assumption that the total quantities of chloride entering the bottom land in ground water in a period of a year or longer equal the amounts leaving by ground-water outflow or seepage into the river during the same period. This assumption implies that over long periods no appreciable amounts of chloride are accumulated in the soil, in the tissue of the plants, or in the ground water of the bottom land, although for periods of less than a year small changes may occur. Chloride dropped on the soil in the process of guttation by saltcedar probably is periodically removed by floods or heavy rains. Some chloride may be accumulated in the plant tissue of the vegetation as a result of increased growth from one year to another, but such accumulation probably is small enough to be negligible. The periodic sampling of selected observation wells showed only small changes in concentrations of chloride in the ground water at a given well during the study, and it has been assumed, therefore, that any changes in the concentration of chloride were negligible during the period of the investigation. However, any accumulation of chloride in the soil or plants of the bottom land would tend to give low results for use of water as computed by the chloride-increase method.

In applying the method to lower Safford Valley, wells located near the outer edge of the bottom land were selected for determining the chloride concentration of the water representing net underground inflow to the bottom land. Other wells, near the river, were selected for determination of chloride concentration in underground outflow from the bottom land into the river. Of the 1,300 or more observation wells in the three reaches, 480 wells were selected for use in applying the chloride-increase method. Thus, over one-third of all the wells in the bottom land were used in the application of the method. The wells extended to a depth of about 10 feet beneath the water table. The water samples collected are assumed to have been representative of the ground waters in the vicinity of the wells, as each well was pumped thoroughly before a sample was collected.

In using these data the general assumptions were made that the chloride concentration of the net underground inflow into the bottom land and of the underground outflow to the river can be determined by means of water samples taken from selected wells along the outer edge of the bottom land and near the river, respectively. Also the assumption was made that the observed increase in chloride concentration of ground water within the bottom land is a result of transpiration and evaporation in the phreatophyte-covered part of the bottom land.

With regard to the assumption that the chloride concentration of the net underground inflow into the bottom land can be determined from samples from wells along the outer edge of the bottom land, care was taken that samples from these wells would represent accurately the average concentration of chloride in ground water at the well locations. Data collected during the investigation showed that there is little or no change in concentration of chloride with increasing depth at these well locations. In some places part of the net underground inflow may enter the bottom land as artesian seepage from beneath. In the areas where there is an appreciable recharge of this type, part of such recharge occurs near enough to the wells along the outer edges of the bottom land that the concentration of chloride in the water sampled at these wells was representative of all the ground water that enters the bottom land. Wells were also selected to obtain samples of ground water entering the upper end of each reach. The wells, therefore, are believed to have been adequate to determine chloride concentration in the ground water entering each reach of bottom land.

To insure that the chloride concentration of the underground outflow to the river was properly sampled, data were used only from wells near the river that extended deeper than the deepest part of the river channel near them. It was assumed that the samples obtained from these wells were representative of the outflow of ground water to the river, even though some of the outflow might be occurring as upward percolation in the bottom of the river channel. Where movement of water from the river to the ground-water reservoir was occurring, care was taken to use no wells affected by outflow from the river.

The observed increase in chloride concentration of ground water within the bottom land is assumed to be a result of transpiration and evaporation in the phreatophyte-covered part of the bottom land. During the period of the investigation the increase in the concentration of chloride in the ground water of the bottom land, as a result of leaching of salt deposits in the soil, was negligible. Accretions to the ground-water reservoir from recharge that was not sampled at the lines of wells at the outer edges of the bottom land would affect the computed difference in concentration of chloride between the outer and inner lines of wells. However, most of the accretion from artesian seepage probably was sampled, and accretions from infiltration of irrigation waste and canal seepage, rainfall, and floods in the river and washes were negligible during the investigation.

For the chloride-increase method the total movement of ground water through the bottom land should be used to compute water use. However, total movement of ground water cannot be computed with the available data. Because the total movement of ground water is probably greater than the net underground inflow, the chloride-increase method tends to give results for use of water that are lower than the true value.

Under equilibrium conditions, the following relation holds for any reach:

$$Q_i\ C_i\ K = Q_o\ C_o\ K$$

in which Q_i = rate of net underground inflow to bottom land, in acre-feet per year;

C_i = concentration of chloride in inflow, in parts per million;
Q_o = theoretical average rate of ground-water outflow, in acre-feet per year;
C_o = concentration of chloride in outflow, in parts per million;
K = conversion factor to change units to tons of chloride per year.

Eliminating K, this relation may be written

$$Q_o = Q_i \frac{C_i}{C_o}$$

also

$$Q_d = Q_i - Q_o$$

in which Q_d = draft on ground water in the bottom land by transpiration and evaporation, in acre-feet per year.

Substituting and solving for Q_d, Q_o is eliminated, and the above equation becomes

$$Q_d = Q_i - Q_i \frac{C_i}{C_o}$$

In applying the method, the quantity Q_i is considered to remain constant for the year. The value of the ratio C_i/C_o is based on averages of analyses for pairs of wells, one well in each pair being near the outer edge of the bottom land and the other near the river.

COMPUTATION OF RESULTS

The chloride-increase method was used to compute use of water in the bottom land in the three reaches between Thatcher and Black Point. The method could not be applied in the Black Point-Calva reach because there were too few wells to indicate chloride changes in the ground water. Therefore results could not be obtained for the entire lower Safford Valley, from Thatcher to Calva. Computation for the Fort Thomas-Black Point reach, for which the most complete data are available, is discussed in detail, and the application of the method to the other two reaches is discussed more briefly. Results of the computations are included in table 52.

FORT THOMAS-BLACK POINT REACH

The rate of net underground inflow to the bottom land, or Q_i in the equation for use of ground water, was taken from the table at the end of part 2. This rate was 18.8 second-feet, or 13,600 acre-feet a year.

The average value for the ratio C_i/C_o for the entire reach was obtained by the following procedure: after a study of analyses of all samples of water from the bottom-land observation wells and maps showing contours of the water table (pl. 4), 66 pairs of wells were selected. These pairs of wells were chosen so as to be spaced as evenly as possible throughout the reach on both sides of the river in those areas where the direction of ground-water movement appeared to be approximately constant. The first well of each pair was located at a point where ground water was entering the bottom land, as shown by the water-table contours. The second well of each pair was located near the river and as directly as possible down the slope of the water table from the first well. Water from the second well thus represented the same ground water that was sampled at the first well, but with an increased chloride concentration caused by passing through the phreatophyte-covered area. All wells in the reach were sampled at least twice, once in the summer of 1943 and once in the spring of 1944, at periods of low and high water table, respectively. The average chloride concentration was computed for each of the 132 selected wells from the analyses of these and other available samples. From these average chloride concentrations for each well, a value was computed for the ratio C_i/C_o for each of the 66 pairs of wells. These 66 ratios were then averaged arithmetically to give the mean ratio 0.736 for the entire reach.

On substituting these figures in the equation $Q_d = Q_i - Q_i \frac{C_i}{C_o}$, the figure obtained for Q_d is 3,590 acre-feet, the annual draft on ground water in the phreatophyte-covered area. It was assumed that all precipitation on the phreatophyte-covered area from October 1, 1943, to September 22, 1944, was transpired or evaporated. According to table 10, the quantity of precipitation during the period was 1,020 acre-feet. Adding this figure to Q_d gives 4,610 acre-feet, the total use of water during the year.

Application of the chloride-increase method to this reach is complicated somewhat by the fact that about one-fifth of the total phreatophyte-covered area is within the San Carlos Indian Reservation, where there were no observation wells. Hence, the value of the ratio C_i/C_o could be computed only on the basis of the wells upstream from the Indian reservation line. It was necessary to assume that this ratio could be applied to the entire reach without serious error.

GLENBAR-FORT THOMAS REACH

Water use by bottom-land vegetation in the reach from Glenbar to Fort Thomas was computed by a procedure similar to that described for the Fort Thomas-Black Point reach. According to the table at the end of part 2, Q_i was 15.5 second-feet, or 11,200 acre-feet annually. The ratio C_i/C_o for the reach was computed from the analyses for 78 pairs of observation wells. The mean ratio was 0.534 for the reach. Substituting the figures of Q_i and C_i/C_o in the equation developed for the method, the resulting value for Q_d was 5,220 acre-feet. Precipitation was 964 acre-feet. (See table 10.) Adding the precipitation to Q_d and rounding off the figure for total use of water gives 6,180 acre-feet for the 12-month period.

THATCHER-GLENBAR REACH

The figure of net underground inflow for this reach, given in the table at the end of part 2, was 27.8 second-feet, or 20,200 acre-feet per year. The ratio C_i/C_o for the reach, 0.702, was based on the average of analyses for 96 pairs of wells in the bottom-land area. Substituting these figures in the equation, Q_d was found to be 6,020 acre-feet per year. Precipitation amounted to an additional 1,190 acre-feet of water. (See table 10.) Therefore, the total use of water in the reach was 7,210 acre-feet for the 12-month period.

TABLE 52.—*Annual use of water by bottom-land vegetation, based on chloride-increase method*

Reach	Underground inflow, Q_i (acre-feet per year)	Chloride ratio, C_i/C_o	Draft on ground water, Q_d (acre-feet per year)	Total use (acre-feet)[1]
Thatcher to Glenbar	20,200	0.702	6,020	7,210
Glenbar to Fort Thomas	11,200	.534	5,220	6,180
Fort Thomas to Black Point	13,600	.736	3,590	4,610

[1] Includes precipitation, October 1, 1943, to September 22, 1944.

SLOPE-SEEPAGE METHOD

THEORY

The slope-seepage method is based on the fact that the transmissibility of an aquifer is a characteristic of the aquifer[53] and is a constant for a given position of the water table, so that for a given slope of the water table (hydraulic gradient) a given amount of water will move through a unit width of the aquifer. The coefficient of transmissibility may be expressed in field terms as the number of gallons of water a day that percolates under prevailing conditions of temperature through each mile of water-bearing bed under investigation (measured at right angles to the direction of flow) for each foot per mile of hydraulic gradient.

If the transmissibility of the aquifer is known, the slope of the water table at any point is a measure of the rate of movement of ground water past the point. As the cross-sectional area of the aquifer is constant except for small changes as a result of fluctuations of the water table, for practical purposes the rate of movement of ground water at the point is a measure of the quantity of ground water moving past the point.

[53] Theis, C. V., The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: Am. Geophys. Union Trans., 1935, pt. 2, p. 520.

Therefore, if the mean slope of the water table is known along the lines at the two outer edges of the bottom land, the rate of movement, or quantity of ground water moving across these lines per unit of time, can be determined. If a seepage run along the river were made at the time for which the mean slope of the water table had been determined, the rate of movement of ground water into the river would also be known. The difference between the rate of movement of ground water across the outer edges of the bottom land and the rate of movement of ground water into the river, adjusted for changes in ground-water storage, will be the rate of use of ground water by transpiration and evaporation in the bottom land.

BASIS OF COMPUTATIONS

The slope-seepage method was applied to the Thatcher-Glenbar reach, the Glenbar-Fort Thomas reach, and the Fort Thomas-Black Point reach. Data were inadequate to apply the method to the Black Point-Calva reach.

DETERMINATION OF SLOPE

In applying the method it was necessary to determine the mean slope of the water table for each side of the river, by reaches, for each of the 15 seepage runs. Contours were plotted to show the position of the water table at the time of each of the seepage runs, and the mean slopes were determined from the contour maps.

POINTS FOR WHICH SLOPES WERE DETERMINED

As the ground water moves across the bottom land toward the stream more and more water is withdrawn by the root systems of the phreatophytes and by evaporation, so that less and less water remains to enter the stream. Thus, the slope of the water table is steepest at the outer edge of the bottom land and becomes progressively less steep as the river is approached. A profile of the water table between the outer edges of the bottom land and the stream during the period when transpiration is occurring may be likened to a huge bow, the string of the bow representing the position of the water table when transpiration is not occurring. (See fig. 40.)

Base data were not always available so that contours of the water table could be plotted to the outer edges of the bottom land. Rather than omit an individual determination in the areas where the base data were inadequate, some of these determinations of slope were made for points closer to the river than was desirable. Thus, the individual determinations did not represent the slope at the outer edges of the bottom land. Furthermore, in order to determine the slopes over the longest possible line and so reduce error, the slopes were determined by measuring the distance and computing the difference in elevation for at least two contour intervals, usually for distances of 1,500 feet or more. Therefore, a measured slope did not in every case represent the maximum slope that existed or the maximum amount of water transmitted. It was anticipated, therefore, that the use of water calculated by the slope-seepage method would probably represent a minimum figure for use of water by phreatophytes.

DIRECTION IN WHICH SLOPES WERE DETERMINED

Several different procedures for determining the slope of the water table were attempted during development of the slope-seepage method. First, slopes were determined perpendicular to the contours. The objection to this procedure was that each of the 15 sets of contours indicated slopes in slightly different directions, so that the average of a group of measurements from a set of contours on one date was meaningless with respect to the average of a group of measurements from a set of contours on another date. The greatest difficulty in this procedure lay in determining the slope for a point where the direction of slope had reversed between the dates of measurement of two sets of contours.

The second procedure attempted was to determine slopes between pairs of selected wells, without respect to the contours. The objection to this procedure was that seldom were the pairs of wells ideally situated. Some wells were too close to the river and some were too far from the river; the lines between some pairs of wells were parallel to the river and the lines between other pairs were at many different angles with respect to the river.

The procedure finally developed was, first, to base the computation of slope entirely on contours, second, to draw a base line perpendicular to the river at intervals of approximately 2,000 feet, and third, to determine the slope of the water table along each of these lines (fig. 44). Slopes toward the river were assigned positive values, and slopes away from the river were assigned negative values. The same base lines were used for each of the 15 sets of seepage measurements, so that the mean slopes computed from the sets of contours were all on a comparable basis.

For a given set of contours, determinations of slope were made on each side of the river for about 25 places, evenly spaced in each reach. The mean slope on each side of the river in each reach was then computed for each seepage run. The effective mean slope for a reach was taken as the sum of the mean slopes on the two sides of the river, so that the effective width of the aquifer was equal to the length of the reach.

COMPUTATION OF TRANSMISSIBILITY

As the mean slope for each reach for a given date was computed from determinations along lines that were not perpendicular to the contours, the "coefficient of transmissibility" defined by Theis [54] could not be evaluated. A constant was determined, however, similar to the coefficient of transmissibility, for which the term "apparent transmissibility" is used here. The units of expression and the direction of determination of the slope are not the same for the apparent transmissibility as for the Theis coefficient of transmissibility.

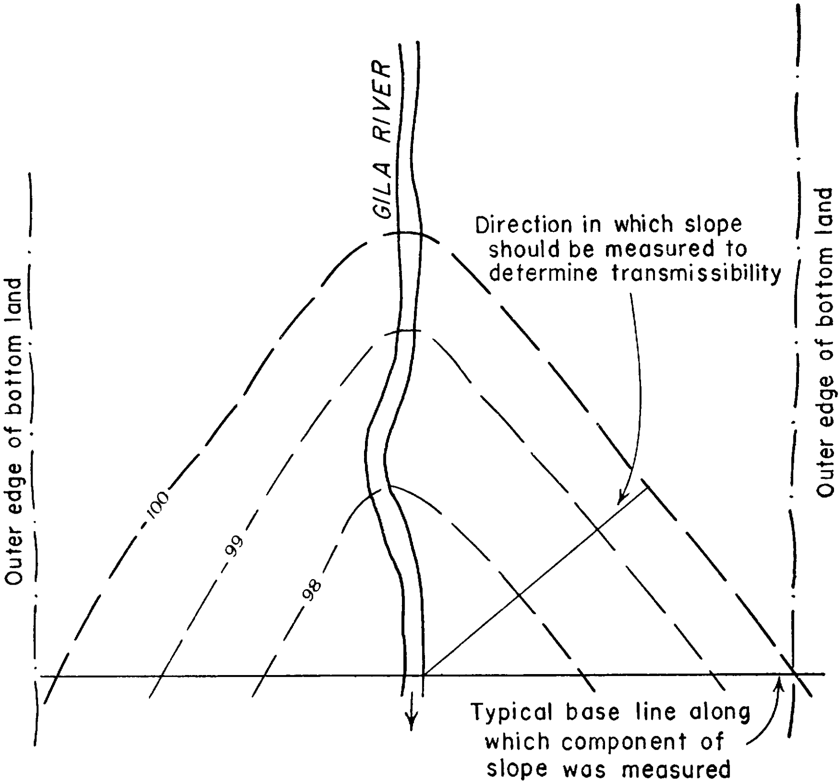

FIGURE 44.—Idealized sketch of part of Gila River and contours of the water table, showing typical base line along which components of the slope of the water table were measured for the slope-seepage method.

The apparent transmissibility was calculated on the basis of seepage runs made during the winter when transpiration was not occurring and the rate of movement of ground water into the bottom land, adjusted for changes in ground-water storage, was essentially equal to the rate of movement of ground water into the river. The apparent transmissi-

[54] Theis, C. V., op. cit., p. 520.

bility, in second-feet per foot of width, was computed from the following equation, based on Darcy's Law:[55]

$$\text{Apparent transmissibility (second-feet per foot of width)} = \frac{\text{Seepage inflow (second-feet)}}{\left[\text{Length of reach (miles)}\right]\left[\text{Effective mean slope of water table perpendicular to river (feet per mile)}\right]}$$

The term apparent transmissibility as used here refers only to the constant that represents the water-transmitting capacity of the aquifer as determined under the stated conditions.

A figure of apparent transmissibility was determined for each of the upper three reaches from results of each of the four seepage runs made from December to March. The mean apparent transmissibility for a reach was taken as the weighted average of the four determinations for the reach. The figures for December and March were each assigned a relative weight of 1, and the figures for January and February were each assigned a relative weight of 2. The figures for January and February were given greater weight, as those months were considered to be more typical of winter conditions than December and March. It may be that weights of 1 and 2 are not the best values, but any error introduced by their use is believed to be small.

COMPUTATION OF RESULTS

For a given seepage run the rate of transpiration and evaporation of ground water, in second-feet, in a reach of bottom land was determined in two steps. First, the rate of movement of ground water across the outer edges of the bottom land was computed, using the equation

$$\left[\text{Rate of movement of ground water across outer edges of bottom land (second-feet)}\right] = \left[\text{Apparent transmissibility (second-feet per foot of width)}\right]\left[\text{Length of reach (miles)}\right]\left[\text{Effective mean slope of water table perpendicular to river (feet per mile)}\right]$$

This equation is derived from the equation for apparent transmissibility. Second, the rate of movement of ground water into the river, adjusted for rate of change in ground-water storage (tables 35-37), was subtracted from the rate of movement of ground water across the outer edges of the bottom land, which gave the rate of use of ground water in second-feet.

[55] Wenzel, L. K., Methods for determining permeability of water-bearing materials, with special reference to discharging-well methods: U. S. Geol. Survey Water-Supply Paper 887, p. 4, 1942.

TABLE 53.—*Use of ground water by bottom-land vegetation, Thatcher-Glenbar reach, based on slope-seepage method*

[Length of reach, 10.6 miles]

	Slope of water table		Effective mean slope (feet per mile)	Seepage run (inflow to bottom land minus use by phreatophytes, in second-feet)[1]	Apparent transmissibility[2]	Inflow including use by phreatophytes (second-feet)[3]	Rate of use by phreatophytes (second-feet)	Period between runs		
	South side (feet per mile)	North side (feet per mile)						Mean use by phreatophytes (acre-feet per day)	Length of period (days)	Use by phreatophytes (acre-feet)
1943										
June 24	9.66	2.99	12.65	0.2		22.7	22.5			
June 24 to Sept. 15								39.6	84	3,326
Sept. 16, 17	8.69	3.46	12.15	4.4		21.8	17.4			
Sept. 16-30								23.2	15	348
Oct. 1 to Nov. 3								23.2	34	789
Nov. 4	9.93	4.45	14.38	19.8		25.8	6.0			
Nov. 4-24								10.9	21	229
Nov. 25	11.22	3.82	15.04	21.9		26.9	5.0			
Nov. 25–30								5.0	6	30
Dec. 1–12								0	12	0
Dec. 13	9.57	4.44	14.01	26.5	0.178	25.1				
Dec. 13 to Jan. 12								0	31	0
1944										
Jan. 13	11.02	5.22	16.24	23.8	.138	29.1				
Jan. 13 to Feb. 13								0	32	0
Feb. 14	11.64	5.04	16.68	36.4	.206	29.9				
Feb. 14 to Mar. 14								0	30	0
Mar. 15	10.45	4.86	15.31	24.4	.150	27.4				
Mar. 15–31								0	17	0
Apr. 1–11								16.5	11	182
Apr. 12	12.34	5.23	17.57	15.0		31.5	16.5			
Apr. 12 to May 2								25.8	21	542
May 3	9.73	4.09	13.82	15.3		24.8	9.5			
May 3–23								30.0	21	630
May 24	10.06	4.69	14.75	5.7		26.4	20.7			
May 24 to June 20								39.0	28	1,092
June 21	8.35	2.93	11.28	1.6		20.2	18.6			
June 21–Sept. 30								31.2	102	3,182
Oct. 1–28								31.2	28	874
Oct. 28, 30	9.53	3.34	12.87	10.2		23.1	12.9			
Total Oct. 1, 1943, to Sept. 30, 1944										6,680

[1] From last column, table 35.

[2] Apparent transmissibility (second-feet per foot of width)

$$= \frac{\text{Inflow, in second-feet, to bottom land (not including use by phreatophytes)}}{\text{Length of reach (miles)} \times \text{effective mean slope (feet per mile)}}$$

[3] Inflow including use by phreatophytes = apparent transmissibility × length of reach (miles) × effective mean slope (feet per mile). Apparent transmissibility was 0.169 for this reach, computed as ⅙ (1 × Dec. factor + 2 × Jan. factor + 2 × Feb. factor + 1 × Mar. factor).

TABLE 54.—*Use of ground water by bottom-land vegetation, Glenbar-Fort Thomas reach, based on slope-seepage method*

[Length of reach, 11.1 miles]

	Slope of water table		Effective mean slope (feet per mile)	Seepage run (inflow to bottom land minus use by phreatophytes, in second-feet)[1]	Apparent transmissibility[2]	Inflow including use by phreatophytes (second-feet)[3]	Rate of use by phreatophytes (second-feet)	Period between runs		
	South side (feet per mile)	North side (feet per mile)						Mean use by phreatophytes (acre-feet per day)	Length of period (days)	Use by phreatophytes (acre-feet)
1943										
June 24	3.57	1.49	5.06	−2.3		16.5	18.8			
June 24 to Sept. 16								41.2	85	3,502
Sept. 17	4.26	2.23	6.49	−1.5		21.2	22.7			
Sept. 17–30								32.1	14	449
Oct. 1 to Nov. 4								32.1	35	1,124
Nov. 5	3.74	1.47	5.21	7.3		17.0	9.7			
Nov. 5–25								16.1	21	338
Nov. 26	3.35	.27	3.62	5.3		11.8	6.5			
Nov. 26–30								6.5	5	32
Dec. 1–15								0	15	0
Dec. 16	4.34	−1.03	3.31	10.3	0.280	10.8				
Dec. 16 to Jan. 13								0	29	0
1944										
Jan. 14	4.01	.76	4.77	17.4	.329	15.6				
Jan. 14 to Feb. 14								0	32	0
Feb. 15	4.47	−.04	4.43	14.8	.301	14.4				
Feb. 15 to Mar. 15								0	30	0
Mar. 16	4.35	1.08	5.43	13.4	.222	17.7				
Mar. 16–31								0	16	0
Apr. 1–12								1.0	12	12
Apr. 13	3.52	−.32	3.20	9.5		10.4	.9			
Apr. 13 to May 3								10.3	21	216
May 4	2.93	1.34	4.27	4.4		13.9	9.5			
May 4–24								19.5	21	410
May 25	2.89	−.10	2.79	−1.1		9.1	10.2			
May 25 to June 21								24.4	28	683
June 22	3.18	.47	3.65	−2.5		11.9	14.4			
June 22 to July 16								26.2	25	655
July 17	2.18	.88	3.06	−2.0		10.0	12.0			
July 17 to Aug. 6								22.3	21	468
Aug. 7	1.77	1.11	2.88	−1.1		9.4	10.5			
Aug. 7 to Sept. 30								12.6	55	693
Oct. 1–25								12.6	25	315
Oct. 26	2.55	−1.20	1.35	2.2		4.4	2.2			
Total Oct. 1, 1943, to Sept. 30, 1944										4,630

[1] From last column, table 36.

[2] Apparent transmissibility (second-feet per foot of width)

$$= \frac{\text{Inflow, in second-feet, to bottom land (not including use by phreatophytes)}}{\text{Length of reach (miles)} \times \text{effective mean slope (feet per mile)}}$$

[3] Inflow including use by phreatophytes = apparent transmissibility × length of reach (miles) × effective mean slope (feet per mile). Apparent transmissibility was 0.294 for this reach, computed as ⅙ (1 × Dec. factor + 2 × Jan. factor + 2 × Feb. factor + 1 × Mar. factor).

TABLE 55.—*Use of ground water by bottom-land vegetation, Fort Thomas-Black Point reach, based on slope-seepage method*

[Length of reach, 9.9 miles]

	Slope of water table		Effective mean slope (feet per mile)	Seepage run (inflow to bottom land minus use by phreatophytes in second-feet)[1]	Apparent transmissibility[2]	Inflow including use by phreatophytes (second-feet)[3]	Rate of use by phreatophytes (second-feet)	Period between runs		
	South side (feet per mile)	North side (feet per mile)						Mean use by phreatophytes (acre-feet per day)	Length of period (days)	Use by phreatophytes (acre-feet)
1943										
June 25	1.75	1.50	3.25	0.7		10.9	10.2			
June 25 to Sept. 17								22.0	85	1,870
Sept. 17, 18	5.34	−.63	4.71	3.8		15.8	12.0			
Sept. 17–30								15.5	14	217
Oct. 1 to Nov. 8								15.5	39	604
Nov. 9	2.57	1.25	3.82	18.4		12.8	[4]−5.6			
Nov. 9–22								15.5	14	217
Nov. 23	2.18	2.34	4.52	11.6		15.2	3.6			
Nov. 23–30								3.6	8	29
Dec. 1–13								0	13	0
Dec. 14	1.82	3.13	4.95	20.0	0.408	16.6				
Dec. 14 to Jan. 14								0	32	0
1944										
Jan. 15	2.26	2.91	5.17	19.6	.383	17.4				
Jan. 15 to Feb. 17								0	34	0
Feb. 18	5.92	1.81	7.73	20.9	.273	25.9				
Feb. 18 to Mar. 16								0	28	0
Mar. 17	2.49	2.38	4.87	15.1	.313	16.3				
Mar. 17–31								0	15	0
Apr. 1–13								1.4	13	18
Apr. 14	2.21	1.83	4.04	12.2		13.6	1.4			
Apr. 14 to May 4								7.9	21	166
May 5	1.95	2.84	4.79	9.5		16.1	6.6			
May 5–25								15.0	21	315
May 26	2.42	1.54	3.96	4.8		13.3	8.5			
May 26 to June 22								23.3	28	652
June 23	1.74	2.81	4.55	.3		15.3	15.0			
June 23 to July 17								26.9	25	672
July 18	1.48	2.60	4.08	1.6		13.7	12.1			
July 18 to Aug. 7								23.5	21	494
Aug. 8	1.00	2.56	3.56	.3		11.9	11.6			
Aug. 8 to Sept. 30								11.5	54	621
Oct. 1–26								11.5	26	299
Oct. 27	−.49	1.56	1.07	4.0		3.6	[5]−.4			
Total Oct. 1, 1943, to Sept. 30, 1944										3,790

[1] From last column, table 37.

[2] Apparent transmissibility (second-feet per foot of width)

$$= \frac{\text{Inflow, in second-feet, to bottom land (not including use by phreatophytes)}}{\text{Length of reach (miles)} \times \text{effective mean slope (feet per mile)}}$$

[3] Inflow including use by phreatophytes = apparent transmissibility × length of reach (miles) × effective mean slope (feet per mile). Apparent transmissibility was 0.339 for this reach, computed as ⅙ (1 × Dec. factor +2 × Jan. factor + 2 × Feb. factor + 1 × Mar. factor).

[4] Not used in computations.

[5] Used 0 in computations.

The rate of use of ground water in each of the three reaches from Thatcher to Black Point was computed by this method for each of the seepage runs. The steps followed to complete the calculations are the same as for the seepage-run method: First, the instantaneous use of ground water was converted to acre-feet per day for each seepage run; second, the use, in acre-feet per day, between two successive runs was computed as the mean of the use on the days of the seepage runs; third, the mean use for a period between seepage runs was multiplied by the number of days in the period; and fourth, the use of ground water, in acre-feet, in the 12-month period October 1, 1943, to September 30, 1944, was determined by adding the use in the appropriate periods between seepage runs. Use of ground water was considered to be zero from December 1 to March 31. The results for the three reaches are given in tables 53-55. The method could not be applied to the reach from Black Point to Calva because too few wells existed to provide data for plotting contours of the water table.

The use of water thus computed represents draft on ground water and does not include use of precipitation. Table 56 gives results, in acre-feet, for the year ending September 30, 1944, in terms of draft on ground water and total use including precipitation.

TABLE 56.—*Annual use of water by bottom-land vegetation in 1943-44, in acre-feet, based on slope-seepage method*

Reach	*Draft on ground water*	*Total use*
Thatcher to Glenbar	6,680	7,870
Glenbar to Fort Thomas	4,630	5,590
Fort Thomas to Black Point	3,790	4,810

PART 4. COMPARISON AND EVALUATION OF RESULTS

In this part of the report the relative accuracy, sources of error, and the conditions necessary for application to other areas are discussed for each method. Comparisons of the results by all six methods are made. Three methods that could not be successfully applied to lower Safford Valley are described briefly, as they might be applicable to other areas. The possible effects of clearing the bottom land of natural vegetation are discussed. The conclusions derived from the investigation are given following part 4.

POSSIBLE ERRORS IN METHODS USED

Table 57 lists many of the possible sources of error in the determinations of use of water, classified as to the method affected, the direction of the error, and its relative importance. Many errors are noncompensating. The saving feature, however, is that the effect of errors in one direction is often reduced or offset by the effect of other errors in the opposite direction. In spite of unavoidable errors in all the methods, the results agree within a relatively small range considering first, the wide range of variation in the many factors that were evaluated and, second, the fact that the methods applied were not closely related to each other.

TABLE 57.—*Evaluation of errors in methods applied to determine use of water by bottom-land vegetation*

Sources of error	Method affected[1]	Error		Remarks
		Direction[2]	Relative importance[3]	
Coefficients of drainage and saturation.	T	C	3	Affects computed amount of water represented by changes in water level from month to month.
	TW	C	1	Affects entire result.
	SR	C	3	Affects computed amount of water represented by changes in ground-water storage in bottom land.
	IO	C	3	Do.
	CI	C	4	Do.
	SS	C	3	Do.
Transpiration at night.	TW	NC	2	More determinations will improve accuracy of factor for night transpiration.

See footnotes at end of table.

TABLE 57.—*Evaluation of errors in methods applied to determine use of water by bottom-land vegetation*—Continued

Sources of error	Method affected[1]	Error		Remarks
		Direction[2]	Relative importance[3]	
Volume density in field.	T	C	3	Errors in individual determinations are compensating; errors in method are noncompensating.
	TW	C	3	Do.
Volume density in tanks.	T	NC	3	Relative importance is 1 for cottonwood.
Volume density at transpiration wells.	TW	C	4	Area of 50-foot circle may not be correct basis for determining volume density at well.
Interpolation and extrapolation of results by periods.	SR	NC	2	Method includes interpolation of results between seepage runs.
	IO	NC	4	Use during 14-day period was estimated by extrapolation.
	CI	NC	2	Method includes extrapolation of results from two sets of water analyses.
	SS	NC	2	Method includes interpolation of results between seepage runs.
Interpolation and extrapolation of results by areas.	T	NC	1	Results from 17 tanks are applied to 9,303 acres.
	TW	NC	2	Results from 17 wells are applied to 9,303 acres.
Assumption that net underground inflow is constant.	SR	+	2	Net underground inflow may be less in summer than in winter.
	IO	+	2	Do.
	CI	+	2	Do.
Overlooking small quantities in base data.	TW	–	2	Possible to assume transpiration at well was negligible for day when fluctuations of water table were small.
	IO	–	3	Possible to overlook small quantities of surface water.
Infiltration of surface water within bottom land.	IO	–	4	Seepage from small unmeasured amounts of surface water crossing bottom land.
	SR	–	4	Do.
	CI	–	4	Do.
	SS	–	4	Do.
Adjustment of seepage runs for evaporation from river surface and wet sand bars.	SR	+	4	Seepage runs usually made at time of day when evaporation was at peak rate, although adjustment for evaporation was made on basis of mean evaporation during 24 hours.
	SS	+	4	Do.
Volume-density determinations do not apply to evaporation from soil.	T	C	4	Error is in one direction in computing results in terms of use of water per unit of volume density; error is in opposite direction in computing area of 100-percent volume density in field.
	TW	C	4	Do.
Seepage runs in one reach not made at peak of transpiration season.	SS	–	4	For Thatcher-Glenbar reach, results were interpolated for 102-day period between June 21 and Sept. 30, 1944. No adjustment was made for higher rate of use in July and August.
Assumption that transmissibility of aquifer is constant.	SS	C	4	Transmissibility varies slightly according to thickness of saturated portion of aquifer. Thickness varies according to position of water table.

See footnotes at end of table.

TABLE 57.—*Evaluation of errors in methods applied to determine use of water by bottom-land vegetation*—Continued

Sources of error	Method affected[1]	Error		Remarks
		Direction[2]	Relative importance[3]	
Water samples from shallow wells may not be representative of water in entire thickness of aquifer.	CI	C	4	Dissolved mineral content of ground water may not be uniform throughout depth.
Assumption that all chloride in water passing lines of wells at outer edges of bottom land also passes lines of wells along river.	CI	−	2	Artesian inflow from older fill beneath alluvium of bottom land increases chloride content at line of wells along river.
	CI	+	3	Chloride is removed from ground water in bottom land by plant guttation and by accumulating in woody fiber of plants, reducing chloride content at line of wells along river.
Determination of changes in ground-water storage.	IO	C	4	Changes were computed from large-scale maps and on basis of 4-foot contours for upper three reaches; for Black Point-Calva reach, changes were computed on basis of changes at three lines of wells.
	SR	C	4	Changes were computed from well records for week preceding each seepage run.
	CI	C	4	Do.
	SS	C	4	Do.
Changes in flow of river.	SR	C	3	Evaluation of effects of time of travel of stream, changes in channel storage, and diurnal fluctuations in stage may be in error.
	CI	C	4	Do.
	SS	C	3	Do.
Result magnifies errors in base data.	IO	C	2	Method determines result by differences between relatively large quantities.
Assumption that dissolved mineral matter does not accumulate in bottom land.	CI	−	1	
Determination of effective mean slope of water table.	SS	−	1	Slope should be determined for outermost edge of bottom land.
	SS	C	4	Individual determinations may be slightly in error.
Experiments performed on plants younger than average plant in field.	T	+	2	Applies particularly to cottonwood.
Effect of dissolved solids concentration on rate of use of groundwater.	T	+	3	Plants in field possibly use less water than plants in tanks.
	TW	C	4	Dissolved-solids concentrations at well locations may be above or below average in field.
Recharge to phreatophyte area from river	CI	−	2	Recharge from river adds water that is not measured as underground inflow, and may affect chloride concentrations.
Computation of water use for short periods.	IO	C	1	Relative importance 4 for yearly figure.

[1] T, tank method; TW, transpiration-well method; SR, seepage-run method; IO, inflow-outflow method; CI, chloride-increase method; SS, slope-seepage method.
[2] +, result too high; −, result too low; C, error is compensating; NC, error is noncompensating but direction is unknown.
[3] 1, major effect; 2, medium effect; 3, minor effect; 4, negligible in result.

COMPARISON OF RESULTS OBTAINED BY EACH METHOD

Table 58 gives the results obtained by each method in terms of draft on ground water. The table also gives the draft on ground water computed as the average of all methods used in each reach and the total use of water in each reach. Use of water was determined by all six methods for the two reaches between Glenbar and Black Point.

TABLE 58.—*Use of water by bottom-land vegetation, in acre-feet, October 1, 1943, to September 30, 1944, based on six different methods*

Reach	Draft on ground water							Total use of water[2]
	Tank Method	Transpiration-well method	Seepage-run method	Inflow-outflow method[1]	Chloride-increase method	Slope-seepage method	Average	
Thatcher to Glenbar.....	9,070	6,740	8,590	(3)	6,020	6,680	7,420	8,610
Glenbar to Fort Thomas	7,420	5,900	6,500	5,180	5,220	4,630	5,810	6,770
Fort Thomas to Black Point..	5,060	3,940	5,970	5,880	3,590	3,790	4,700	5,720
Black Point to Calva.......	6,000	4,850	4,990	4,290	(3)	(3)	5,030	7,250
Thatcher to Calva	27,550	21,430	26,050	(3)	(3)	(3)	[4]22,960	[4]28,350

[1] Based on computations for bottom land. Use for Fort Thomas-Black Point reach was 4,370 acre-feet, based on computations for entire inner valley.
[2] Includes total precipitation on phreatophyte-covered part of bottom land, October 1, 1943, to September 22, 1944.
[3] Not computed.
[4] Sum of average use by reaches.

Table 59 lists the results obtained by each method for these two reaches combined, in terms of percent above or below the average by all methods.

TABLE 59.—*Use of water from Glenbar to Black Point, as computed by each method, in terms of percent above or below the average by all methods*

Method	*Percent above (+) or below (−) average*
Tank	+18.7
Transpiration-well	−6.4
Seepage-run	+18.6
Inflow-outflow	+5.2
Chloride-increase	−16.2
Slope-seepage	−19.9

The results by all methods check within plus or minus 20 percent. This gives some indication of the possible accuracy of the final figures for water use (table 58), which are the averages for all methods.

COMPARISON OF WATER USE BY SPECIES

Based on figures computed by the tank and transpiration-well methods for the 12-month period ending September 30, 1944, the mean total use of water by the species of phreatophytes common to lower Safford Valley, computed for growth of 100-percent volume density, was: Saltcedar, 7.2 feet; baccharis, 4.7 feet; cottonwood, 6.0 feet; and mesquite, 3.3 feet. These figures include 0.57 foot derived from precipitation.

According to table 29, saltcedar used more than 75 percent of the ground water used by phreatophytes in lower Safford Valley during the 12 months ending September 30, 1944. However, saltcedar occupied only 50 percent of the gross area and comprised only 60 percent of the total growth when converted to 100-percent volume density.

The annual rate of use of water per acre, computed by dividing the total use of water by the total area of 100-percent volume density, was different for each reach. For example, the total use of water per acre of 100-percent volume density of growth, computed by the tank and transpiration-well methods, was 6.7 acre-feet per year in the Thatcher-Glenbar reach and 5.6 acre-feet per year in the Fort Thomas-Black Point reach. The use was high in the first reach because saltcedar, a plant of high water use, comprised 69 percent of the vegetation, whereas, in the other reach, saltcedar comprised only 34 percent of the vegetation.

COMPARISON OF 1944 GROWING SEASON WITH OTHER SEASONS

Use of water by bottom-land vegetation during the water year October 1, 1943, to September 30, 1944, is shown in table 58. Records for a complete growing season can be obtained from these data if the records for the end of the 1943 growing season are used to complete the records for the 1944 growing season. From records at the Glenbar experiment station there were 150 frost-free days in that composite growing season from the last day of frost in the spring, May 17, to September 30, 1944, and from October 1, 1943, to the first day of frost in the fall, October 14. On the basis of a 26-year period of record at Thatcher, the average date of the latest killing frost in the spring was April 11, and the average date of the earliest killing frost in the fall was October 31, giving an average of 203 frost-free days annually. The latest and earliest killing frosts recorded at Thatcher occurred May 7 and October 6, respectively.

With the exception of a severe storm on September 24-25, 1944, the water year 1944 was a year of subnormal precipitation, with a consequent subnormal river flow and a decline of the water table. Thus, it is possible that the phreatophytes had greater difficulty in obtaining ground water than in years with more abundant water supplies, so that in 1944 the plants used a smaller amount of water than in most other years. On the other hand, there is the possibility that, as little soil

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moisture was available to the plants in 1944, they withdrew more water from the ground-water reservoir than in an average year.

On the whole, it is believed that the amount of water used by the bottom-land vegetation in 1944 was less than in most years, as a result of both the unusually short growing season and the uneven distribution of precipitation.

ADVANTAGES OF METHODS AND APPLICATION TO OTHER AREAS

No single method of investigation as given in this report is deemed better than any other method. The cost and amount of time required to apply each method was about the same, as some of the methods required more field work, and others required more office work. Two of the methods, the tank and transpiration-well, required data that could not be used for the other methods. Each of the other four methods used some of the same base data.

For an approximate result, the seepage-run method would probably produce results at a lower cost and in a shorter time than any of the other methods. The transpiration-well method would probably produce the most accurate results for the least amount of money, provided that the determinations of the coefficient of drainage were sufficiently accurate. In applying any of the methods, much better results would be obtained if studies were continued for two or more growing seasons rather than for only one growing season.

In applying the methods for determining use of ground water by phreatophytes to other areas the following should be considered:

1. Tank method. Theoretically, the method can be applied to any area containing phreatophytes. Practically, the method is not applicable for determining the use of water by large trees or for areas in which the water table lies more than a few feet below the land surface.

2. Transpiration-well method. Theoretically, the method can be applied to any area of phreatophytes in which diurnal fluctuations of the water table occur in measurable amounts as a result of transpiration. Practically, the diurnal fluctuations of the water table are difficult to measure in areas containing plants that use small amounts of ground water and in areas in which the water-bearing materials are loose and have a high coefficient of drainage. The advantage of this method is that the use of ground water by plants in their natural habitat is determined under undisturbed conditions.

3. Seepage-run method. Theoretically, the method can be applied to an area where ground water is used by phreatophytes, in which there is a surface stream gaining water from the ground-water reservoir, provided that the net underground inflow to the area of use is constant

in amount. Practically, the method is not applicable to areas in which the flow of the surface stream is highly complicated by sporadic diversions and surface inflows or where the underground inflow is not constant within reasonable limits.

4. Inflow-outflow method. Theoretically, the method can be applied to almost any area where ground water is used by phreatophytes. The accuracy of the method is reduced in areas where the quantities of water measured are greatly in excess of the use of ground water by phreatophytes. Practically, the method is not applicable to areas where the flow of the surface stream is excessively complicated by diversions and surface inflows.

5. Chloride-increase method. Theoretically, the method can be applied to any area where ground water is used by phreatophytes, into which there is an inflow of ground water constant in amount and direction, and from which sufficient ground water is discharged (other than by transpiration and evaporation) to prevent accumulation of dissolved mineral matter. Application of the method is limited to areas in which little or no surface water percolates to the water table and within which a measurable change in concentration of some constituent exists.

6. Slope-seepage method. Theoretically, the method can be applied to any area where ground water is used by phreatophytes, in which there is a surface stream in intimate contact with the ground-water reservoir, provided that changes in the slope of the water table as a result of transpiration and evaporation occur in measurable amounts. Practically, application of the method is limited to areas where use of ground water is large and the errors involved in computing the average slope of the water table do not exceed the permissible limit.

OTHER METHODS OF DETERMINING USE OF WATER

Three additional methods were proposed at the start of the investigation but could not be carried through to obtain quantitative results. As the methods may be applicable in other areas, they are described here:

1. Water inventory of the entire inner valley from Thatcher to Calva. This method required measurement of all water entering and leaving the valley. Stream-flow records were incomplete, no crop survey was made between Thatcher and Glenbar, and the consumptive use of crops was not determined in the field. Therefore, this method could not be applied.

2. Cut-twig method. This method involves determination of the loss of weight of plant cuttings when placed in the sun for 1 hour. Fresh cuttings are set out every hour, so that a continuous record of

transpiration is obtained for 1 day. Hourly readings are taken of temperature, humidity, and evaporation. The cuttings are later dried in the sun until they reach a constant weight. The results are calculated in terms of weight of water transpired each hour for a unit weight of air-dried plant material, and the sum of the hourly rates is taken to be the daily rate of transpiration for the day studied. The experiments are repeated several times during the growing season. This method is satisfactory for obtaining the relative rates of transpiration among several types of plants, but large errors may occur when the results are applied to large areas.[56]

3. Ground-water rating curve.[57] This method required plotting two curves showing average depth to ground water in wells on the farmed land versus seepage to or from the river. One of the curves is for the growing season and the other for the nongrowing season. A modification of this method lay in plotting the first curve for a tract occupied by transpiring vegetation, and the second curve for the same tract after the vegetation was removed. The water withdrawn from the ground-water reservoir by vegetation in the area studied is determined from the difference between the two curves. The method was unsuccessful in lower Safford Valley because the curves for the growing season and nongrowing season could not be defined separately as the range of fluctuation of the water table was too small. Furthermore, few wells on the farmed land were available for measurement of water levels.

Another way of applying the ground-water rating-curve method would be to plot the average depth to water in wells in the bottom land against seepage gain or loss in the river. This modification of the method was not applicable to lower Safford Valley because, as a result of the narrow range of fluctuation of the water table, the summer and winter curves could not be defined separately. This modification of the method also might have been applicable to the problem if clearing had been undertaken.

Another method, the turbulent-transport, described by Thornthwaite and Holzman,[58] provides for direct determination of evaporation from a land or water surface by the use of observations of wind, moisture gradients, and temperature. Although this method shows great promise, instrumentation difficulties have not at this time been completely overcome, particularly for the precise determination of moisture gradients. For that reason the method was considered to be impracticable for this investigation.

[56] Raber, Oran, Water utilization by trees, with special reference to the economic forest species of the North Temperate Zone: U. S. Dept. Agr. Misc. Pub. 257, p. 76, 1937.

[57] Meinzer, O. E., and Stearns, N. D., A study of ground water in the Pomperaug Basin, Conn., with special reference to intake and discharge: U. S. Geol. Survey Water-Supply Paper 597-B, pp. 127-129, 1929.

[58] Thornthwaite, C. W., and Holzman, B., The determination of evaporation from land and water surfaces: U. S. Weather Bureau, Monthly Weather Rev., vol. 67, pp. 4-11, 1939.

CLEARING OF BOTTOM-LAND VEGETATION

Removal of the existing nonbeneficial bottom-land vegetation can accomplish two purposes: Additional appropriations of surface water would be possible if land is cleared and new growth prevented, and the crop potential of lower Safford Valley would be increased without additional irrigation if the nonbeneficial phreatophytes were replaced with phreatophytes of economic value. With respect to the second possibility, Meinzer [59] states:

> 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.

METHODS OF CLEARING

Experiments in lower Safford Valley during the investigation indicate that saltcedar is the only plant growing in the bottom land that is difficult to eradicate. Two experimental methods of clearing natural vegetation from small tracts of bottom land were tested during the investigation. The first, cutting all the growth level with the ground, was used in determining the weight of vegetation per unit of volume density. As a means of permanently removing the phreatophytes, the method was unsuccessful, for in 3 months the saltcedar was again 2½ feet high (see fig. 6). The second method used was to burn the vegetation while it was green, searing the limbs and apparently killing the plants. A small tract of bottom land was burned over with a flame thrower by the Phelps Dodge Corp. in the fall of 1943, but by the next year the saltcedar plants were again growing (see fig. 45). It is believed that if permanent clearing is to be accomplished the roots of the plants will have to be removed or destroyed. Perhaps a specific hormone could be found that would be toxic to saltcedar but harmless to economic crops.

One method of keeping the land cleared would be to plant the cleared tracts with pasture grasses that use little water and that reduce

[59] Meinzer, O. E., Plants as indicators of ground water: U. S. Geol. Survey Water-Supply Paper 577, pp. 88-89, 1927.

the possibility of erosion by wind or by floods, and to destroy new growth of natural vegetation by plowing and replanting the land occasionally. In this manner the nonbeneficial plants that are high users of water will be kept out by beneficial grasses that are low users of water, and the water saved will be available for use elsewhere. Young and Blaney [60] state that, over a 3-year period, saltgrass in a tank

FIGURE 45.—Saltcedar plot 100 yards west of Glenbar experiment station, August 24, 1944. It was burned September 29, 1943, while green. New growth is 7½ feet tall, which shows that burning will not kill saltcedar. Photograph by T. W. Robinson.

near Santa Ana, Calif., used an average of 13.4 inches of water a year at a depth to the water table of 4 feet, and that over a 2-year period Bermuda grass in a tank near San Bernardino, Calif., used an average of 28.2 inches of water a year at a depth to the water table of 3 feet. Although these figures cannot be applied directly to lower Safford

[60] Young, A. A., and Blaney, H. F., Use of water by native vegetation: California Dept. Public Works, Div. Water Resources, Bull. 50, pp. 43, 50, 1942.

Valley, they indicate that saltgrass and Bermuda grass are relatively low users of ground water. Other plants, whose rate of use of water is not known, may be suitable for planting in the cleared areas.

EFFECTS OF CLEARING

The hazard from floods probably would be reduced by clearing part of the bottom land, as the flood-carrying capacity of the channel of Gila River would be increased. If belts of natural vegetation were allowed to remain, bank cutting and channel changes as a result of floods would be partly prevented.

The amount of water that could be saved by clearing the bottom land from Thatcher to Calva would be less than 28,000 acre-feet a year (see table 58). If clearing were done, the belts of natural vegetation that probably would have to be left would continue to use water. Furthermore, the cleared lands probably would have to be planted to pasture grasses or other vegetation that would prevent erosion of the bottom land. The grasses undoubtedly would use all the precipitation that would fall on the area they would occupy, and in addition they probably would withdraw water from the ground-water reservoir. If grass or other soil cover were not planted, evaporation of precipitation and of small amounts of ground water would occur. Because the water table would be higher, the direct evaporation would be greater than at present. Thus it is not possible to predict the actual amount of water that could be saved each year by clearing all or part of the bottom land, as the rate of use of water from the area after clearing would depend on subsequent treatment of the area.

The ground water that would be saved by clearing all or part of the bottom land would appear as an increase in flow of the Gila River. Seepage runs, made along the river after clearing was accomplished, would be one basis of determining the amount of ground water saved by the clearing.

Waterlogging of the bottom land or of adjacent farm lands probably would not occur as a result of clearing, as the bottom land is well-drained in most places.

Under existing conditions, over a period of a year or more the amount of salts entering the bottom land in ground-water inflow and the amount leaving the area probably are about equal. If the anticipated effects on movement of ground water were brought about by clearing, some general trends in quality of water would necessarily follow. Upon removal of the growth this equilibrium would be upset, and conditions would remain unstable for an indefinite period. During the period of instability, the amount of salts carried into the river by seepage would probably be larger than it is during an equal period of time under existing conditions. After a new equilibrium became established, the total amount of salts leaving the bottom land would again approximate the amount entering, and these quantities probably would be about the same as before clearing. If all the water were saved, the ultimate effect of clearing on the quality of water in the Gila River would be equivalent to diluting the river flow with a quantity of distilled water equal to the amount of water now used by transpiration.

Clearing the bottom-land growth would have an effect on the concentration of dissolved solids in ground water entering the river. According to computations made for the chloride-increase method, transpiration by bottom-land growth in lower Safford Valley increases the concentration of chloride in ground water entering the area by an average of more than 60 percent as the water passes through the transpiration area. Stopping transpiration in the bottom land thus should have the effect of reducing the concentration of dissolved solids in ground waters that seep into the river, and hence would improve the quality of the river water. Presumably, the concentration of dissolved solids in the ground waters of the bottom land is now at a maximum, and reduction of water use should be effective in reducing this concentration and in improving the quality of the ground waters within a short time after transpiration stops.

Removal of bottom-land growth would have no direct effect on quality of ground water in the cultivated areas of the valley.

SUMMARY AND CONCLUSIONS

1. The total use of water by bottom-land vegetation was about 28,000 acre-feet in the 46-mile reach of Gila River from Thatcher to Calva during the 12-month period ending September 30, 1944. Of this total, about 23,000 acre-feet was derived from the ground-water reservoir and about 5,000 acre-feet was derived from precipitation. This water was used by vegetation growing on 9,303 acres, equivalent to 4,861 acres of plant growth at 100-percent volume density.

2. For the 12-month period ending September 30, 1944, the total use of water by phreatophytes common to lower Safford Valley, computed for growth of 100-percent volume density was, in acre-feet per acre, saltcedar, 7.2; baccharis, 4.7; cottonwood, 6.0; mesquite, 3.3.

3. Six methods of determining use of water by bottom-land vegetation were applied. Three of the methods were developed during the investigation and had not been applied previously to any area. Results by each method were within 20 percent of the average of results by the six methods.

4. The volume-density method of evaluating variations in density of growth of bottom-land vegetation, as developed during the investigation, is considered applicable to other areas and to other types of phreatophytes.

5. Water use can be reduced by clearing the bottom land of natural vegetation. The amount that can be made available by clearing an area would be less than the amount now being used in the area, as evaporation of ground water would continue.

6. The flow of the Gila River would be increased downstream from any area that might be cleared.

7. The total load of dissolved mineral matter in the water of Gila River probably would be the same after clearing as before, except during an interim period when excess dissolved mineral matter would be removed from the cleared area. The concentration of dissolved mineral matter in the water of Gila River eventually would be reduced downstream from the cleared area.

8. Clearing all or part of the bottom land probably would cause no change in the quality of the ground water beneath the farmed lands.

9. Clearing the bottom lands would increase the capacity of the river channel, thereby reducing the hazard of floods.

10. During the investigation no methods were developed for permanently eradicating saltcedar from the bottom land, as methods of clearing were not an objective of the investigation. As a result of field observations it is believed, however, that the roots of the plants will have to be removed or destroyed if permanent clearing is to be accomplished.

11. No method was evolved from the investigation by which results obtained in lower Safford Valley could be applied directly to other areas.

12. The investigation was started in an effort to obtain additional water from a stream from which all available water had been appropriated. There are many such streams in the arid parts of the Southwest and many thousands of acres of nonbeneficial phreatophytes using water that would otherwise be available for agricultural use. As the demand for water increases, more and more emphasis will be placed on preventing the waste of water, particularly the waste through use by nonbeneficial vegetation. The economic position of agriculture in the Southwest could be materially improved by replacing these plants with ground-water plants of economic value or by destroying the nonbeneficial plants and applying the water saved to irrigated lands that now have an insufficient supply of water.

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