The Relationship between Oak Tree Roots and Groundwater in Fractured Rock As Determined by Tritium Tracing

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Abstract. The depths to which trees can extend their roots to obtain water have commonly been estimated to equal the height of the aerial portion of the plants. A detailed hydrogeologic investigation on a foothill pilot watershed has included diamond core drill holes which penetrate the fractured and jointed metamorphic rock well into the saturated zone. These holes provide observation wells for groundwater measurements and access for the injection of tritiated water into the groundwater zone. Over a 3-year period, injections have been made at various locations where the groundwater occurs at different depths from ground surface. In all the injection tests, significant amounts of tritiated water have been found in the water extracted from the fractured rock by the oak trees. Size and species of the oak trees do not influence the uptake of the injected tritiated water from the groundwater. Results of the 1962 experiment show that the oaks extend roots through the fractured rock to depths in excess of 70 ft. The number of oak trees in which the uptake of injected tritiated water has been detected indicates that all oak trees in the study area use water from the capillary zone immediately above the water table during the summer and fall months, a fact supported by observations of the decline of groundwater levels during these seasons. The decline occurs at nearly the same rate regardless of the depth to groundwater or the location of the well on the watershed.

Introduction. The measurement of transpiration of deep-rooted chaparral and tree species in upland areas has long been a problem to hydrologists. Depths of soil in many upland areas are in the range 3 to 6 ft. Estimates of transpiration obtained by soil moisture sampling procedures have often been limited by the difficulties of obtaining samples in shallow, rocky soil. Many worthwhile investigations have been made, but most investigators have realized that chaparral and tree species send roots into the weathered and fractured rock below the soil zone to extract available moisture.

Rooting depths of 20 ft in soil have often been reported for alfalfa, and *Meinzer* [1927] recorded a report of alfalfa roots in the roof of a mine tunnel in Nevada at 129 ft below ground surface. *Phillips* [1963] reported on live roots found 175 ft below the original ground surface of an open pit mine in Arizona. Although these roots could not be traced to a plant on the surface, they were believed to be from mesquite.

Description of plant-water and groundwater systems. The studies reported here do not involve such extensive depths of rooting, but they are based on the numerous reports of direct transpiration of groundwater by many species of plants from various depths below the ground surface. In these cases the plant roots extract water from either the saturated zone or the contiguous capillary fringe, the latter being the more likely source because the negative pressures would permit root respiration.

Oak trees in a watershed study area in Placer County, California, were suspected of extracting groundwater during the summer months from the fractured and jointed rock underlying the 2- to 4-ft soil zone. The injection of tritiated water into the zone of saturation below the water table seemed to be a suitable means of tracing the possible uptake of groundwater by the trees. Tritiated water (THO) contains one atom of oxygen, one atom of hydrogen isotope of mass 1, and one atom of hydrogen isotope of mass 3. Tritium is radioactive, decaying by β-particle emission. *Raney* [1962] reviewed the literature and conducted several experiments, all showing the usefulness of tritiated water for studying the movement and distribution of water in plants. His work showed that a plant whose roots are placed in a solution containing THO can transpire THO vapor without accumulating an equilibrium THO content in the plant water. Raney demonstrated that the relationship of THO content in the transpired vapor to the THO content in the external solution is a function of the transpiration rate. *Cline* [1953] and *Biddulph et al.* [1961] have shown that THO concentration of water in plant leaves approaches 50 per cent of the THO concentration of an external solution within 24 hours after the roots are placed in the solution.

A detailed hydrogeologic investigation of the watershed study area was initiated in 1961 to determine the groundwater storage and groundwater outflow components of the hydrologic cycle. Since the unconfined groundwater generally occurs at depths below the weathered zone, diamond core drilling has been used extensively. Recovered cores are used to delineate the subsurface geology and to estimate the water storage capacity of the fractured and jointed rock, which is in the range of 1 to 2 per cent by volume. The boreholes are cased through the weathered zone for use as observation wells and to provide access to the saturated zone for injections of THO in the uptake studies.

The material underlying the Placer County study area is metamorphosed sedimentary and igneous rock with two open joint systems and vertical foliations which are open at depths of 50 ft.

A portion of the photographic core log from well 10B is presented in Figure 1. In the core recovered from the Placer County wells, the presence of iron-staining has been used to identify those joints which are open to the seepage and storage of water. Other joints and fractures in the core appear to have opened only when internal stresses were relieved by the penetration of the drill. The freshly opened joints show fresh crystals on the joint plane; the iron-stained joints show very few crystal faces.

The open joints in the cores appear to be of supercapillary size, and some have widths of 0.01 ft. The frequency of joint occurrence and the width of the joint openings generally decrease with increasing depth. The medium in which the groundwater occurs in the study area is therefore quite complex. The same complexities will affect tree rooting in the fractured rock below the weathered zone.

Groundwater recharge occurs as a result of the winter rains each year in the Placer County watershed. During the winter and spring, when groundwater levels are responding to the recharge and outflow, conditions are not suitable for a dual-purpose tracer study. For this reason, injections of THO to study the continuity of groundwater movement and the depth of rooting of trees have been made at the end of summer (during July, August, and September) when groundwater fluctuations are at a minimum.

1961 injections. Two injections of THO were made in the groundwater observation wells in the summer of 1961. The injections were made by pouring the THO through a tube extending below the water table.

On June 28, 1961, 11.83 fluid oz of THO with a total radioactivity of 437 mc was injected into well 3BN, which is located near the stream channel in the center of watershed B.

On July 31, 1961, 26.46 fluid oz of THO with a total radioactivity of 978 mc was injected into well 6A, which is high on the southern slope of watershed A near the boundary of watershed B. These two wells are shown as black squares in Figure 2.

After the injections, leaf samples from 10 trees downslope from the wells were collected at daily, semiweekly, weekly, and biweekly intervals. One handful of leaves was collected from each tree on each sampling date. The leaves were placed in polyethylene bags; the bags were tied tightly to prevent exchange of air and stored in a deepfreeze. By this means the water was retained in the leaf tissues. At a later time the water was extracted from the leaf tissues by freeze-drying. The water was then analyzed for tritium by an automatic liquid scintillation spectrometer. 0.0169-oz aliquots of the extracted water were placed in glass vials containing 0.51 oz of a scintillation solution. These vials were placed in the scintillation spectrometer, which was adjusted for optimum detection of β-particle emission by tritium atoms. The activity of each sample was counted for two 5-minute periods. Several blanks were also counted to determine the background counting level of the machine. Tritium standards of known concentration were also counted for two 5-minute periods. The absolute values of the tritium concentrations in the samples were then calculated from these counts [*Hours and Kaufman,* 1959].

In the period following the injections, significant concentrations of tritium were detected in all of the trees sampled at both sites. Table 1 lists the depths to the water table in the wells

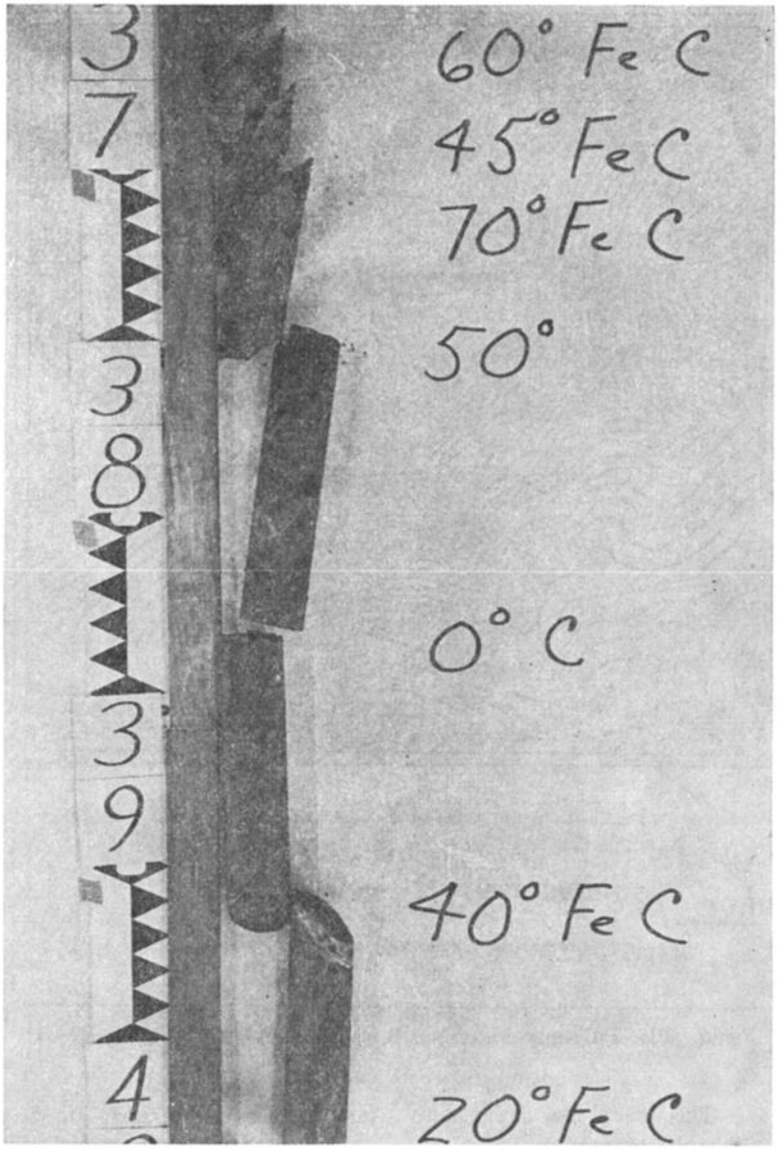

Fig. 1. Portion of photographic core log from well 10B, Placer County watershed. The numbers on the left indicate the depth below ground surface, the numbers on the right indicate the degrees of dip for each fracture and joint, and the letters indicate the presence of iron-staining on the joints and the presence of carbonate minerals in the rock.

at the time of injection, and the number, species, height, diameter at breast height, and horizontal distance from the injection well for each tree.

The results showed that the trees listed in Table 1, representing all of the oak species occurring on the Placer County watersheds, obtained water from the groundwater or from the contiguous capillary zone above the water table. The exact depth of groundwater at the location of each sampling tree cannot be predicted accurately from the available data.

Results of this first THO injection were used in the design of a second experiment to learn more about the depths to which the oak trees could extend roots, since the indicated depths of 24 and 42 ft were not believed to be a maximum

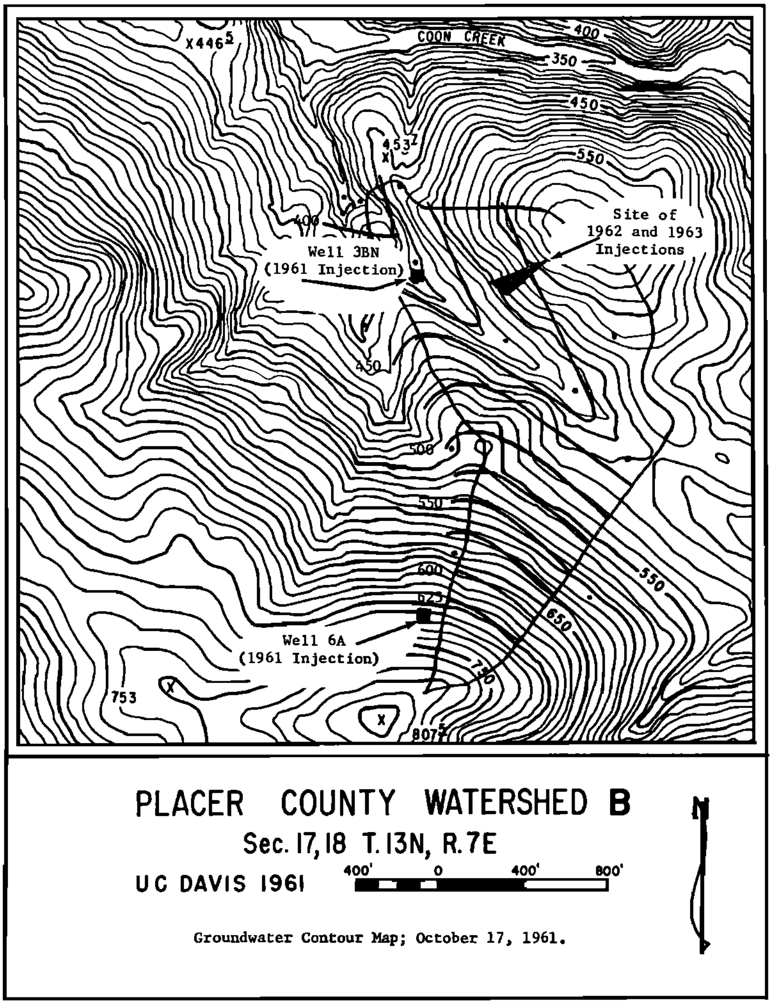

Fig. 2. Placer County watershed B, showing sites of THO injections.

1962 injection. This study was designed to determine accurately the depth of rooting of the oak trees and the groundwater flow velocities in the jointed rock. A site high on the eastern side of watershed B was selected for drilling the well for THO injection. The water table at this site is between 60 and 90 ft deep, depending on the time of year. Two observation and sampling wells were drilled 250 ft downhill from the injection well. The three wells are at the corners of the black triangle in Figure 2. The locations of these wells were selected so that the straight line between each of them and the injection well was approximately normal to the water-table contours. This arrangement of wells permits an accurate estimate to be made of the groundwater elevation at any point within the triangle enclosed by the three wells. The depth to groundwater in the two lower wells ranges between 40 and 70 ft during the year. If tritiated water were detected in trees within the triangle formed by the three wells, the trees must necessarily have roots extending approximately 50 to 80 ft through the fractured rock to the groundwater. Depending upon the location of any tree, the depth of rooting could be determined from knowledge of the position of the water table.

The injection studies in 1961 showed no differentiation between species of oak tree regarding the uptake of tritiated water. Thus any

TABLE 1. Positions of Groundwater and Sampling Trees Relative to Tritium Injection Wells, 1961

Well No.	Tree No.	Depth to Groundwater, ft	Species of Oak	Tree Height, ft	DBH,‖ in.	Horiz. Dist. from Well, ft
3BN		24.3				
	1		Live*	24	4	20
	2		Blue†	30	9	42
	3		Valley‡	17	3	30
	4		Live	50	11	69
	5		Live	30	5	115
	6		Live	30	20	84
	7		Blue	44	14	230
	8		Blue	18	6	325
	9		Blue	35	13	370
	10		Valley	53	18	530
6A		42.1				
	1		Black§	24	8	20
	2		Blue	23	7	6
	3		Black	25	8	22
	4		Blue	10	3	54
	5		Blue	25	7	24
	6		Blue	22	12	35
	7		Black	19	9	89
	8		Black	25	7	111
	9		Black	28	13	166
	10		Black	28	7	296

* Quercus wislizenii.
† Quercus douglasii.
‡ Quercus lobata.
§ Quercus kellogii.
‖ Diameter at breast height.

species of oak tree could be selected for sampling to determine the maximum rooting depth. However, only live oak and blue oak occurred on the slope where the 1962 tracer study was conducted. Fifteen trees in the triangle bounded by wells I-B1, I-B2, and I-B3 were selected for sampling after the injection. Of the fifteen trees sampled, nine were blue oaks and six were live oaks. A relatively uniform coverage of the study area was obtained by planned selection of trees (Figure 3).

In the 1961 studies, leaves were collected from each tree at the time of sampling and water for analysis was extracted from the leaves by freeze-drying. To expedite the processing of samples, it seemed desirable to eliminate the freeze-drying operation in the laboratory. A preliminary trial on several trees showed that a large polyethylene bag tied tightly over the end of a branch would collect from 0.5 to 1 fluid oz of transpired water during a 24-hour period. This technique provided a direct sample of water from the oak trees, representing the time during which the bag was on the tree branch. This technique was used to obtain samples of water from the trees before and after the injection. The daily procedure involved draining the condensed water from the bag while it remained on the tree and tying on a new bag for the following day. A fresh branch was selected every day to prevent severe burning and desiccation of the leaves. The samples were collected in the early evening (near the end of the daily transpiration period).

Background samples of water from the 15 sampling trees were obtained on September 20 and 21, 1962. On the afternoon of September 21, 28.16 fluid oz of THO with a total radioactivity of 333 mc was injected below the water table in well I-B1. Samples of transpired water from the fifteen trees were collected and analyzed daily until October 2.

The only samples which contained significantly detectable quantities of tritium were

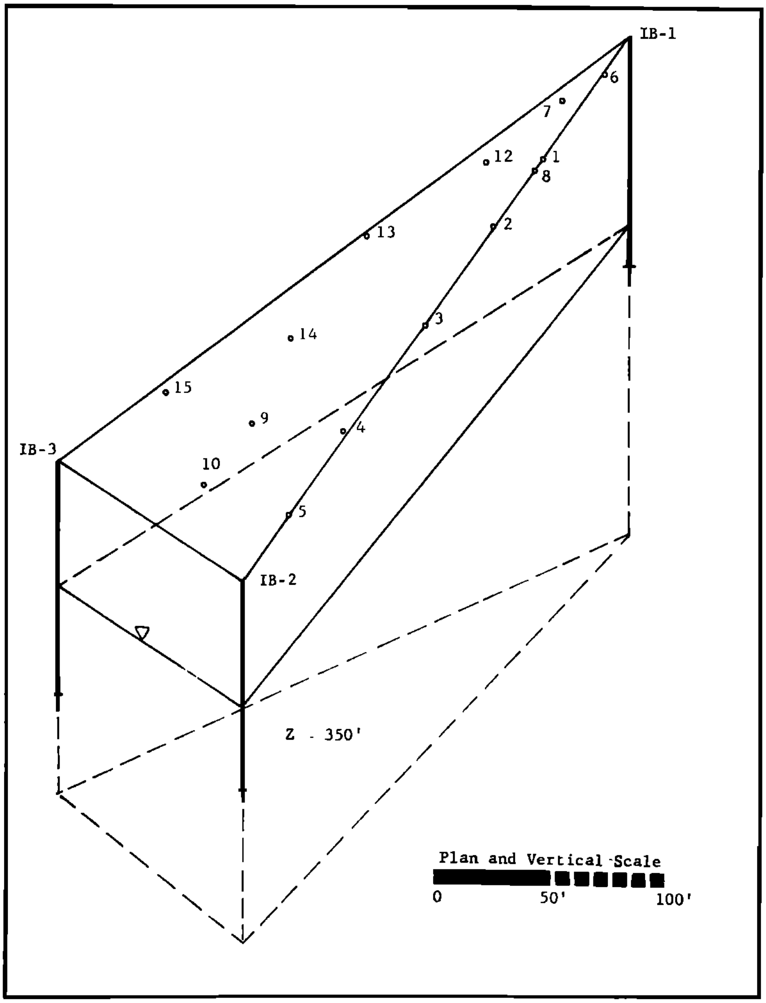

Fig. 3. Diagrammatic section showing relationship of wells, trees, ground surface, and water table at the site of the 1962 and 1963 injections.

TABLE 2. Positions of Groundwater and Sampling Trees Relative to Well I-B1 on September 21, 1962

Well No.	Tree No.	Depth to Groundwater, ft	Species of Oak	Tree Height, ft	DBH, in.	Horiz. Dist. from I-B1, ft
I-B1		82.9				
I-B2		54.9				246
I-B3		54.8				271
	2	73	Blue	35	10	76
	3	68	Live	30	8	131
	6	80	Blue	30	7	20
	7	79	Blue	30	7	34
	9	62	Live	30	6	202
	14	66	Live	25	4	171

TABLE 3. Times and Concentrations of Selected Groundwater and Tree-Water Samples, 1962

Sample	Date (1962)	Time	Concentration, $\mu c/oz \times 10^{-4}$
Well I-B1	Sept. 21	1500	16,795,000
Well I-B1	Sept. 23	2000	2,572,000
Well I-B2	Sept. 22	7000	59
Well I-B3	Sept. 22	7000	177
Well I-B2	Sept. 23	7000	59
Well I-B3	Sept. 23	7000	30
Tree 2	Sept. 22	1900	18
Tree 6	Sept. 22	1900	18

those taken from six of the trees on September 22. Samples taken before the injection did not contain sufficient THO for detection by the liquid scintillation spectrometer. Tables 2 and 3 list the results of the 1962 injection experiment. Many of the sample trees obtain water from the groundwater or capillary zone when groundwater levels in the fractured and jointed rock are 60 to 80 ft below the ground surface.

The movement of the THO through the groundwater system was much more rapid than was expected. This anomalous behavior was in some way caused by the conditions existing immediately after the wells were drilled. Approximately 4000 gallons of circulating water was lost in the rock during the drilling of well I-B1, which was completed only a month before the experiment.

1963 injection. The injection experiment of 1962 was repeated in 1963 to confirm the earlier results and to obtain a result under normal groundwater conditions. Groundwater recharge due to rainfall raised water levels 15 to 20 ft at the site during the winter of 1962–1963. By August 1963 the rate of decline of water levels had become constant, and the only change from the 1962 conditions was a 10-ft net rise in the water level at well I-B1.

Background samples of transpired water were obtained from the same trees, with the exception of no. 10. On August 27, 1963, 46.54 fluid oz of THO with a total radioactivity of 584 mc was injected below the water table in well I-B1. Samples of transpired water from the fifteen trees were collected and analyzed daily until September 5. Background samples again showed no detectable THO.

The presence of tritium in the samples persisted over the 9-day period of sampling, and more trees were showing transpired tritium toward the end of the period. Tables 4 and 5 list the results of the 1963 injection experiment.

The rates of groundwater movement in the 1963 experiment were more than 10 times slower than in 1962 and are more reasonable values. The results of the 1963 experiment confirm the results obtained in 1962, namely that oak trees obtain water from groundwater at depths of 70 ft or more.

Discussion of results. The results obtained show that the maximum depth of rooting of oak trees in the fractured rock of the study area is at least 80 ft. If a capillary zone were estimated to extend as much as 5 ft above the water table,

TABLE 4. Positions of Groundwater and Sampling Trees Relative to Well I-B1, August 27 to September 5, 1963

Well No.	Tree No.	Depth to Groundwater, ft	Species of Oak	Tree Height, ft	DBH, in.	Horiz. Dist. from I-B1, ft
I-B1		71.9				
I-B2		54.0				246
I-B3		55.7				271
	1	67	Blue	25	6	55
	2	66	Blue	35	10	76
	3	60	Live	30	8	131
	4	58	Blue	40	9	180
	5	55	Blue	40	7	216
	7	70	Blue	30	7	34
	8	67	Blue	20	4	59
	12	66	Blue	25	9	71
	15	57	Blue	20	4	221

TABLE 5. Times and Concentrations of Selected Groundwater and Tree-Water Samples, 1963

Sample	Date (1963)	Time	Concentration, $\mu c/oz \times 10^{-4}$
Well I-B1	Aug. 27	1400	12,064,000
Well I-B1	Sept. 1	1300	275,000
Well I-B1	Sept. 5	1130	27,500
Well I-B2	Sept. 5	1200	59
Well I-B3	Sept. 5	1200	30
Tree 1	Aug. 28	1200	38
Tree 1	Aug. 28	1200	59
Tree 15	Sept. 5	1200	24
Tree 15	Sept. 5	1200	44

this maximum rooting depth would have to be reduced to 75 ft. Since the depth of groundwater under the conditions of the 1962 experiment did not exceed the rooting depth of the oak trees, it is reasonable to believe that oak trees are capable of rooting to depths beyond 80 feet. These conclusions are valid in spite of the fact that only six of the fifteen trees sampled in 1962, and nine of the fifteen trees sampled in 1963, showed detectable uptake of tritiated water. Two facts contribute to the validity of the conclusions: First, there is a high dilution of the injected tritiated water as it enters the groundwater system, is picked up by tree roots, and enters the tree-water system. Second, the fixed nature of the available tracer flow paths in the jointed rock and the limited access of roots downward through the fractured rock limit the opportunity for the intersection of a tracer flow path and a tree root.

The mechanism of vapor phase transfer of THO from the water table to the roots is ruled out as a factor in producing the observed results because of the rapid uptake of THO (observed 1 day after injection) and because of the small differences between THO concentrations in the groundwater and the transpired water.

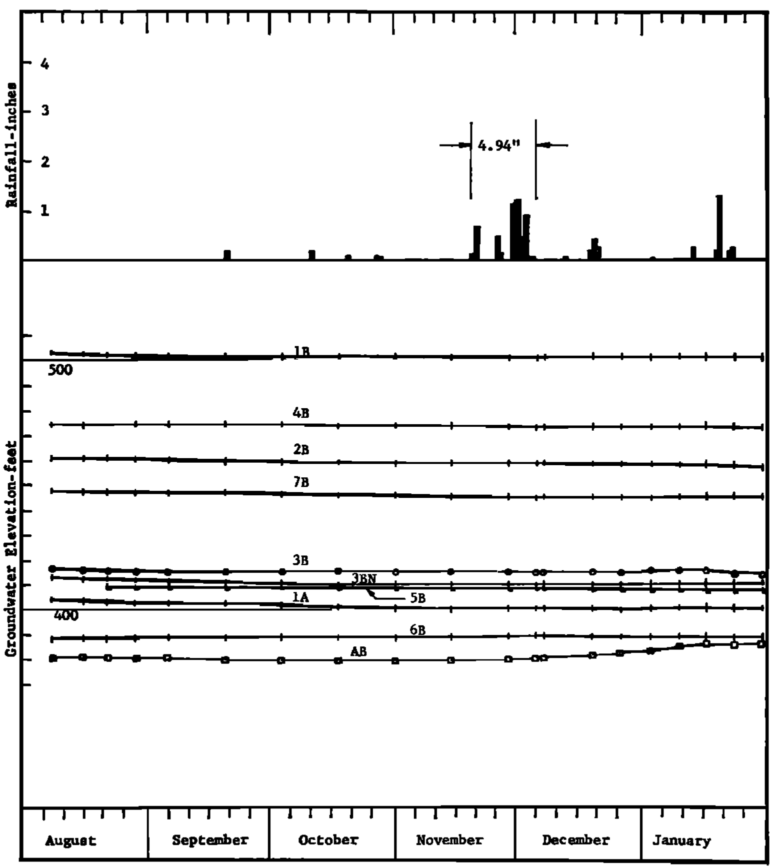

Fig. 4. Groundwater elevations and rainfall, Placer County watershed B, 1961–1962.

The 75- to 80-ft maximum rooting depth determined for the oak trees implicates all trees on the Placer County watershed study area as users of groundwater during the summer and fall months. Qualitative evidence in support of this fact can be gained from inspection of the graphs of groundwater elevation versus time for the observation wells (Figures 4, 5, and 6). During the months of July through October the water levels decline at a uniform rate regardless of elevation or location on the watershed. The graph for 1961 is particularly significant because it shows a uniform decline of groundwater levels until October, followed by a 2-month period of no change in groundwater levels. This slope change on the graph corresponds to the beginning of cold weather and the dormant period for the oak trees.

Two possibilities for additional investigations are indicated. It would be possible to design a study in which the appearance of tritium in the oak trees was used to trace the direction and continuity of groundwater movement following an injection of THO into the groundwater. It should also be possible to determine water-use rates by the oak trees from careful analyses of groundwater data.

Conclusions. The fact that oak trees can extend roots more than 70 ft through fractured and jointed rock to obtain groundwater has three important implications.

To the ecologist, who studies the relationship of the oak tree to its environment, the results of these studies clearly define the lower limit of the environment of the oak tree as being below the water table.

To the hydrologist, who studies the occurrence and distribution of water, the trees are analogous to a number of pumps spread uniformly over an area, all operating to depress the water

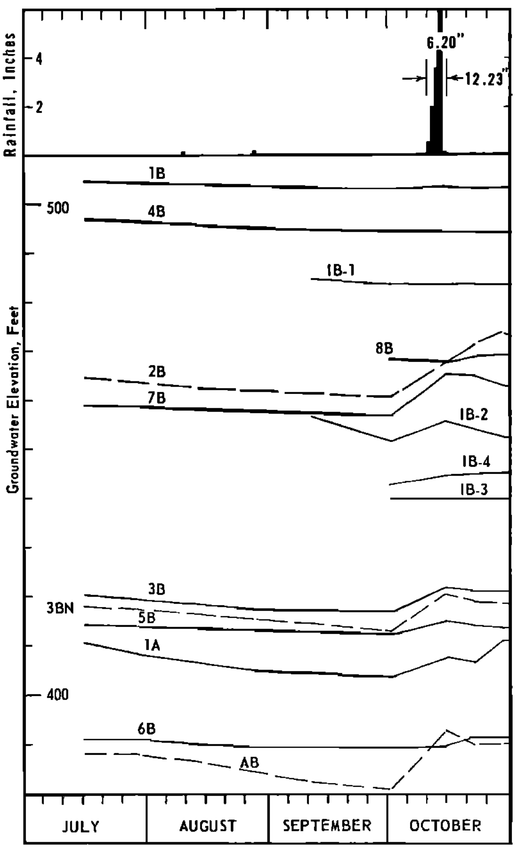

Fig. 5. Groundwater elevations, Placer County watershed B, 1962.

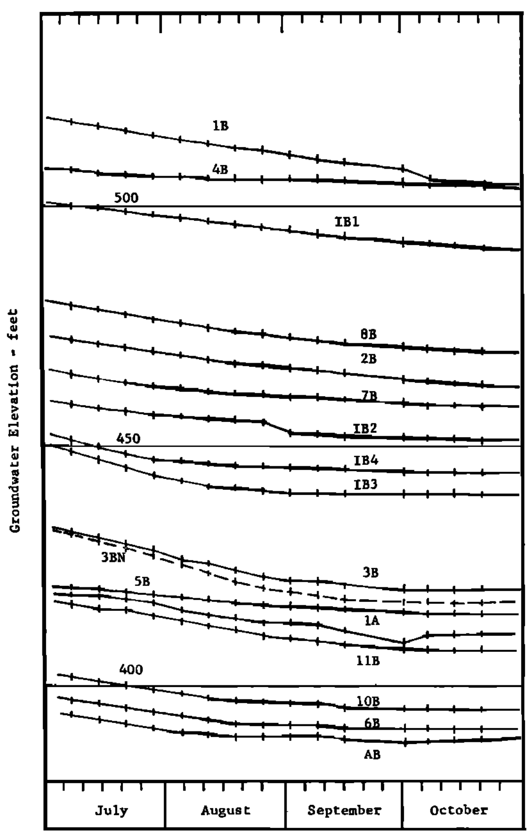

Fig. 6. Groundwater elevations, Placer County watershed B, 1963.

table. In the situation which has been studied, soil moisture sampling cannot measure summer transpiration by trees. Furthermore, the analogy helps to explain the mechanism of response to treatment in watershed management programs which include killing or removal of oak trees. When the direct transpiration of groundwater is eliminated (the pumps are permanently removed), groundwater levels will rise and be maintained at higher levels by natural recharge.

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