GROUNDWATER INVESTIGATION OF AN ALLUVIAL TERRACE, REDWOOD CREEK, HUMBOLDT COUNTY, CALIFORNIA, USING A FLOOD-WAVE RESPONSE MODEL

by

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A Thesis
Presented to
The Faculty of Humboldt State University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

December, 1983

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ABSTRACT

Recent channel aggradation along Redwood Creek, Humboldt County, California, has posed a hazard to streamside groves of coastal redwood (*Sequoia sempervirens*) by elevating the water table adjacent to the creek. This causes a prolonged inundation of the rooting zone, thereby "drowning" streamside trees. This investigation summarizes and interprets data collected at three recording piezometer wells and other pertinent survey and streamflow data in order to document groundwater behavior in a typical Redwood Creek alluvial terrace.

A U.S. Geological Survey flood-wave response computer program was modified to efficiently determine aquifer diffusivity. Results of the flood-wave response program supported the hypothesis that the terrace material comprising the aquifer becomes finer away from the creek. The terrace has a good hydraulic connection with Redwood Creek, and the creek is the dominant factor controlling groundwater elevation in the terrace. Other factors influencing groundwater elevation, such as hillslope recharge and rainfall infiltration, are most apparent away from the creek. At times during the summer the groundwater table can be lower than the surface of Redwood Creek. The results of this study may be applied to investigations relating groundwater to redwood tree ecology. Stage hydrographs and stage duration curves that would be important in conducting those investigations are presented.

ACKNOWLEDGEMENTS

For allowing me to undertake this project and for providing continuous support along the way, I would like to thank Steve Veirs of Redwood National Park. His editorial skills greatly improved the quality of the final report. My advisor, Dean Freeland, gave generous encouragement and practical advice in rendering this groundwater investigation accessible to the watershed manager, forest ecologist, and other non-specialists in groundwater hydrology. Richard Iverson of the U.S. Geological Survey conveyed useful criticism of the text and computer programs and helped clarify my initial ruminations on groundwater concepts.

I wish to thank Bill Lennox, also of Redwood National Park, who provided the initial momentum of getting the data into the computer and who wrote useful programs to make the data accessible to analyses. The personnel at the U.S. Geological Survey field office in Eureka, especially John Palmer, showed notable patience and flexibility in allowing frequent distractions from my regular duties in favor of work on this thesis. Alex Williamson, also of the U.S. Geological Survey, suggested much in the way of the approach to the problem and pointed to some very useful literature.

Other staff at Redwood National Park, especially Ron Knickerbocker, Mary Ann Madej and Nick Varnum, provided important logistical support. Finally, I would like to express my appreciation to my wife, Julie, who assisted with the figures, and was an inspiration through the many weeks needed to complete the study.

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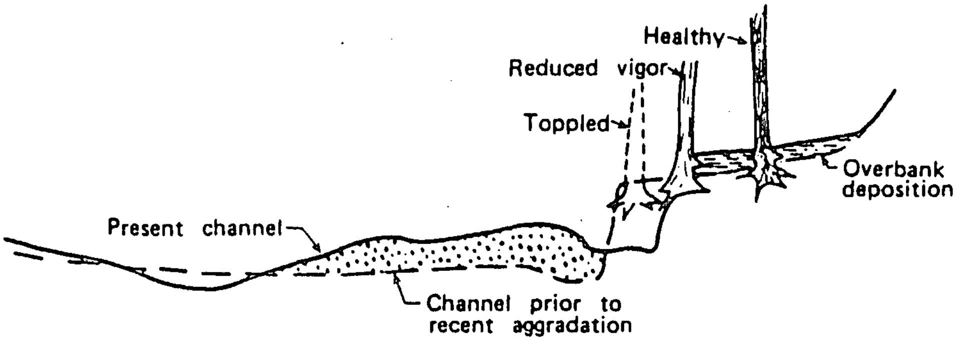
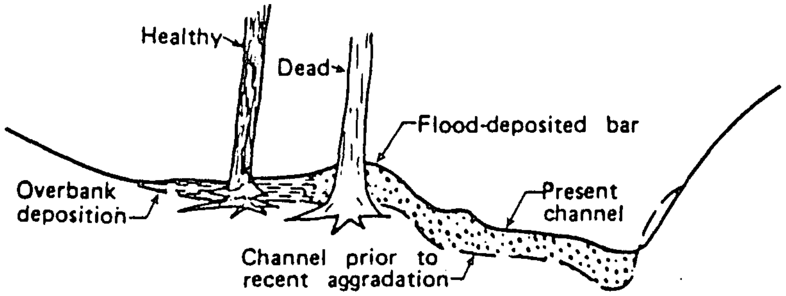
INTRODUCTION

The lower one-third of the Redwood Creek basin in northwestern California is now included in Redwood National Park. In the Redwood Creek watershed past land-use practices, principally timber harvesting, combined with intense storm runoff and naturally unstable terrain, has led to extensive sedimentation problems. A consequence of increased upland fluvial erosion and mass wasting has been recent channel aggradation of 10 feet or more along large portions of the Redwood Creek channel (Janda et al., 1975). Channel aggradation has had an adverse effect on streamside vegetation as illustrated in Figure 1. Public concern for this problem has focused in particular on the risk of damage from erosion and aggradation to streamside groves of coast redwoods (*Sequoia sempervirens*). The first, second, third and sixth tallest measured trees in the world grow on the streamside alluvial terraces along Redwood Creek, within the boundaries of Redwood National Park (see Figure 2 for location).

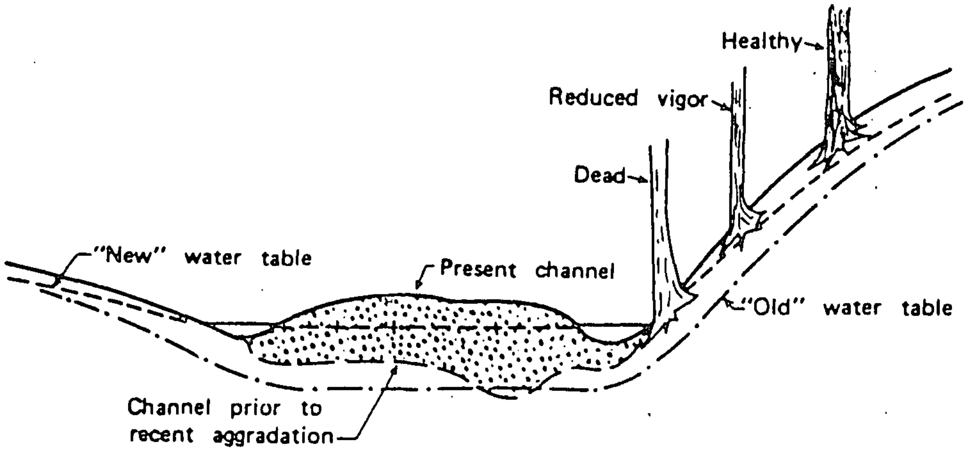
It is believed that channel aggradation has locally elevated the adjacent water table, thereby "drowning" many streamside trees (Veirs, personal communication). The main objective of this research was to investigate and quantitatively describe groundwater conditions in a typical alluvial terrace along Redwood Creek (Figure 3). Groundwater investigations in this northern coastal region of California (Evenson,



A.. Impact of streambank erosion



B. Impact of burial by coarse-grained (abrasive, "drought-fickle") sediment



C. Impact of higher streamside water table

FIGURE 1 -- Schematic representation of some adverse impacts of recent channel geometry changes on streamside vegetation. Taken from Janda (1977).

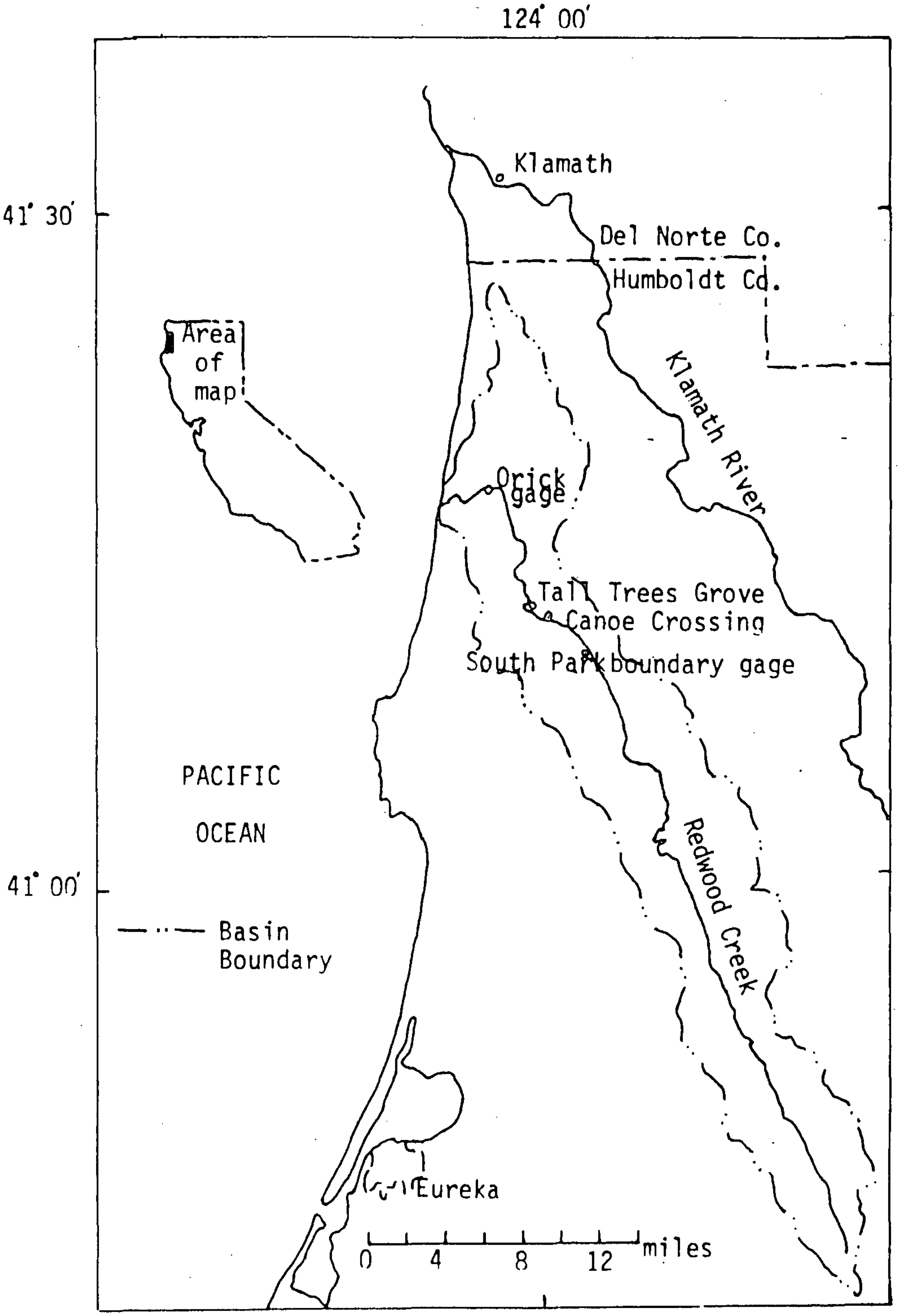


FIGURE 2. Location map.

1959; Olmsted, 1956; Johnson, 1978) have dealt with groundwater availability for domestic, agricultural and commercial uses. The research presented here is believed to be the first detailed study of groundwater conditions in alluvial terraces supporting superlative redwood groves. Groundwater conditions could be a critical factor in the well-being of redwoods growing on streamside alluvial terraces, especially where raised water tables are encroaching into the rooting zone of streamside trees. My purpose was not to investigate the physiological response of redwood trees to elevated groundwater conditions, though the research presented here will be necessary for such investigations.

Explanations offered by Zinke (1981) and Becking (1969) do not seem adequate in explaining the widespread damage to riparian groves in the redwood region. Becking (1969) and Zinke (1981) have suggested that affected trees in Rockefeller Forest were exposed to unfavorable anaerobic soil conditions following the 1964 flood. Becking hypothesized that floods in successive years, December 1964 and January 1966, formed a sealing layer of silt that would not allow deep drying of the soil. Decay of buried organic material was thought to lead to the anaerobic conditions. Becking also suggested that a prolonged inundation by surface flood waters may have been a critical factor, whereas Zinke proposed that a change in deposition to coarser sediments may have been responsible for tree mortality.

The secondary objective of this research was to develop and refine two computer programs for studying stream and alluvial aquifer interactions. To aid in interpretation and in visually portraying the stage changes at upstream and downstream gages and simultaneously see the changes in groundwater elevation with time, a stage-time graphics computer program was developed.

The second program was developed as a modification of a U.S. Geological Survey program (Kernodle, 1978) to determine aquifer diffusivity (T/S). Diffusivity can be thought of as the rate at which a change in head (i.e. groundwater stage) will propagate through an aquifer [refer to Figure 16 for an explanation of T (transmissivity), S (storage coefficient) and some other terms used throughout this report]. In the U.S.G.S. version a trial-and-error approach is used, which can be quite time consuming. My objective was to develop a new version which employs a computer search routine to find the best estimate of aquifer diffusivity. My version should also test the applicability of the general algorithm for determining aquifer diffusivity when the location of the impermeable valley wall (i.e., the boundary) of the aquifer is not exactly known.

Background Information

National Park Service Research Scientist Steve Veirs and U.S.G.S. Geologist Richard Janda initiated monitoring of groundwater conditions along Redwood Creek in 1976 using a series of groundwater wells installed in several alluvial sites, including the Tall Trees Grove. An excellent data set now exists, documenting on a nearly continuous basis the piezometric level at three well networks along the creek (Table 1).

Table 1. Date of installation, placement of digital recorders and elevation to mean sea level (MSL) of piezometer well features.

Site	Well No.	Digital Recorder (ADR)	Measuring Point(MSL)	Elevation Ground(MSL)	Date Installed	Date ADR Placed
Tall Trees	1	X	126.76	121.45	Nov 1976	Dec 1979
	3	X	124.55	119.13	" "	" "
	4	X	123.20	117.69	" "	" "
	5	X		114.69	" "	" "
	6	X		110.78	" "	" "
Canoe Crossing	8	X	139.72	134.08	" "	Jan 1979
	9	X	137.67	132.13	" "	" "
	10	X	135.19	129.62	" "	" "
Emerald Creek	11	X	142.94	137.63	Nov 1977	Oct 1980
	12		131.05		" "	
	13	X	138.25	133.22	" "	Oct 1980
	14		137.81		" "	
	15	X	145.73	140.54	" "	Oct 1980
	16	X	144.28	138.55	" "	" "
	17	X	148.67	143.68	" "	" "
	18		139.73		" "	

To reduce the great amount of raw data to a manageable level, my evaluation was limited to the Canoe Crossing site (Figure 5). At this site, the three recording wells and a surveyed stream channel cross-section are aligned nearly perpendicular to the channel, a nearly ideal spatial arrangement for theoretical analysis. This aspect allowed for effective computer analysis of aquifer diffusivity.

Physical Setting

The Canoe Crossing terrace was formed by a series of overbank deposits during past flood events (Figures 3, 4 and 5). An excavation into the right bank in April, 1978 (Figure 3) revealed distinct layers of dark sand separated by thinner layers of silt, clay and small pieces of wood. Although this cut exposed only six feet of terrace deposits, it is reasonable to assume that similar stratigraphy exists to greater depths for two reasons. First, terrace stratigraphy at the Tall Trees Grove, exposed by stream bank erosion; and at Rockefeller Forest along the South Fork Eel River, exposed by trenching into a terrace by Zinke (1981), show similar deposits. The terraces in these cases are about 20 to 30 feet thick. Second, field notes by U.S.G.S. technician J. Duls during well installations at Canoe Crossing state, "(the terrace material) consisted of fine sand and silt with possible layers of small drift and buried material. The largest material hit could not have been greater than pea gravel size. Material was well compacted and/or sorted."

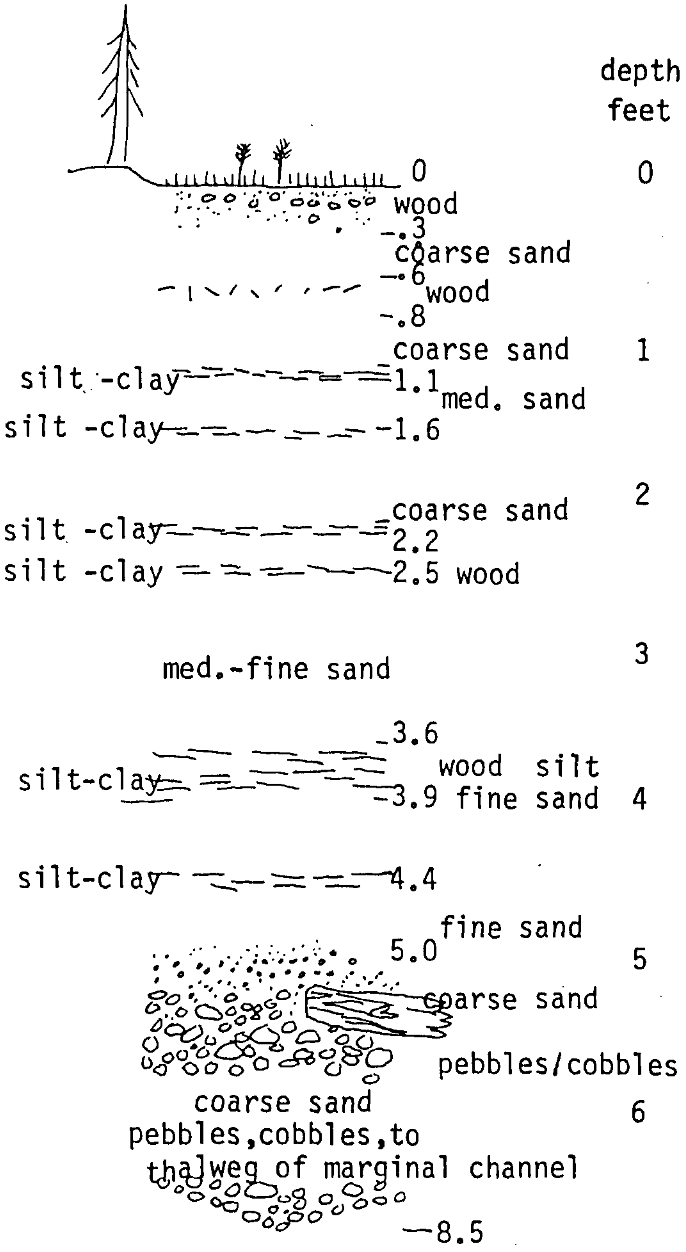


Figure 3. Cut into right bank reveals stratigraphy of Canoe Crossing terrace. A similar exposed bank at Tall Trees Grove downstream had plants growing preferentially along the silt-clay layers. Moisture seepage above these layers suggest they act as aquitards. (Redrawn from notes by USGS technician Tom Stephens)

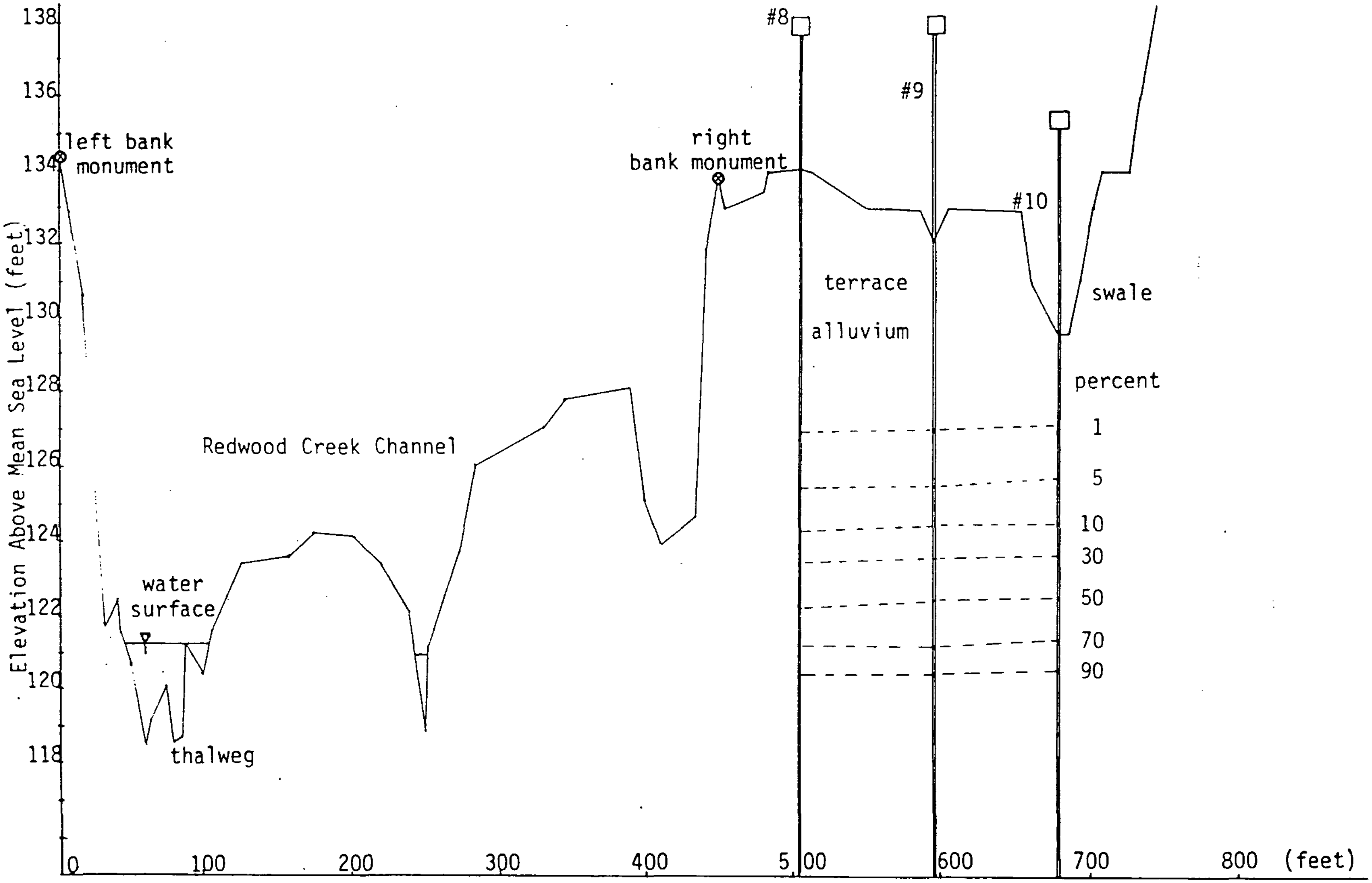


Figure 4. Profile view of study area from 1982 survey, viewed from upstream. Dashed lines refer to percent time a given stage was equaled or exceeded in the 1980 water year (see Figure 8). Each well was driven approximately 20 feet into the terrace without encountering bedrock.

The depth to bedrock is not known although a geologic map (Harden _et al_., 1981) indicates the study area to be underlain by schists of the Franciscan formation. Redwood Creek follows the trace of the Grogan fault until approximately 1½ miles above the study area. The terrace is at its widest (300 feet) at the location of the wells and is about ½ mile long. At the back of the terrace, a 33 percent slope rises approximately 40 feet to another terrace. A small creek incises the upper terrace and crosses the lower terrace downstream of the wells. The Canoe Crossing terrace supports a dense stand of uncut redwoods ranging in size from a few inches to 10 or 12 feet in diameter.

Redwood Creek at the Orick gage drains an area of 278 square miles in the Coast Range south of the Klamath River basin. The basin is roughly linear in shape (Figure 2) and is about 55 miles long. Most of the basin is underlain by rocks of the Franciscan assemblage (Bailey _et al_., 1964). Redwood Creek flows in a northwesterly direction throughout its length. Elevation of the watershed ranges from sea level to about 5,000 feet. Because the mountains are relatively low and in proximity to moderating ocean influences, there is little snowmelt runoff. Vegetation varies from coastal brush and prairies to redwood and Douglas-fir forests. Timber harvesting has been extensive in the basin but logging operations are now continuing on a reduced scale. Because of the relative impermeability of the bedrock underlying the surface soil mantle, base flow is poorly sustained. Therefore, the major runoff occurs during, and shortly after, the rains of late fall and winter. The maximum recorded flow at the Redwood Creek gage at Orick is 50,200 cubic feet per second whereas summer minimums can fall below 10 cubic feet per second. At the Canoe Crossing study area, summertime reveals a wide, mostly dry channel bed consisting of sediment derived from the Franciscan formation. Schist, sandstone, siltstone, greenstone and chert, in sizes ranging from fine sand to cobbles, are the predominant channel materials.

The climate along the coast is marked by moderate and equable temperatures, heavy and recurrent fogs, and prevailing west-to-northwest winds. Inland temperatures have a wider range, and winds in the interior are generally moderate. Temperatures are influenced largely by elevation and by the topography of the immediate vicinity. Precipitation is distinctly seasonal, most of it occurring October through May. Most of the flood-producing storms are of the extra-tropical type moving onto the coast from the west or northwest. Heaviest precipitation occurs when the storm becomes semi-stationary off the coast sending in frontal systems spaced at 12- to 24-hour intervals (Elford and McDonough, 1964; U.S.G.S., Eureka, station description file).

MATERIALS AND METHODS

Data Collection and Management

Eighteen well tubes in three networks were placed along Redwood Creek between fall 1976 and fall 1977. Each well tube consists of coupled sections of two-inch diameter steel pipe. On the wells fitted with digital recorders and floats, a five-foot pipe extension was added in hope of placing the recorders above high water. The well pipes were pounded into the ground with a portable hoist derrick and a 100- pound drop weight apparatus. The tubes are open at the top and closed with a point at the base. Four to six 3/8-inch holes are drilled in the bottom one foot of the pipe to allow the entrance of groundwater. This design, as opposed to a well tube that is perforated throughout its length, makes these wells piezometers (Fetter, 1980).

A piezometer is a small diameter well open only at the top and bottom along its length. The height that water will rise in piezometers is a measure of hydraulic head (H) at the perforated zone of the well casing (Fetter, 1980), which can be expressed as:

$$H = h_e + h_p + h_v = z + \frac{1}{g}\int_{P_a}^{P} \frac{dp}{\rho} + \frac{V^2}{2g}$$

where: H = total head

h_e = elevation of the perforated zone above a datum

h_p = height of a column of static water that can be supported by the static pressure at the perforated zone

h_v = the height the kinetic energy of the liquid is capable of lifting the liquid

ρ = density of water

z = elevation of perforated zone above datum

g = gravitational acceleration

v = absolute flow velocity

p = water pressure at perforated zone

p_a = is the atmospheric pressure (Lohman et al., 1970)

The integral term is only equal to the pressure head (h_p) for incompressible fluid flow. In the case of a shallow unconfined aquifer such as studied here, the assumption of incompressibility is very good (Fetter, 1980). Normally in ground water studies the velocity term (h_v) can be ignored because ground water velocities are very low. In an unconfined aquifer, such as studied here, "if the hydraulic gradient is less than one percent and the transmissivity is more or less uniform, the water table is also an accurate representation of the potentiometric surface of water in the aquifer" (Davis and DeWiest, 1966). In the study area the hydraulic gradient does not exceed one percent with the possible exception of transient flood-wave response for brief periods. Because the aquifer is well-sorted, transmissivity is assumed to be uniform. In a shallow piezometer, the water level will normally rise above the perforated zone of the well casing to a level equal to the water table. This is due to the pressure (h_p) exerted by the height of the water adjacent to the piezometer. Therefore, I ignore the velocity term (h_v) and assume the wells reflect water table elevation.

Thirteen of the wells have automatic digital recorders (ADR's), including the three wells at Canoe Crossing used in this study. The data are recorded by hourly punches on paper tape. All the wells were measured periodically with a steel tape to hundredths of a foot. The raw data are stored on the U.S.G.S. Daily Values file in Reston, Virginia; Humboldt State University's CDC CYBER 170-720(2) system; and on card decks.

Repeated surveys of 58 main stem cross-sections are part of an ongoing sediment study in the Redwood Creek basin (Nolan, 1979; Varnum, personal communication). Cross Section Number 19 runs only 9 degrees east of the alignment of Wells 8, 9, and 10 at Canoe Crossing and has been surveyed at least every summer since 1973. Thus, groundwater elevations can be compared to Redwood Creek water surface and channel feature elevations as tabulated in Table 2.

Data from two gaging stations, Redwood Creek South Park Boundary near Orick (#11-4822.00) and Redwood Creek at Orick (#11-4825.00) were used in this analysis (Figure 2). Surveys run by the U.S.G.S. in 1977 and by Varnum and party in 1982 were used in determination of relative elevation of features to each other and to mean sea level (Figure 5).

Computer Techniques

Nearly all the computer work was done using the Wang 2200 VP minicomputer at the U.S.G.S office in Eureka. Groundwater stage hydrographs and stage duration curves were computer generated using my program, "GWPLOT4" and "SORT" (Appendix C) as seen in Figures 6, 7, 8 and 9. Stage hydrographs are a visual method for comparing the varied

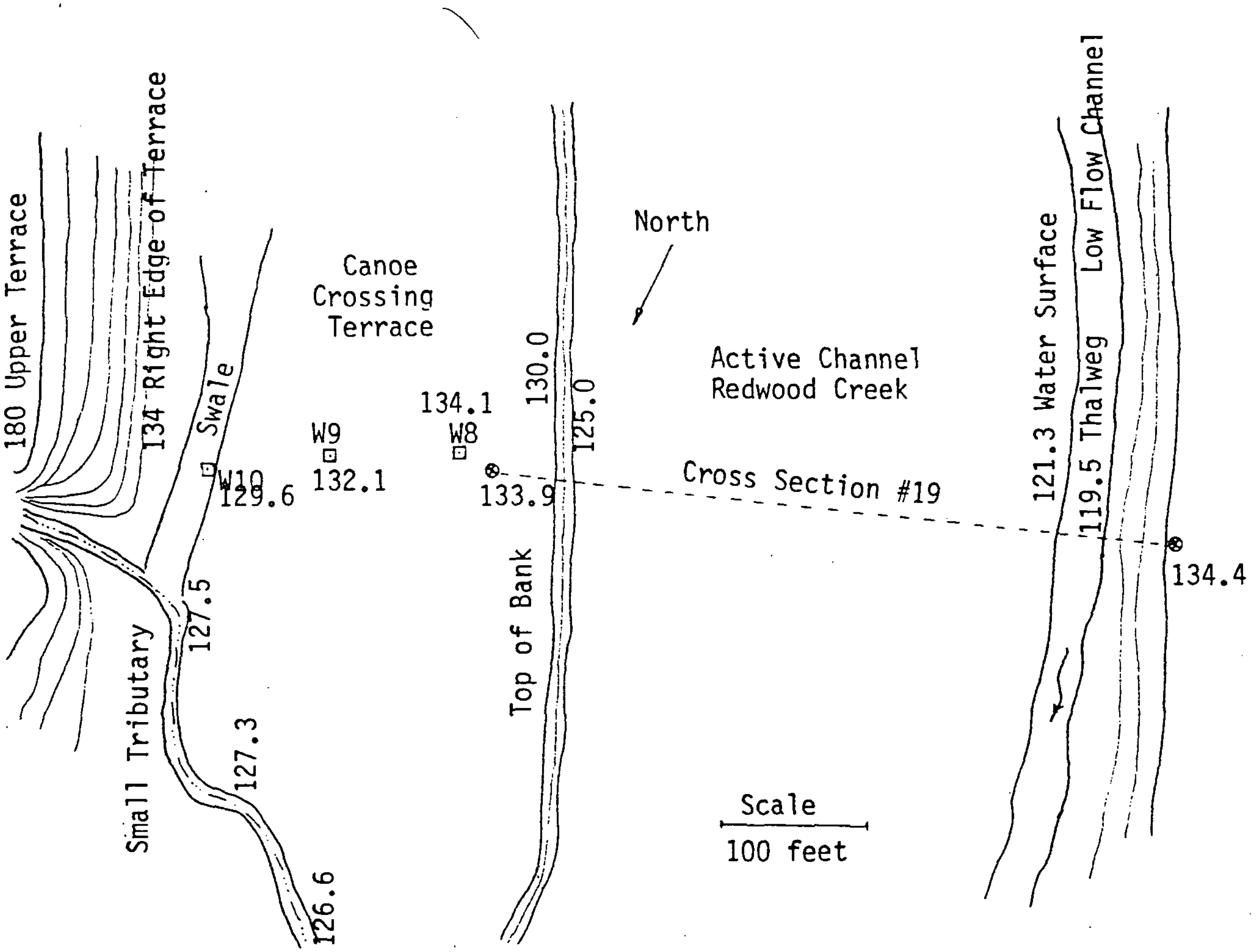


Figure 5. Plan view of Canoe Crossing study area. W8, W9, W10 refer to well locations. Selected features are referenced to elevation above mean sea level in feet. September 1982 survey.

response of each well with time. A stage duration curve is a cumulative frequency curve that shows the percent of time specified stages were equaled or exceeded during a given period. When groundwater stages are plotted according to frequency of occurrence, the resulting curve shows the integrated effect of the various factors that influence stage.

Time-Stage Computer Plot Program

A computer program was developed using a moving graphics display to depict on the computer screen the temporal changes in stage at three groundwater wells and two stream gages over a year or a single storm event (Figure 17). Editing features allow files up to 370 entries per well or per gage. Datum corrections or updating of any value are easily done. This program is especially useful in studying storm response of the aquifer and in gaining a quick intuitive feel for groundwater behavior (see Appendix C for listing, "GWPLOT4").

Flood Wave Response Model

In recent years, techniques to determine aquifer diffusivity: the ratio of transmissivity (T) to storage (S); for aquifers bounded by streams have been described by Pinder et al. (1969), Grubb and Zehner (1973), Kernodle (1978), and others.

Aquifer diffusivity is related to hydraulic conductivity by:

$$D = \frac{T}{S} = \frac{kb}{S}$$

where: b = thickness of the aquifer (length)

D = diffusivity (length^2/time)

k = hydraulic conductivity (length/time)

S = storage coefficient (dimensionless)

T = transmissivity (length^2/time)

By knowing the value of k and using Darcy's law (Fetter, 1980), the darcian velocity (or specific discharge) of groundwater, and hence the discharge (Q) in any given area can be determined (Figure 16).

Theoretical Development. The flood-wave response model used here approximates the well stage hydrograph by a series of incremental steps. The effect of a change in stream stage on the head in the aquifer adjacent to the stream may be found by solving the following set of equations (Pinder et al., 1969).

$$\frac{\partial^2 h}{\partial x^2} = \frac{S}{T} \frac{\partial h}{\partial t} \qquad (1)$$

$$h(0,t) = \begin{cases} 0 & \text{when} \quad t \leq 0 \\ \Delta H_m & \text{when} \quad t > 0 \end{cases} \qquad (1a)$$

$$\frac{\partial h\ (L,t)}{\partial x} = 0 \qquad (1b)$$

$$h\ (x,0) = 0 \qquad 0 \leq x \leq L \qquad (1c)$$

where: h = hydraulic head (length)

L = the distance from the stream to the impermeable boundary of the aquifer (length)

x = distance from the stream (length)

S = storage coefficient (dimensionless)

T = transmissivity (length^2/time)

t = time

Equation (1) arises from combining Darcy's Law with the Conservation of Mass equation:

Darcy's Law

$$V = -k\frac{\partial h}{\partial x} = -\frac{T}{b}\frac{\partial h}{\partial x} \qquad (2)$$

Conservation of Mass (water)

$$\frac{\partial V}{\partial x} = -\frac{S}{b}\frac{\partial h}{\partial t} \qquad (3)$$

Differentiating (2):

$$\frac{\partial V}{\partial x} = -\frac{T}{b}\frac{\partial^2 h}{\partial x^2} \qquad (4)$$

Combining (3) and (4):

$$\frac{\partial^2 h}{\partial x^2} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (1)$$

where: V = darcian velocity, or specific discharge (length /time)

k = hydraulic conductivity (length/time)

b = aquifer thickness (length)

The solution to the problem represented by eq. (1) may be obtained by using a finite step equivalent of Duhamel's formula which is used in the programs "DIFFUSE1" and "DIFFUSE3" to obtain theoretical groundwater-level-response curves (Grubb and Zehner, 1973):

$$hp = \sum_{m=1}^{p} \sum_{n=1}^{\infty} (-1)^{n-1} \left[\Delta H_m \ \mathrm{erfc}\ 0.5U \left(\frac{\frac{2n-1}{x/L} - 1}{\sqrt{p-m}} \right) + \mathrm{erfc}\ 0.5U \left(\frac{\frac{2n-1}{x/L} + 1}{\sqrt{p-m}} \right) \right]$$

where: $U = \frac{x}{\sqrt{(T/S)\ Wt}}$

L = distance from the river (or Well 1) to the impermeable boundary

x = distance from the point where the aquifer response is observed to the impermeable boundary

h_p = head at a distance (L-X) from the river (or Well 1) at time $\pm\ \rho\Delta t$

ΔH_m = instantaneous rise in stage at the beginning of the time increment $m\Delta t$ where m is an integer

T/S = diffusivity of the aquifer

erfc = complementary error function, which is approximated by:

$$\mathrm{erfc}\gamma = (a_1 b + a_2 b^2 + a_3 b^3)\ e^{-2} - \varepsilon \cdot \gamma$$

where: $b = \frac{1}{1+c\gamma}$, $| \varepsilon \cdot \gamma | \leq 2.5 \times 10^{-5}$

and: $c = 0.47047$ $a_2 = -0.0958798$

$a_1 = .3480242$ $a_3 = .7478556$

The flood-wave response technique used here was described by Pinder et al. (1969) and adapted to Wang BASIC computer language and programable calculators by Kernodle (1978). By varying the selection of diffusivity a series of type curves are generated from the head changes at a well adjacent to a stream. The trial value of diffusivity which generates a type curve that matches observed head changes at a well further from the stream is the theoretical aquifer diffusivity.

The computer program modification I developed uses a search routine that operates by comparing areas under two theoretically generated groundwater-level-response curves to the area under the observed groundwater curve. One trial diffusivity value will generate an area smaller than the observed area, the second will generate an area larger than the observed area. The value that generates an area closer to the observed area will be retained. The second value will be replaced by a new trial value.

If both trial values do not yield areas that bracket the observed area then the program increments the trial values until they do. The process then repeats until within ½ percent of the area being modeled or after 15 iterations. In the Kernodle program (1978), each trial value must be compared manually with the original data. My modification enables the computer to do that comparison. Occasionally the routine will fail due to the iteration limit. A rerun with new starting values can solve this problem. See Appendix B for program output and Appendix C for listing "DIFFUSE1".

Model Assumptions. Kernodle states:

> "The aquifer to be modeled is assumed to be bounded below and on one side by impermeable materials and on the opposite and parallel side by a stream which fully penetrates and is in complete hydraulic connection with the aquifer. Both the stream and the impermeable side are assumed to be infinite in length. The aquifer is also assumed to be isotropic, homogeneous, and of uniform saturated thickness.
>
> "The section line for the head response calculations must be constructed through the aquifer perpendicular to the stream and impermeable side. Head changes at a point along the line are calculated for steps in time as a result of changes in stage of the stream. For situations where the stream is not in full hydraulic connection with the aquifer, head changes at an observed point near the stream along the main section line may be used to replace stream stage changes in the model." (Kernodle, 1978)

These are standard assumptions made in such studies.

It has been demonstrated by Pinder et al. (1969) that satisfactory results can be obtained when non-ideal conditions exist for the flood-wave response model. In the study area the exact location of the impermeable boundary is not known. A provision is made in my program for incrementing the assumed boundary. The best type curves for selected boundary distances and values of diffusivity that generate reasonable fits to the observed data were then tested (see Figures 10 to

15). Boundary distances were selected based on the assumption that the impermeable valley wall is located somewhere between the back of the terrace (54 feet from Well 10) and, in terms of the model, an infinite distance (about 500 feet from Well 10).

RESULTS

Hydrograph analysis (Figures 6 and 7) and the time-stage program ("GWPLOT4", Appendix C) demonstrated that the level of Redwood Creek is the dominant factor controlling water table fluctuations in the Canoe Crossing study area. The time-stage program and well stage and stream hydrographs show that the wells respond quickly to a stream rise, indicating relatively high hydraulic conductivity. Well 10, farthest from the stream, has a relatively dampened response to a rise in Redwood Creek. Although hourly variations in the levels among the three wells are significant, especially during storm events, the mean daily values are nearly always close (within ± .3 feet) to the same elevation. Well data and direct investigation of the alluvial terrace suggests that the aquifer is not confined. Some vertical variation in hydraulic conductivity might be expected due to the bands of silty-clay layers. Stream cross section surveys at the site made since 1973 indicate that summertime water surface and thalweg have shown no large change or definite trend at this cross section (#19, in the study area) in nine years (Table 2) although the mid-channel bar has aggraded. Examination of Table 2 also reveals that during the summer, stream elevations can be higher than the groundwater table. This implies that Redwood Creek, at this particular reach, can be a losing stream; that is, it is losing surface flow to the groundwater.

Flood-Wave Response Model

A summary of the flood-wave response program results, including those plotted in Figures 10 through 15, are given in Table 3. Lower values for aquifer diffusivity were determined between Well 9 and Well 10 than between Well 8 and Well 9. Values between Well 8 and Well 10 were intermediate.

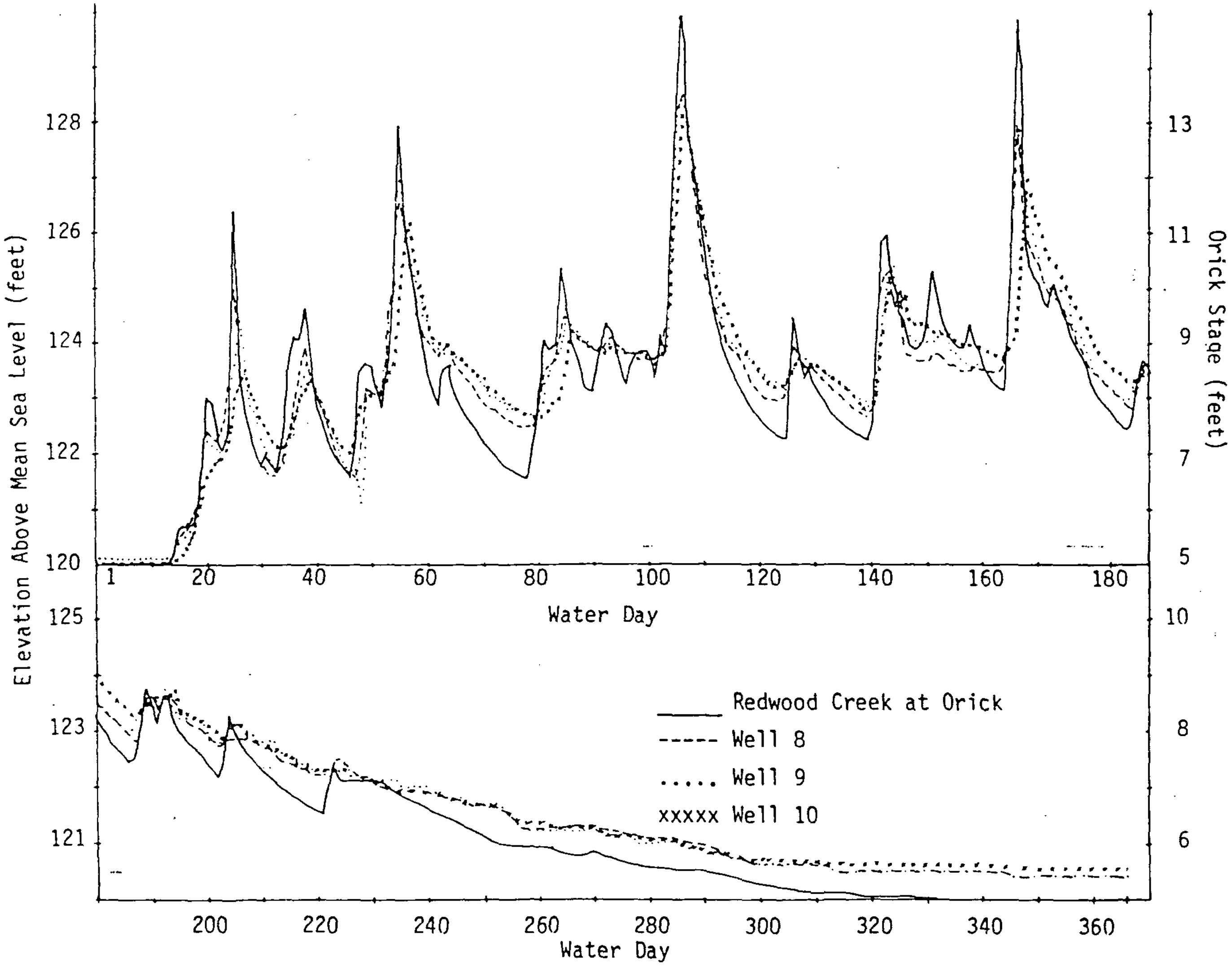


Figure 6. 1980 water year stage hydrographs of Redwood Creek gage at Orick and Canoe Crossing Wells.

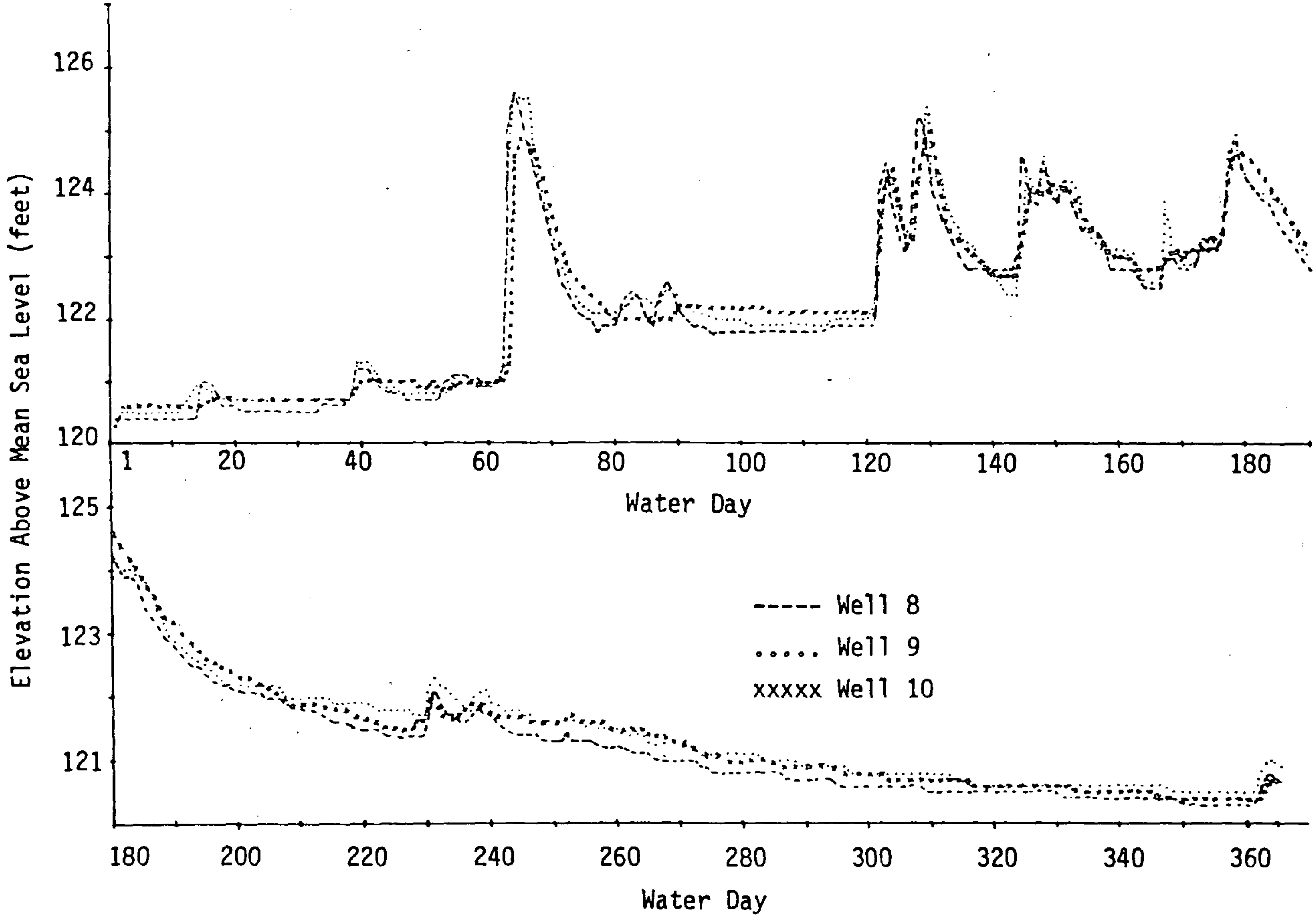


Figure 7. 1981 water year stage hydrographs of Canoe Crossing Wells.

Table 2. Selected elevations to mean sea level (MSL) of Canoe Crossing water surface and related features.

Date	Water Surface				Thalweg	Channel Bar	High-water Mark
	Creek	Well 8	Well 9	Well 10			
10/ 5/73	120.7				119.6	124.1	134.4
5/13/74	122.4				120.5	125.9	
7/ 3/75	120.6				119.5	125.4	
7/16/76	122.5				122.0	124.5	
11/24/76		121.60	121.54	121.62			
7/ 5/77		122.09	122.00	122.08			
7/29/77		121.89	121.82	121.87[a]			
8/ 9/77	122.4				122.0	124.5	
9/ 8/77		121.76	121.65	121.67[a]			
9/22/77	122.9				122.1	124.8	
2/10/78	125.7				122.0	126.0	131.8
4/18/78	122.77	123.17	121.03[b]	123.53			
5/31/78		122.73	122.79	122.51			
6/15/78	123.2				121.9	126.4	132.0
6/28/78	123.2				121.9	126.4	132.0
1/25/79		123.37	122.98	122.85			
2/ 9/79	123.2				120.1	126.1	130.1
3/22/79		122.68	123.01	122.89			
7/25/79	120.8	120.89			119.8	126.2	127.6
8/ 2/79			120.78	120.65			
6/12/80	121.7	121.36		121.28[a]	119.2	128.1	127.2
7/24/81	121.2	120.63	120.84	120.82[a]	119.3	128.2	
7/ 1/82	121.6				118.6	128.1	130.4
9/22/82	121.2	120.26	120.52	120.51[a]	119.62	126.85	

[a] -- Indicates dates when creek water surface was higher than water table.

[b] -- Questionable observation.

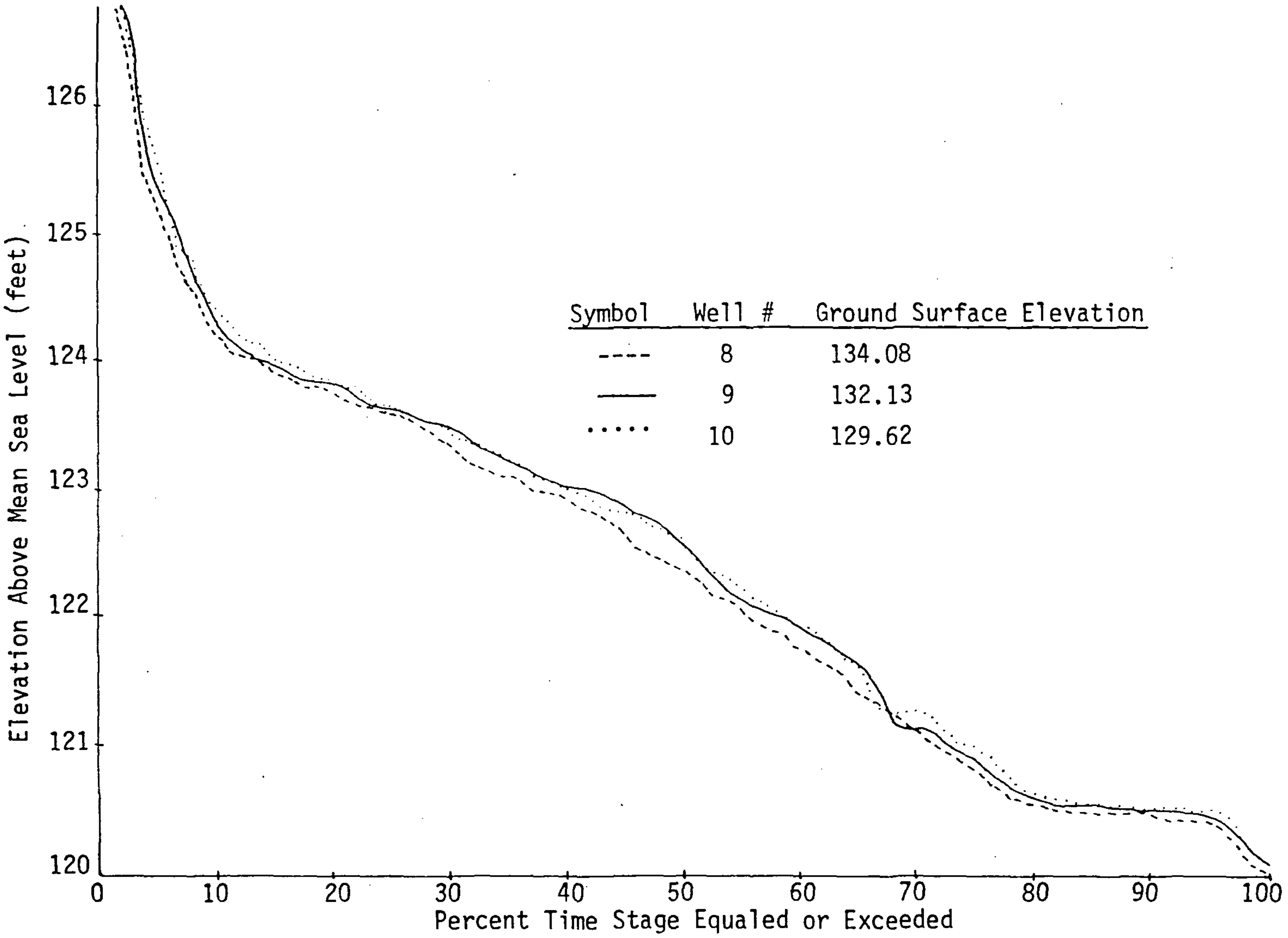


Figure 8. Stage-duration curves for Canoe Crossing wells, 1980 water year.

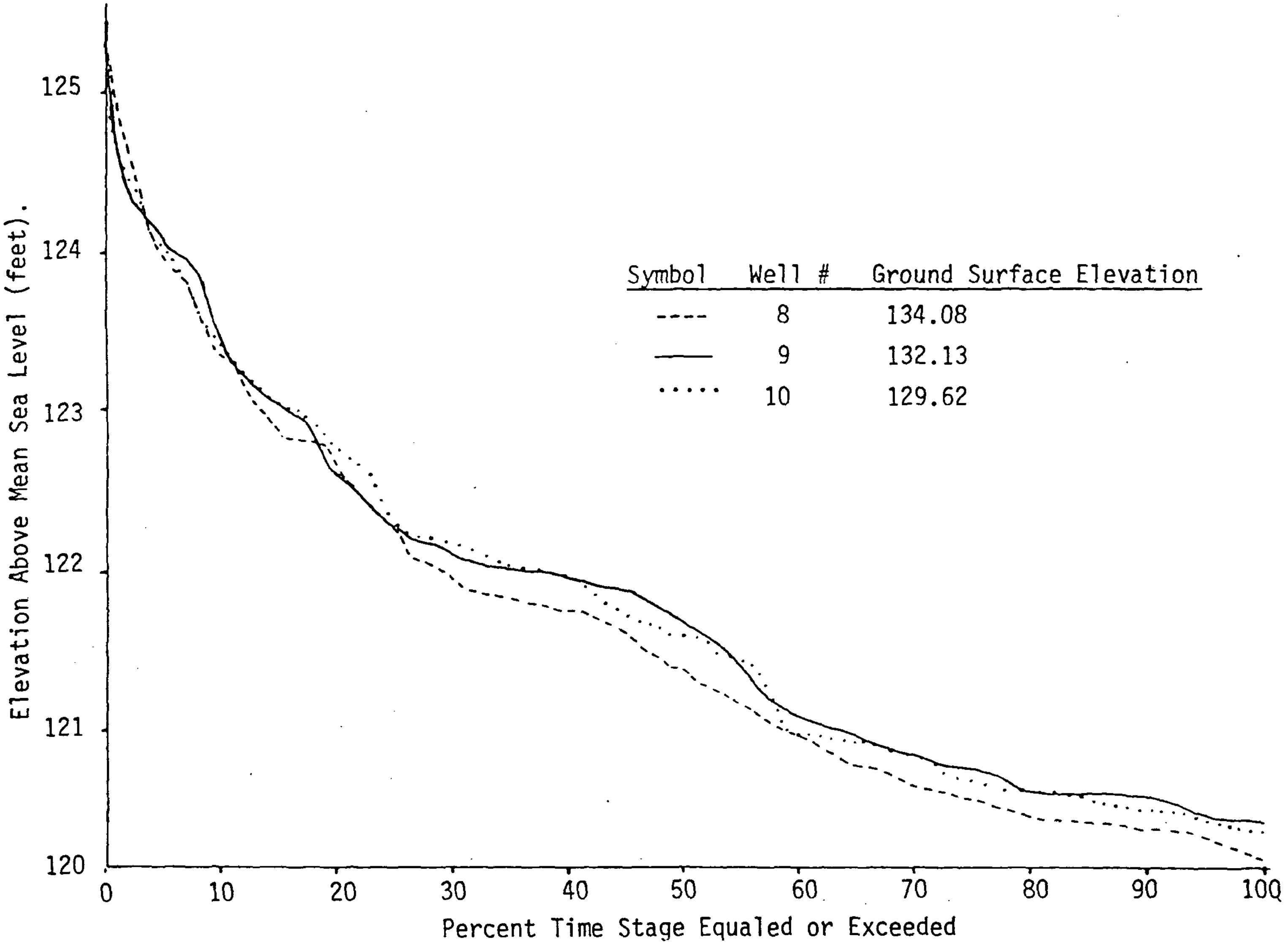


Figure 9. Stage-duration curves for Canoe Crossing wells, 1981 water year.

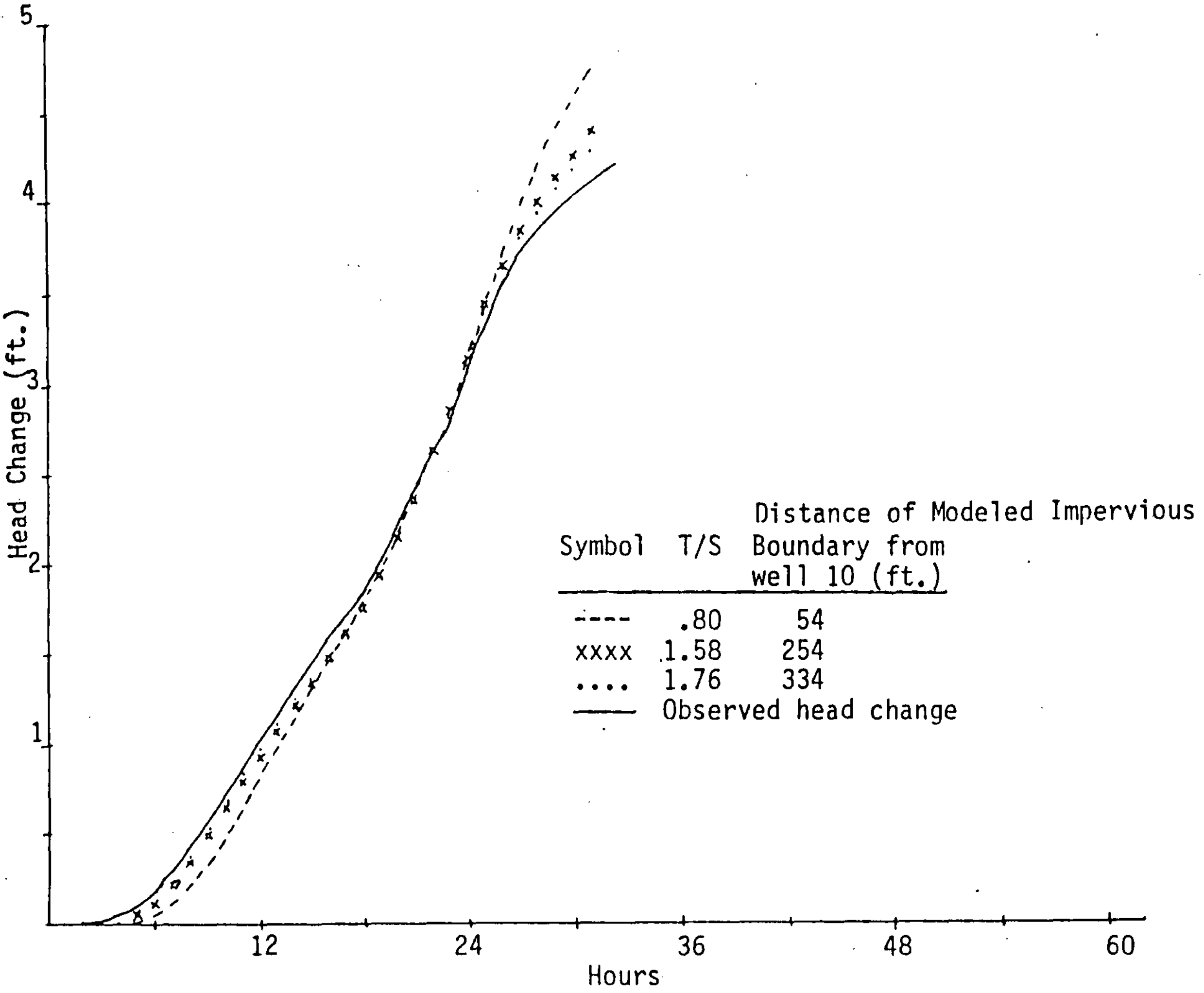


Figure 10. Observed head changes at well 10 and modeled head changes at well 10 from well 8 data using the flood wave response model. The values selected for T/S gave the best fit to the observed rise for the specified aquifer valley wall boundary. Jan. 10, 1979 rise.

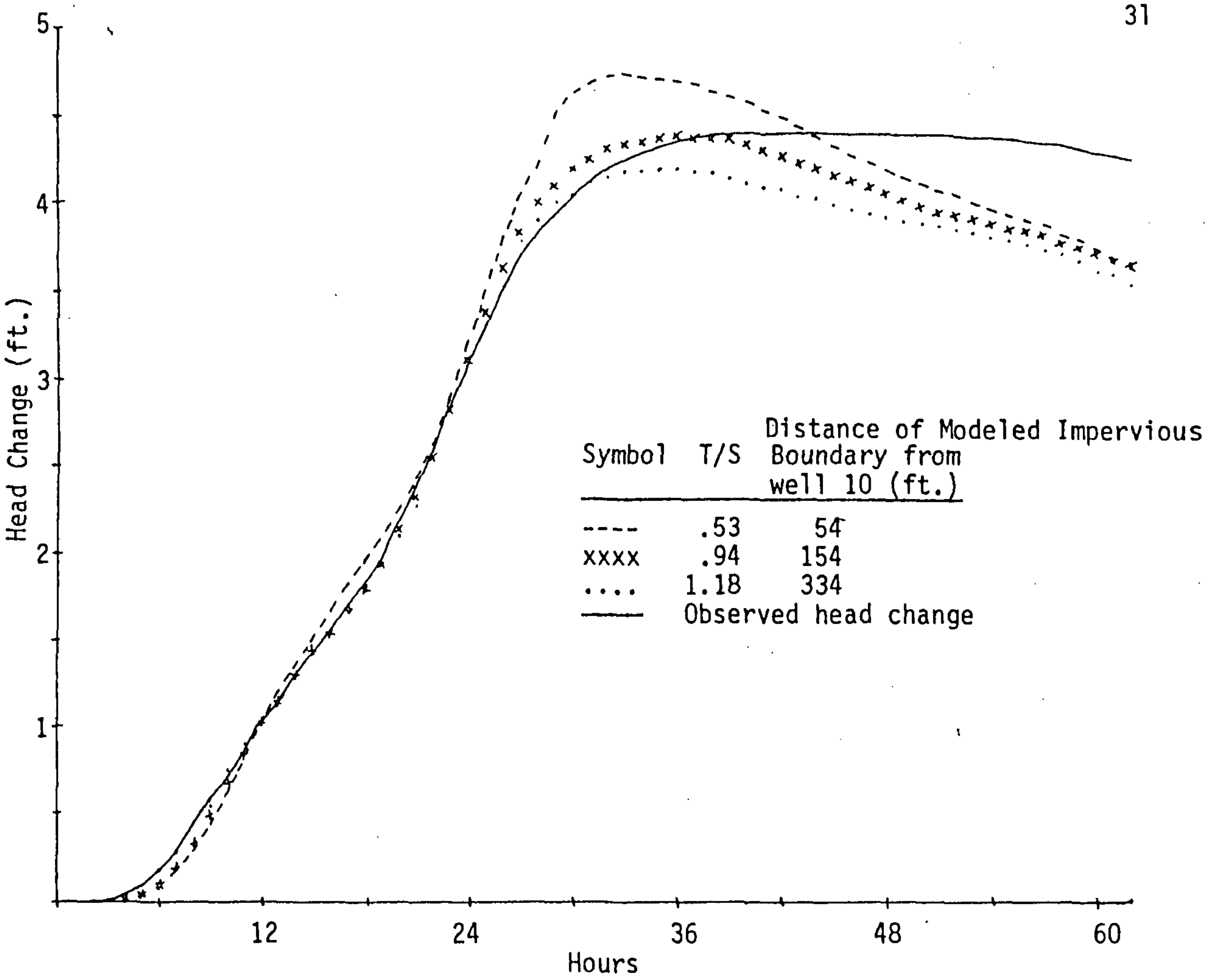


Figure 11. Observed head changes at well 10 and modeled head changes at well 10 from well 9 data using the flood response model. The values selected for T/S gave the best fit to the observed rise for the specified aquifer valley wall boundary. Jan. 10, 1979 rise.

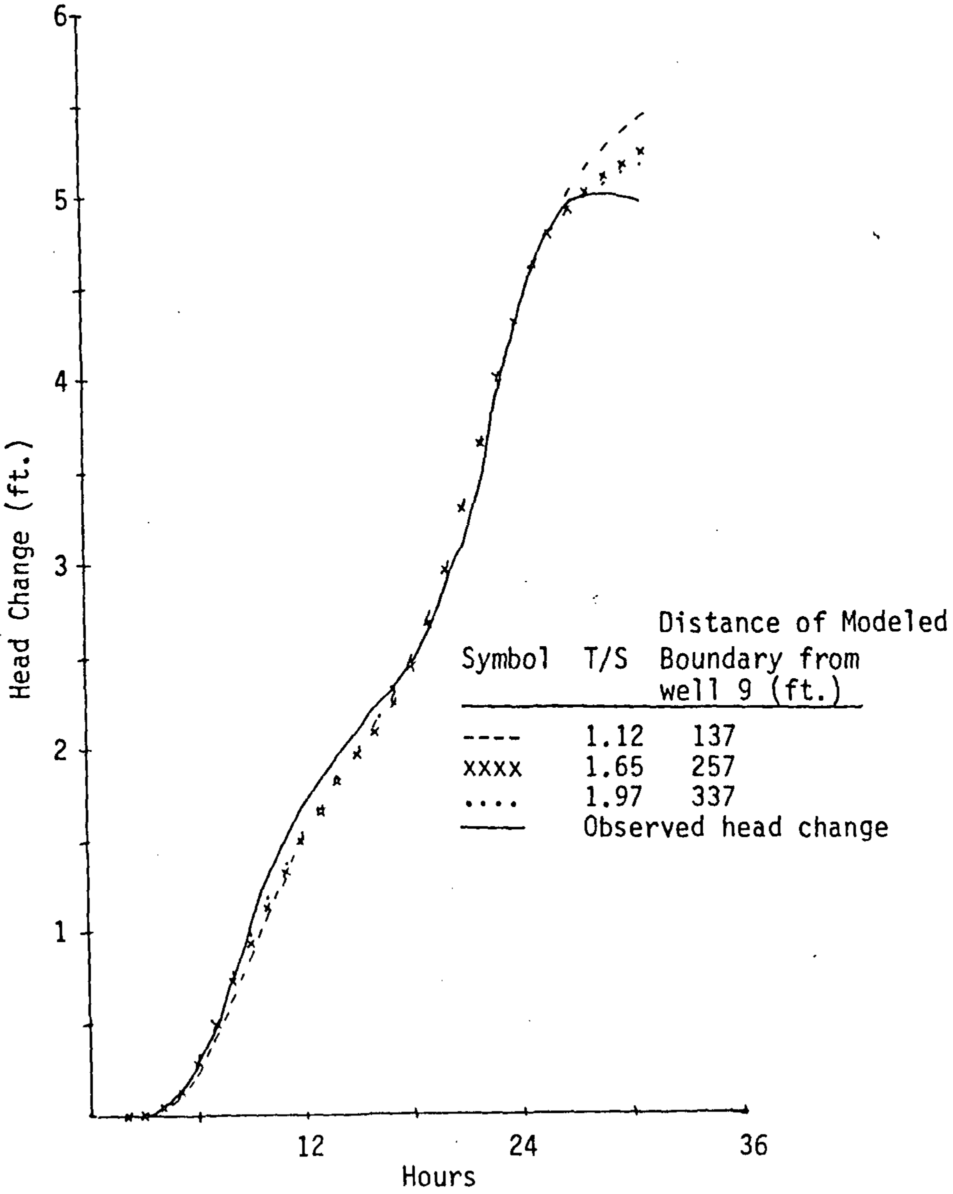


Figure 12. Observed head changes at well 9 and modeled head changes at well 9 from well 8 data using the flood response model. The values selected for T/S gave the best fit to the observed rise for the specified valley wall boundary. Jan. 10, 1979 rise.

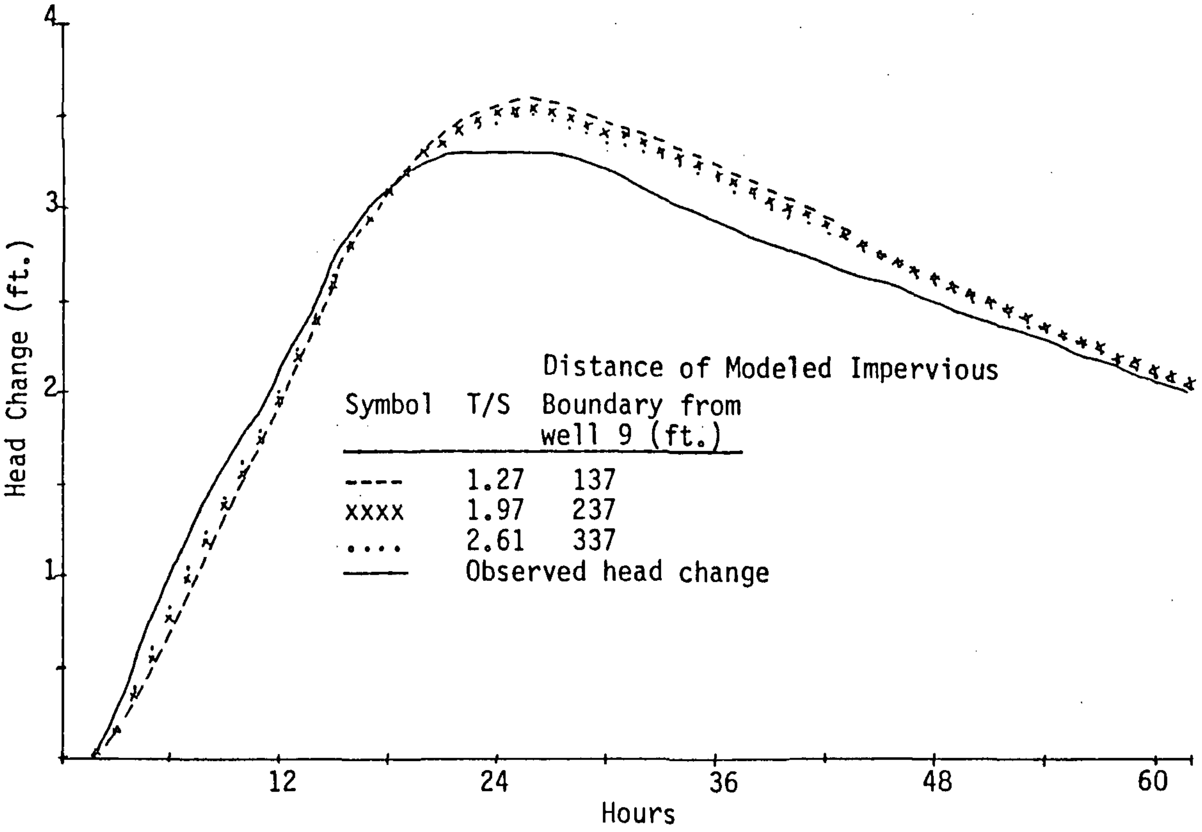


Figure 13. Observed head changes at well 9 and modeled head changes at well 9 from well 8 data using the flood response model. The values selected for T/S gave the best fit to the observed rise for the specified aquifer valley wall boundary. Feb. 13, 1979 rise.

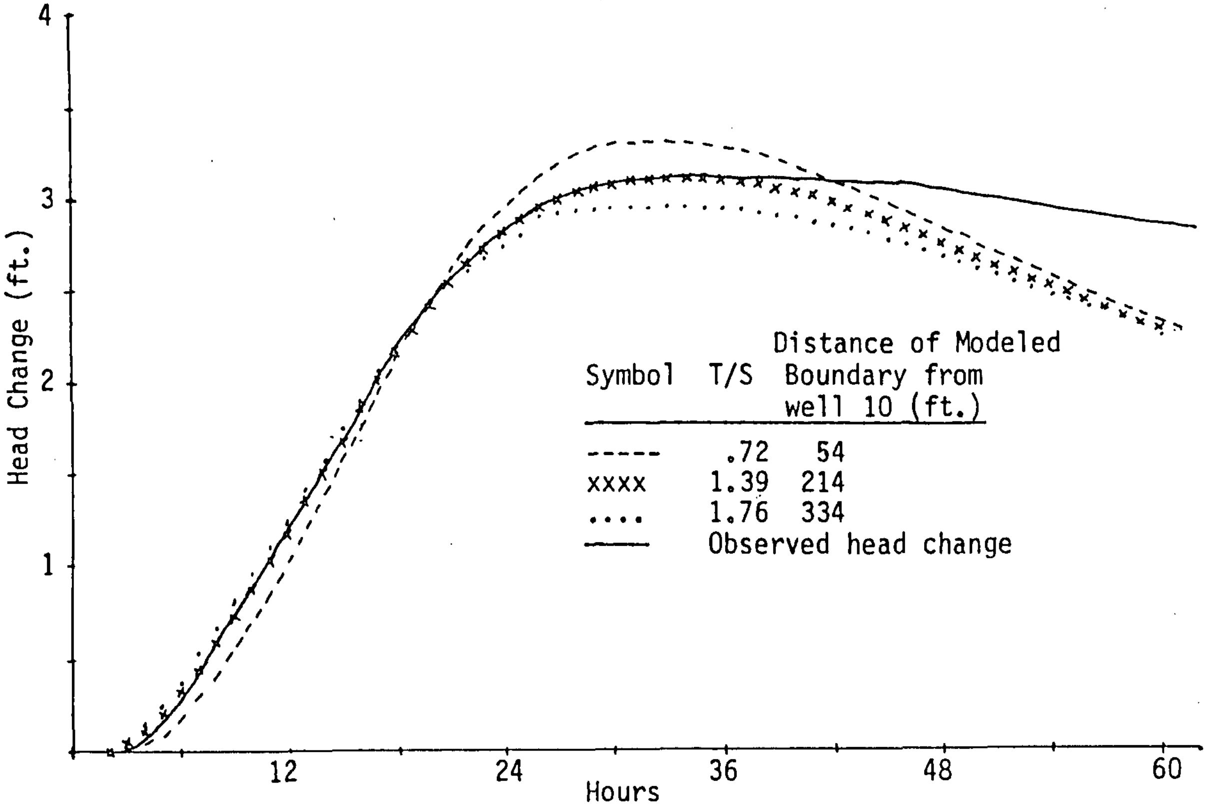


Figure 14. Observed head changes at well 10 and modeled head changes at well 10 from well 8 data using the flood wave response model. The values selected for T/S gave the best fit to the observed rise for the specified aquifer valley wall boundary. Feb. 13, 1979 rise.

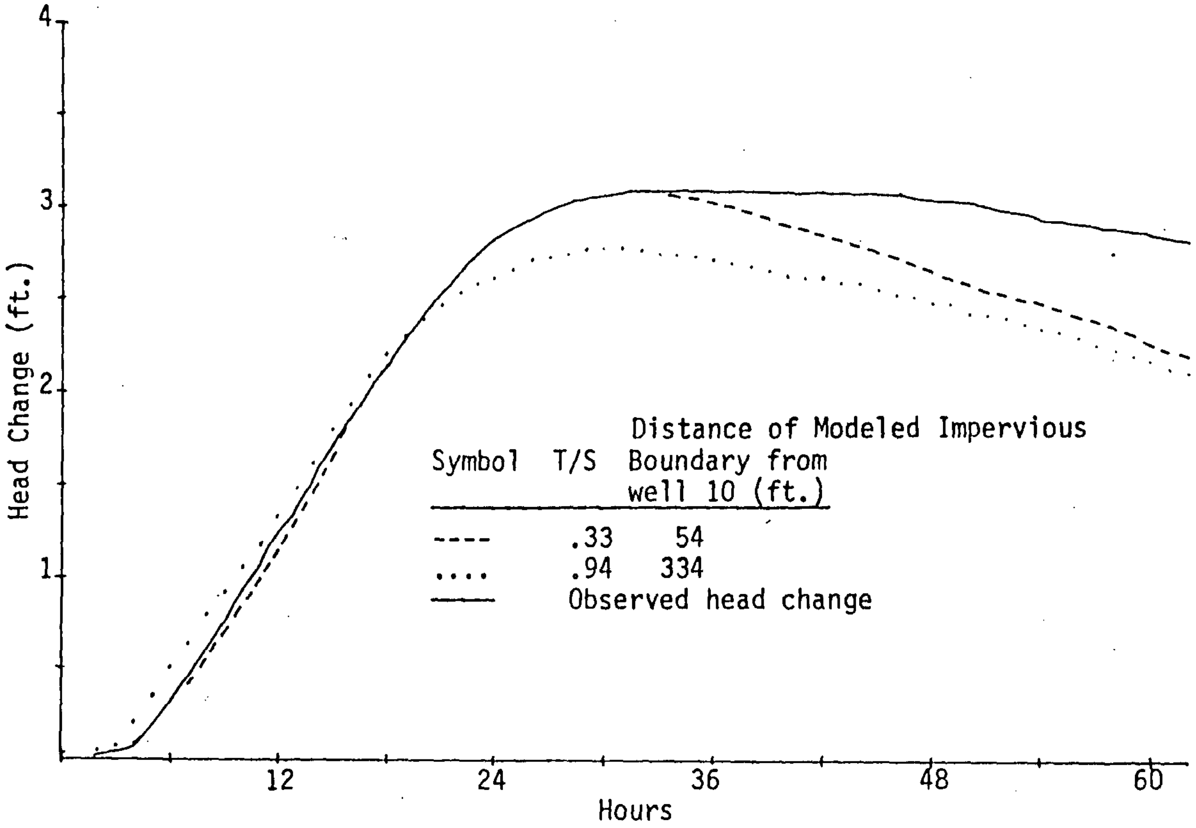


Figure 15. Observed head changes at well 10 and modeled head changes at well 10 from well 9 data using the flood wave response model. The values selected for T/S gave the best fit to the observed rise for the specified aquifer valley wall boundary. Feb. 13, 1979 rise.

Table 3. Summary of results from flood-wave response model. Number under "I" is well being modeled using observed data from well under "II". Tabulated data is theoretical T/S value arrived at for the specified aquifer boundary. The boundary distance is referenced from well 8.

I	II	I	II	I	II
10	from 9	10	from 8	9	from 8
T/S (ft^2/sec)	Boundary (feet)	T/S (ft^2/sec)	Boundary (feet)	T/S (ft^2/sec)	Boundary (feet)
.33	229	.72	229	1.12	229
.53	229	.80	229	1.27	229
.81	409	1.39	409	1.65	432
.94	369	1.58	429	1.97	512
.94	509	1.76	509	1.97	329
1.18	509	1.76	509	2.61	429
1.07	5000	2.06	5000	2.70	5000
1.37	5000	2.28	5000	4.80	5000
1.07	10000	2.28	10000	4.80	10000

DISCUSSION

Although the level of Redwood Creek is the dominant factor in controlling the groundwater elevation in the terrace, other lesser influences include surface water infiltration from rainfall and a small seasonal stream draining onto the back of the terrace and from groundwater movement from the hillslope adjacent to the terrace. The effect of these factors was seen in both the time-stage program and in the flood-wave response program. In the time-stage program (GWPLOT4); Well 10, furthest from the creek, is seen to lag at a higher level after the passage of a storm peak, when the other two wells have already receded considerably. Using the flood-wave response program (DIFFUSE1) it is possible to separate groundwater well hydrographs into two components: influence from the changes in the level of Redwood Creek and influence from all other sources. Well 10 is closest to the small tributary (Figure 3) and located in a swale that may hold water during winter storms. It is somewhat surprising that Well 10 does not exhibit greater influence from the small tributary and the swale. The bed of these features, derived from upland clays and silts, may be far less permeable than the underlying sand layers, thus affording a poor hydraulic connection.

To determine diffusivity with the flood-wave response model, the only test data used were the positive head changes in well elevation.

This was necessary because experience by Grubb and Zehner (1973) and my own results indicate that the model often breaks down in matching the observed recession at the well to be modeled. The model only shows the effects of changes in head that can be attributed to changes in stream stage. Initially the effect of a stream rise is felt faster and in much greater magnitude than other groundwater influences. After a peak, other influences can be seen on an hourly well stage hydrograph. After a value of diffusivity was obtained using 31 input points in the diffusivity search routine ("DIFFUSE1", Appendix C), 62 points were entered to cover the passage of a storm peak. The satisfactory match to observed data on the rise would frequently break down on the recession, especially at Well 10 (Figures 10-15). The departure of the observed recession from the theoretical recession can be explained by a complex of factors involving rainfall infiltration, tributary and surface seepage, and soil moisture movement, all contributing to keep the water level higher than if it were affected only by Redwood Creek.

The explanation for the initial steady increase in diffusivity (Table 3) as the assumed boundary distance is increased is that a faster rate of diffusion (higher diffusivity) would have to exist in order to match observed well data. During a rise, the groundwater backs up when it encounters the impermeable boundary, but at larger distances the calculated diffusivity value levels off as the aquifer assumes effectively infinite width and the backwater effect is lost.

It is worth considering whether individual well characteristics were influencing the observed well response. The installation technique of pounding in each well tube has the undesired effect of compacting the adjacent material. In turn, this compaction could influence the estimation of aquifer parameters by slowing response time in the wells. If this is indeed a factor, it is a coincidence that Well 10, which would be expected to lag because of the influence of the tributary hillslope and swale, is the one so affected.

The stage hydrographs and stage duration curves indicate that there is not a great variation in water-table elevation between the three wells. In a similar study of the alluvial aquifer of the Missouri River, Sharp and Granneman (1976) identified areas of continued high groundwater associated with recharge from adjacent valley walls. In the Canoe Crossing area, the tributary creek may intercept upper slope recharge and channel it away from the area of the wells. In this respect, groundwater influences may be different than normally encountered along Redwood Creek terraces.

Due to the backslope at the Canoe Crossing terrace (Figure 4), the distance from the ground surface to the water table generally decreases away from Redwood Creek until the valley slope is encountered. This feature of the terrace, being higher nearer the creek, was also found in the Tall Trees Grove. The problems associated with an elevated water table may therefore be encountered further from the stream than anticipated.

Insights into the formation of the terrace have been gained during this investigation. Overbank flooding tends to deposit coarser material with greater frequency near the outer margin of the terrace.

This can explain the back slope of the terrace but may also offer an explanation for the results of the diffusivity model. If finer sediments are laid down further from the creek, due to decreased velocity away from the main channel, then associated aquifer parameters should indicate finer material.

The calculated aquifer diffusivity was noticeably less between Well 9 and 10 (further from the creek) than between Well 8 and 9 (closer to the creek). Recall, diffusivity is kb/S, where b = aquifer thickness. If the alluvial material is tapering toward the valley wall then diffusivity would also decrease. The terms k and S both generally vary directly with changing diffusivity; however, k can vary over many orders of magnitude, whereas S will range from about .03 for clays to .37 for medium sand (Dunne and Leopold, 1978). Therefore, a decrease in hydraulic conductivity (k), due to finer material, may also account for the observed diffusivity decrease away from the creek.

Supporting this idea, U.S.G.S. technician J. Duls noted during well installation that bedrock was not encountered at 20 feet, the approximate depth to which the wells penetrate the terrace. He suggested that the wells are all set in the same material; however, weathered colluvium that may underlie the terrace may have not offered greater resistance to the hoist pounding unit than the terrace sands.

Although the depth to bedrock at the study area is not known, Emerald Creek Well 12, located approximately ¼ mile away, was set to bedrock with only 12 feet of pipe. This well is set much lower and closer to the stream. In relative terms, its well point is six to 10 feet closer to the creek thalweg than are Wells 8, 9, or 10.

Application of Findings

A practical use of the flood-wave response model results is given in the following sample calculation of discharge (Q) from a selected cross-section area parallel to the creek. The gradient, or direction of greatest slope, and therefore greatest discharge, was not determined because the wells were aligned in a linear fashion. For the example date chosen (May 20, 1981), the gradient is probably oriented in a downstream direction.

Sample Calculation

From Table 3, a reasonable selection of T/S between Well 8 and Well 9 is 1.97 $\text{feet}^2/\text{second}$. To determine k, a reasonable estimate of S and b must be determined. From five well logs, for a comparable terrace adjacent to the Eel River, Evenson (1959) arrived at .21 as a value for S. A reasonable estimate for b_1 is 20 feet of saturated thickness. Refer to Figure 16B to calculate the discharge (Q) through area $b_1 \times b_2$.

Say: $D = 1.97\ \text{ft}^2/\text{sec}$
$S = .21$
$b_1 = 20\ \text{ft},\ b_2 = 20\ \text{ft}$

Solving for k using equations (4) and (5):
$k = 2.1 \times 10^{-2}\ \text{ft/sec}$

Selecting data from May 20, 1981:

h_2 = 121.89 ft (Well 8)
h_1 = 122.17 ft (Well 9)
L = 92 ft

Solving equation (1) and (2):

$V = 6.4 \times 10^{-5}$ ft/sec
= 5.5 ft/day

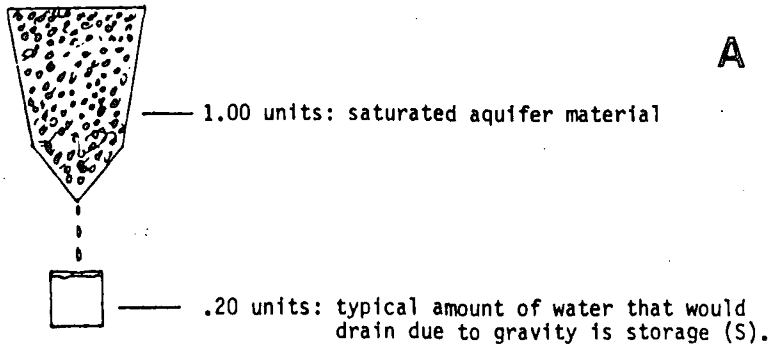
$A = 400$ ft^2

Solving equation (3):

Discharge (Q) = 2,200 ft^3/day

Stage hydrographs (Figures 6 and 7) should be of utility in determining the role of groundwater in redwood tree ecology. The consecutive days above yet-to-be-determined critical stages may be a significant factor in explaining redwood tree mortality and reduction in health of surviving trees in the streamside groves. A convenient method may be to lay a straight edge down on the hydrograph at a stage that coincides with the active rooting zone of the redwood trees. Using the stage hydrographs and knowing the ground surface elevation (listed in Figures 8 and 9), the total days of the year that the water table was within "x" feet of the ground surface, and how many days (even the exact dates) this occurred for one or two of the longest continuous periods can easily be determined. In this way, one could determine if there are long continuous periods of saturation of the rooting zone.

A note of caution with the hydrographs: the 1980 water year was a fairly average runoff year, but 1981 was decidedly below average. The problems of an elevated water table may only be critical and more



1) Darcian Velocity $(V) = -K \cdot \frac{h_2 - h_1}{L}$

2) Area $(A) = b_1 \cdot b_2$

3) Discharge $(Q) = V \cdot A$

4) Transmissivity $(T) = K \cdot b_1$

5) Diffusivity $(D) = T/S$

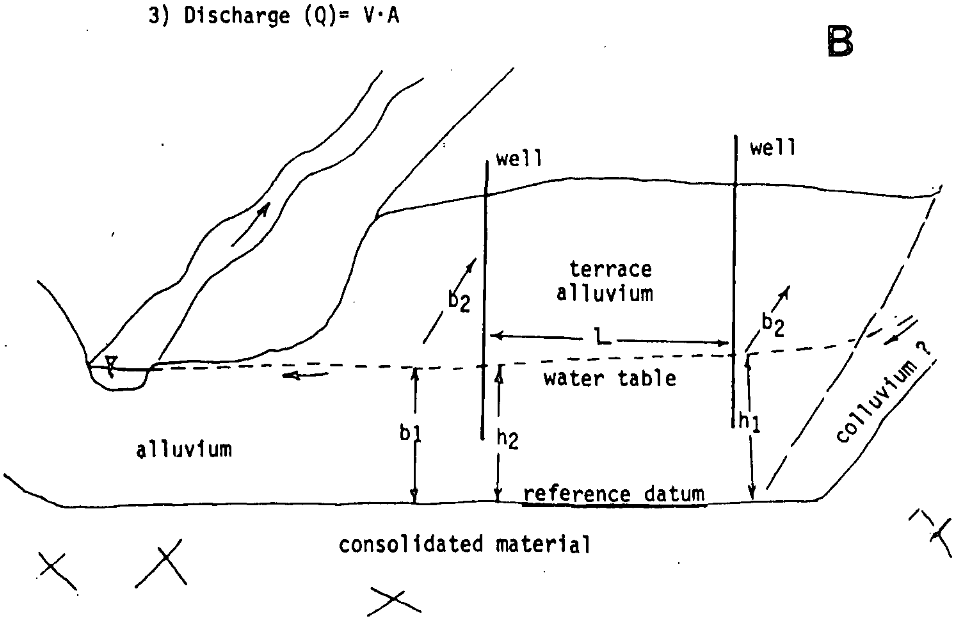


Figure 16. Relevant groundwater concepts. (A) Illustration of storage concept. (B) Related equations and generalized cut-away view of Redwood Creek at low flow show how to calculate discharge (Q) when K, b_1, S, h_1, h_2, & l are known. Eq. 1) is Darcy's law. K is hydraulic conductivity.

pronounced in a wet year such as 1982 or 1983. At the present time the 1982 and 1983 data are unavailable for this analysis.

Stage duration curves were constructed only for 1980 and 1981 water years because only those years had a nearly complete record. The 1980 stage duration curve may approximate the long-term average because it was a nearly average runoff year.

The stage-time program (GWPLOT4) proved useful in gaining an intuitive feel for the timing of changes in the groundwater and stream stages. This program might prove valuable in organizing manpower to sample or measure a network of gages, such as in the Redwood Creek basin. The routing of storm flow and the timing and magnitude of stage changes are clearly demonstrated. The entire software package developed for this study was written in an interactive way, and should prove useful for future investigations of this type.

SPECIFIC RECOMMENDATIONS FOR CONTINUING GROUNDWATER STUDIES ALONG REDWOOD CREEK

Long-term monitoring of groundwater levels will be necessary to determine trends or rapid changes in the groundwater conditions at the Canoe Crossing and other nearby sites. However, the number of digital recorders could be reduced and still provide an accurate record due to the similar response of the wells. I would suggest upgrading the shelter of the remaining wells to make them more waterproof, and if possible, protected from falling debris. Three of the 13 recording wells have been hit in the last two years by falling trees or tree branches, damaging one and completely destroying the equipment at the other two. Well 8 is the preferred choice to continue with digital recorder at Canoe Crossing. Using the results of the flood-wave response program or regression equations, the other two wells' response could accurately be estimated. Periodic measurements of Well 9 and Well 10 would help refine estimates. Evaluation of the Tall Trees Grove and Emerald Creek wells using the techniques developed here should be undertaken soon. The amount of data available is becoming unwieldly, even with computer storage. After initial evaluation, other wells could be eliminated. However, drilling an additional two wells at the Tall Trees Grove near the back of the terrace is recommended because existing wells are located near the stream bank making it difficult to determine groundwater conditions at a greater distance from the creek. Drilling of the well holes is recommended over pounding due to possible compaction problems already discussed. Also, a thorough analysis of materials encountered at various depths when the new wells are installed would improve understanding of terrace composition.

With an understanding of surface water and groundwater stage duration, it is possible to investigate the role of groundwater levels and seasonal rooting zone habitat requirement for the trees composing the outstanding riparian groves along Redwood Creek. It may also be possible to predict the effects of additional streambed aggradation on alluvial groundwater levels and upon the trees in the streamside groves.

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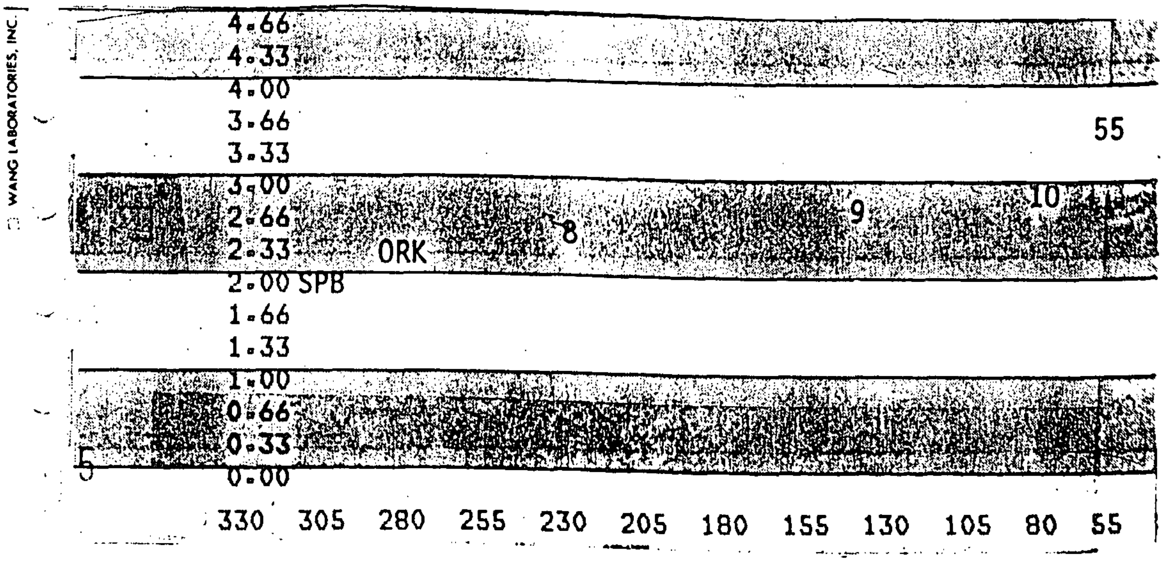
APPENDIX A, Figure 17. Sample output of "GWPLOT4".



Example of display on computer screen of the time-stage plot program "GWPLOT4". The x-axis refers to the relative distance from the start of the valley wall slope. The y-axis is the stage in feet and is adjustable to any range in stage. SPB and ORK refer to Redwood Creek gages at South Park Boundary and Orick respectively. The number in the upper right is a time counter in either hours or days.

APPENDIX B: Sample output from flood-wave response program "DIFFUSE1"

```
  X         T/S                    REL.AREA DIFF.
  ft       sqft/s                    TO   71.5
===================================================
 137        1.59                      74.01
 157        1.46                      71.85
 177        1.99                      65.43 a
 197        1.65                      71.17
 217        1.81                      71.41
 237        1.98                      71.62
 257        2.15                      71.82
 277        2.19                      71.38
 297        2.32                      71.39
 317        2.49                      71.61
 337        2.66                      71.80
 357        2.66                      71.39
 377        2.83                      71.60
 397        2.83                      71.24
 417        2.91                      71.18
 437        2.99                      71.12
 457        2.99                      70.84

NUMBER OF TIME STEPS:   31
LENGTH OF TIME INTERVAL: 1
INITIAL CHOICES FOR T/S: 3  , .3
FILE NAME OF FIRST WELL :W879
FILE NAME OF SECOND WELL:W979
```

[a] See text for explanation, page 21.

APPENDIX C. Program "START", used to display on computer screen additional programs stored on the disk.

```
10 REM **PROGRAM START**
20 REM  USED TO BRING UP MENU OF ADDITIONAL PROGRAMS ON DISK
30 SELECT PRINT 7005(63)
40 PRINT HEX(03)
50 PRINT "FN-0 MENU SELECTION"
60 PRINT "FN-1 PROGRAM DATA LOAD--TO INPUT DATA INTO FILES"
70 PRINT "FN-3 PROGRAM DIFFUSE1--TO ITERATIVELY FIGURE T/S"
80 PRINT "FN-4 PROGRAM DIFFUSE3--TO FIGURE T/S BY TRIAL AND ERRO
R"
90 PRINT "FN-5 FIXIT PROGRAM TO UPDATE DATA FILE"
100 PRINT "FN-6 PLOTS STAGE CHANGES AT GW WELLS AND GAGES"
110 PRINT "FN-7 SORT PROGRAM--USED TO RANK DATA LARGEST TO SMALL
EST"
120 INPUT "COMMAND",R$
130 IF R$<>" "THEN PRINT "        USE SF KEYS PINHEAD"
140 GOTO 120
150 DEFFN'0: LOAD RUN
160 DEFFN'1: LOAD F"DATALOAD"
170 DEFFN'2: LOAD F"GWPLOT1"
180 DEFFN'3: LOAD F"DIFFUSE1"
190 DEFFN'4: LOAD F"DIFFUSE3"
200 DEFFN'5: LOAD F"FIXIT"
210 DEFFN'6: LOAD F"GWPLOT4L"
220 DEFFN'7: LOAD F"SORT"
230 END
```

APPENDIX C. Programs "DATAMOD" and "DATALOAD", used to enter data by keypunching which are then stored on the disk.

```
10 REM **PROGRAM DATA LOAD**
20 REM PROGRAM TO ENTER STAGE DATA INTO A FILE ON THIS DISK
30 PRINT HEX(03)
40 PRINT "  "
50 PRINT "  "
60 PRINT "REMEMBER, DATA CAN BE CORRECTED IN THE FIXIT PROGRAM,S
EE MENU"
70 COM X
75 PRINT : PRINT
80 INPUT "WHAT IS THE SIZE OF THE DATA SET",X
90 LOAD F"DATAMOD"
100 END
```

```
10 REM PROGRAM DATAMOD
20 REM GENERAL PROGRAM FOR ENTERING NUMERIC DATA INTO A SINGLE
30 REM ARRAY OF DIMENSION YOU CHOOSE IN PROGRAM DATALOAD
40 DIM D(X): M=0
50 FOR I=1 TO X: D(I)=0: NEXT I
60 INPUT "WHAT DAY # DO YOU WANT TO START AT",M
70 FOR I=M TO X
80 PRINT "ENTER";I;")";: INPUT D(I)
90 M=M+1
100 IF M=X THEN GOTO 120
110 NEXT I
120 PRINT "YOU ARE THROUGH WITH DATA ENTRY"
130 INPUT "WHAT WILL BE THE NAME OF THIS DATA FILE",A$
140 DATA SAVE DC OPEN F 16,A$
150 DATA SAVE DC D()
160 DATA SAVE DC END
170 DATA SAVE DC CLOSE
180 INPUT "DO YOU WANT TO ENTER ANOTHER DATA SET",Y$
190 IF Y$="Y" OR Y$="YES" THEN LOAD F"DATALOAD"
200 END
```

APPENDIX C. Programs "GWPLOT4L" and "GWPLOT4", used to plot on the computer screen changes in water surface elevation.

```
10 REM PROGRAM GWPLOT4L
20 REM USED TO LOAD GWPLOT4 WITH STAGE AT GAGES
30 COM X
40 PRINT HEX(03)
50 PRINT "  "
60 PRINT "  "
70 PRINT "THIS PROGRAM WILL LOAD THEN PLOT ON CRT OR ON PAPER"
80 PRINT "THE STAGE CHANGES IN GW OR SW DATA SETS STORED ON"
90 PRINT "THIS SAME DISK, DATA MAY BE ENTERED ON THE DATA"
100 PRINT "ENTRY PROGRAM--SEE MENU": PRINT
110 INPUT "WHAT ARE THE NUMBER OF POINTS IN EACH DATA SET, THEY
MUST BE THE SAME SIZE",X
120 LOAD DC F"GWPLOT4"
130 END
```

```
10 REM PROGRAM GWPLOT4 PLOTS GW WELL AND GAGE STAGES
20 COM A1,B1,C1
30 COM X
40 DIM A(X),B(X),C(X),D(X),E(X)
50 FOR I=1 TO X
60 A(X)=2: B(X)=2: C(X)=2: D(X)=6: E(X)=6
70 NEXT I
80 INPUT "WHAT IS FNAME OF 1ST DATA SET",A$
90 INPUT "WHAT IS FNAME OF 2ND DATA SET",B$
100 INPUT "WHAT IS FNAME OF 3RD DATA SET",C$
110 INPUT "WHAT IS FNAME OF UPSTREAM GAGE DATA,IF NONE, ENTER NO
NE",D$
120 INPUT "WHAT IS FNAME OF DOWN STREAM GAGE DATA,IF NONE ENTER
NONE ",E$
130 DATA LOAD DC OPEN F A$: DATA LOAD DC A()
140 DATA LOAD DC OPEN F B$ : DATA LOAD DC B()
150 DATA LOAD DC OPEN F C$ : DATA LOAD DC C()
160 IF D$="NONE" OR E$="NONE" THEN 190
170 DATA LOAD DC OPEN F D$: DATA LOAD DC D()
180 DATA LOAD DC OPEN F E$: DATA LOAD DC E()
190 INPUT "DO YOU WANT OUTPUT ON THE PRINTER",Y$
200 IF  Y$="Y" THEN 620
210 INPUT "DO YOU WANT A PRINT OF THE DATA",Y3$
220 IF Y3$="Y" THEN 820
230 PRINT HEX(03): PRINT
240 PRINT "NOTE,YOU CAN ADJUST THE SENSITIVITY OF THE PLOT BY AL
TERING THE";
250 PRINT "RANGE IN STAGE DURING PROGRAM EXECUTION -- KEY IN:"
```

APPENDIX C. Program "GWPLOT4" continued.

```
260 PRINT "HALT/STEP--RETURN-- H1= selected range --RETURN"
270 PRINT "--WHERE selected range DETERMINES THE SENSITIVITY YOU
 WANT"
280 PRINT
290 INPUT "WHAT IS THE RANGE IN STAGE",H1
300 INPUT "IS THIS A PEAK PLOT (Y) OR A LONG TERM PLOT (N)",Y9$
310 IF Y9$="N"THEN 320: GOTO 330
320 A(1)=119: B(1)=119: C(1)=119
330 H2=15/H1
340 PRINT HEX(03)
350 FOR I=1TO X
360 PRINT HEX(03)
370 H3=-H1/15
380 FOR J=H1 TO 0 STEP H3
390 PRINTUSING 400,J
400 %##.##
410 NEXT J
420 FOR J=33.0 TO 4.5 STEP -2.5
430 PRINT 10*J;
440 NEXT J
450 SELECT P4
460 A1=INT(16-H2*(A(I)-A(1)))+1: B1=INT(16-H2*(B(I)-B(1)))+1: C1
=INT(16-H2*(C(I)-C(1)))+1: D1=INT(16-H2*(D(I)-D(1)))+1 : E1=INT(
16-H2*(E(I)-E(1)))+1
470 IF A1<=0THEN A1=1: IF B1<=0THEN B1=1: IF C1<=0THEN C1=1: IF
D1<=0THEN D1=1: IF E1<=0THEN E1=1
480 IF A1>=16THEN A1=15: IF B1>=15THEN B1=14: IF C1>=15THEN C1=1
4: IF D1>=15THEN D1=15: IF E1>=16THEN E1=15
490 PRINT AT(D1,6);"SPB";AT(E1,10);"ORK";AT(A1,21);8;AT(B1,40);9
;AT(C1,55);10;AT(3,58);I
500 SELECT P0
510 NEXT I
520 PRINT "                    PROGRAM OVER"
530 INPUT "        DO YOU WANT TO RETURN TO MENU SELECTION",Y$
540 IF Y$="Y"THEN LOAD F"START"
550 PRINT HEX(03)
560 INPUT "DO YOU WANT TO RUN IT AGAIN",J1$
570 IF J1$="Y" THEN 230
580 INPUT "DO YOU WANT A HYDROGRAPH PRINTOUT",Y1$
590 IF Y1$="N" THEN 1010
600 REM -----------------------------------------------
610 REM OUTPUT TO PRINTER
620 INPUT "WHAT FILE DO YOU WANT TO PLOT",C$
630 IF C$="W881"THEN GOTO 640: IF C$="W981"THEN GOTO 650: IF C$=
"W1081"THEN GOTO 660
640 FOR I=1 TO X: A(I)=(A(I)-118)*10: NEXT I
650 FOR I=1 TO X: B(I)=(B(I)-118)*10: NEXT I
660 FOR I=1 TO X: C(I)=(C(I)-118)*10: NEXT I
670 SELECT PRINT 215(121)
680 I1=0: J1=118
690 FOR I=1 TO X
```

APPENDIX C. Program "GWPLOT4" continued.

```
700 IF C$="W981"THEN A(I)=B(I): IF C$="W1081"THEN A(I)=C(I)
710 IF I=1 THEN GOSUB 920: IF I=32 THEN GOSUB 920
720 IF I=62 THEN GOSUB 920: IF I=93 THEN GOSUB 920
730 IF I=124 THEN GOSUB 920: IF I=152 THEN GOSUB 920
740 IF I=183 THEN GOSUB 920: IF I=213 THEN GOSUB 920
750 IF I=244 THEN GOSUB 920: IF I=274 THEN GOSUB 920
760 IF I=305 THEN GOSUB 920: IF I=336 THEN GOSUB 920
770 I1=I
780 PRINT I;TAB(A(I));"*"
790 NEXT I
800 SELECT PRINT 005
810 END
820 SELECT PRINT 215(100)
830 REM ---------------------------------------------
840 REM THE FOLLOWING PRINTS DATA FROM THE FILES
850 PRINT D,8,9,10: PRINT "    "
860 FOR I=1 TO 365
870 PRINT I,A(I),B(I),C(I)
880 NEXT I
890 GOTO 1010
900 REM
910 REM ----------------------------------------------------
920 FOR J=118 TO 130 STEP .1: REM SUBROUTINE TO PLOT AXIS
930 IF J<>J1+.5 THEN 970
940 J1=J
950 PRINT "+";: J1=J
960 GOTO 980
970 PRINT "-";
980 NEXT J
990 J1=118
1000 RETURN
1010 END
```

APPENDIX C. Program "DIFFUSE3", used to determine aquifer diffusivity by trial and error.

```
10 REM PROGRAM DIFFUSE3 TO DETERMINE T/S
20 COM X,L,U,A1,A2,A3,D9
30 COM E
40 COM H(62),H9(62),H8(62)
50 COM S,P,B,R$64,R2$64
60 READ A0,A1,A2,A3
70 DATA .4707,.3480242,-.0958798,.7478556
80 INIT(09)R$: INIT(20)R2$: SELECT #2310
90 DEFFN'12: P=C
100 PRINT HEX(03);"LINEAR-GROUNDWATER MODEL (SF '12)": PRINT
110 REM         1         2         3         4         5
120 REM 345678901234567890123456789012345678901234567890
130 %                       WELLS
140 %                      1     2
150 %    X........       ..1.....2...................X
160 %    X.......; RIVER ; 1     2                   X
170 %    X       ;.......; 1     2                   X
180 %    X                 1     2                   X
190 %    XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
200 %                            !------- X ---------!
210 %                      !------------- L ---------!
220 PRINTUSING 130: PRINTUSING 140: PRINTUSING 150: PRINTUSING 1
60: PRINTUSING 170: PRINTUSING 180: PRINTUSING 190: PRINTUSING 2
00: PRINTUSING 210: PRINT
230 INPUT "ENTER THE VALUE FOR'X'",X
240 INPUT "ENTER THE VALUE FOR 'L'",L
250 INPUT "NUMBER OF TIME STEPS",P: INPUT "TIME DURATION (HOURS)
",D9
260 INPUT "DO YOU WANT TO ENTER HEADS FROM DISK",Y$: IF Y$="N"TH
EN 290: IF Y$="NO"THEN 290
270 INPUT "FILE NAME",S$
280 DATA LOAD DC OPEN T#2,S$: DATA LOAD DC #2,H9(): GOTO 340
290 PRINT "OBSERVED HEADS AT WELL 1"
300 FOR I=1 TO P
310 PRINT I;")": PRINT HEX(0C);STR(R$,1,9): INPUT H9(I): PRINT H
EX(0C);STR(R2$,1,64);HEX(0C)
320 NEXT I
330 INPUT "DO YOU WANT TO SAVE THESE HEADS ON DISK",Y$: IF Y$="N
" THEN 340: IF Y$="NO"THEN 340: INPUT "FILE NAME",S$: DATA SAVE
DC OPEN T#2,10,S$: DATA SAVE DC #2,H9()
340 INPUT "DO YOU WANT TO HAVE A RECESSION CORRECTION",Y$: IF Y$
="N"THEN 380: IF Y$="NO"THEN 380
350 INPUT "SLOPE",S7: INPUT "INTERCEPT",I7: D7=INT((-.933*(L↑2)*
S7/86400)*100)/100: PRINT HEX(03);"BY THE WAY WOULD T/S=";D7;"
BE A GOOD FIRST TRY": INPUT Y$: FOR I=1 TO 100: NEXT I
360 PRINT HEX(03) ;"BY THE WAY, T/S=";D7;" WOULD BE A GOOD FIRST
 ESTIMATE"
370 T7=((LOG(H9(1))/LOG(10))-I7)/S7: PRINT "DAY OF FIRST INTERCE
PT =";T7: FOR I=2 TO P: T7=T7+D9/24: H9(I)=H9(1)+(H9(I)-10↑(T7*S
7+I7)): NEXT I: FOR I=1 TO 100: NEXT I
```

APPENDIX C. Program "DIFFUSE3" continued.

```
380 H(1)=0: C=P: FOR I=2TO P
390 H(I-1)=H9(I)-H9(I-1)
400 NEXT I
410 D8=D9*3600
420 PRINT HEX(03): INPUT "(SF '0).DO YOU WISH TO ESTIMATE U OR T
/S",Q$
430 IF Q$="U"THEN 440: INPUT "ENTER T/S";G1: U=X/SQR(G1*D8): PRI
NT "U EQUALS ";U: GOTO 450
440 INPUT "ENTER U",U: G1=((X/U)↑2)/(D8): PRINT "T/S EQUALS ";G1
450 REM ****THE FOLLOWING CALCULATES HEAD RESPONCSE****
460 SELECT PRINT 215(132): PRINT HEX(0C0E0A0A): CONVERT U TO U$,
(####.###): CONVERT G1 TO G1$,(####.###): F1=0
470 F1=F1+1: IF STR(U$,F1,1)<>HEX(30)THEN GOTO 480: GOTO 470
480 F2=0
490 F2=F2+1: IF STR(U$,F2,1)<>HEX(30)THEN 500: GOTO 490
500 PRINT "Calculated Response For Well 2": PRINT HEX(0E0A);"Whe
n U = ";STR(U$,F1,7);",or T/S= ";STR(G1$,F2,7): PRINT : SELECT P
RINT 005(64)
510 FOR J=2 TO P
520 H1=0
530 FOR K=1 TO J-1
540 H2=0
550 L1=0
560 L1=L1+1
570 E1=(2*L1-1)/(X/L)
580 E2=SQR(J-K)
590 E3=.5*U
600 B1=E3*(E1-1)/E2
610 B2=E3*(E1+1)/E2
620 B=B1
630 GOSUB '1(B): REM ERFC
640 S1=S
650 B=B2
660 GOSUB '1(B): REM ERFC
670 S1=S1+S
680 T=((-1)↑(L1-1))*H(K)*S1: IF ABS(T)>.005 THEN 690: GOTO 710
690 H2=H2+T
700 GOTO 560
710 H1=H1+H2
720 NEXT K
730 PRINTUSING 770,K+1,H1
740 CONVERT (K+1)TO K$,(##): CONVERT H1TO H1$,(###.##): F1=0: IF
 STR(K$,1,1)<>HEX(30)THEN 750: STR(K$,1,1)=HEX(20)
750 F1=F1+1: IF STR(H1$,F1,1)<>HEX(30)THEN 760: STR(H1$,F1,1)=HE
X(20): GOTO 750
760 SELECT PRINT 215(132): PRINT "Time Step ";K$,"Head ";H1$: SE
LECT PRINT 005(64)
770 %  TIME STEP ##                ###.##
```

APPENDIX C. Program "DIFFUSE3" continued.

```
780 HB(K)=H1
790 NEXT J
800 INPUT "DO YOU WISH TO TRY AGAIN",B$: IF B$="N"THEN 870: IF B
$="NO"THEN 870: GOTO 420
810 DEFFN'1(B): REM ********  CALCULATE ERFC    *******
820 IF B<4 THEN 830: S=0: RETURN
830 B3=1/(1+A0*B)
840 S=(A1*B3+A2*B3↑2+A3*B3↑3)*EXP(-B↑2)
850 RETURN
860 DEFFN'0: GOTO 420
870 END
```

APPENDIX C. Program "DIFFUSE1", used to determine aquifer diffusivity using a search routine.

```
10 REM  PROGRAM DIFFUSE1
20 REM **PROGRAM TO COMPUTE DIFFUSIVITY AND INVESTIGATE BNDRY.
30 REM ***OF AN AQUIFER USING A RECURSIVE LINEAR MODEL**
40  REM  X,L--BOUNDARY VARIABLES TO BE DETERMINED
50  REM  H(62)--USED TO HOLD INCR CHANGE AT WELL 1
60  REM  H9(62)--USED TO HOLD DATA FROM WELL1
70  REM  H5(62)--USED TO HOLD DATA FROM WELL2
80  REM  H3(62)--USED TO HOLD HEAD CHANGE AT WELL2
90  REM  A0,A1,A2,A3--USED IN CER FUNCTION
100 REM  S3(65),D(65),X1(65)--USED TO HOLD COMPUTED OUTPUT
110 REM  P--TIME STEPS,D9--TIME STEP DURATION(HRS),S$,S1$-FILES
120 REM  THAT HOLD INPUT GW DATA;G7(2)--HOLDS AND RETAINS FINAL
130 REM  DIFFUSIVITY VALUES;M,Z1,I,J,K--COUNTERS
140 REM  U,E1,E2,E3,B,B1,B2,H1,H2,L1--USED IN CALCULATION
150 REM  S8--SUM OF HEADS AT WELL 2(AREA UNDER CURVE)
160 REM  ***************************************************
170 REM
180 COM X,L,U,A1,A2,A3,D9,E,H2,H7
190 COM H(62),H9(62),H5(62),H3(62)
200 COM S,P,B,S1$
210 DIM S3(65),H4(2),D(65),G7(2),X1(65),D1(65),S4(65)
220 DIM S5(65),S6(65),N4(65),G6(2)
230 DIM N7(65),S5(65),S6(65)
240 READ A0,A1,A2,A3
250 DATA .4707,.3480242,-.0958798,.7478556
260 SELECT #2310
270 DEFFN'12: P=C
280 REM HERE WE ENTER DATA
290 REM
300 PRINT HEX(03)
310 INPUT "INPUT # OF TIME STEPS",P
320 INPUT "INPUT LENGTH OF TIME INTERVAL",D9
330 INPUT "ENTER FIRST TWO CHOICES OF T/S (LARGEST FIRST)",T7,T8
340 M=1: M5=0: S8=0
350 INPUT "INPUT FILE NAME OF 1ST WELL",S$
360 DATA LOAD DC OPEN F S$: DATA LOAD DC H9()
370 INPUT "INPUT FILE NAME OF 2ND WELL",S1$
380 DATA LOAD DC OPEN F S1$: DATA LOAD DC H5()
390 INPUT "ENTER INITIAL DISTANCE X",X
400 INPUT "ENTER INITIAL DISTANCE L",L
410 INPUT "ENTER MAXIMUM RANGE OF X",X9
420 SELECT PRINT 005
430 H(1)=0: C=P: FOR I=2 TO P
440 H(I-1)=H9(I)-H9(I-1): H3(I-1)=H5(I)-H5(1)
450 IF H(I-1)>M5 THEN M5=H(I-1): REM FINDS MAX HEAD CHANGE
460 S8=S8+H3(I-1)
470 NEXT I
```

APPENDIX C. Program "DIFFUSE1" continued.

```
480 X=X-20: L=L-20
490 X=X+20: L=L+20: K1=1: Z2=0
500 D8=D9*3600
510 G7(1)=T7: G7(2)=T8: Z1=1
520 H7=0: N7=0
530 G1=G7(Z1)
540 U=X/ SQR(G1*D8)
550 REM ****THE FOLLOWING CALCULATES HEAD RESPONSE****
560 FOR J=2 TO P
570 H1=0
580 FOR K=1 TO J-1
590 H2=0
600 L1=0
610 L1=L1+1
620 E1=(2*L1-1)/(X/L)
630 E2=SQR(J-K)
640 E3=.5*U
650 B1=E3*(E1-1)/E2
660 B2=E3*(E1+1)/E2
670 B=B1
680 GOSUB '1(B): REM ERFC
690 S1=S
700 B=B2
710 GOSUB '1(B): REM ERFC
720 S1=S1+S
730 T=((-1)↑(L1-1))*H(K)*S1: IF ABS(T)>.005 THEN 740: GOTO 760
740 H2=H2+T
750 GOTO 610
760 H1=H1+H2
770 NEXT K
780 IF H3(J)=0 THEN H3(J)=.01
790 H7=H7+H1
800 N7=N7+ABS((H1-H3(J))/H3(J))
810 NEXT J
820 PRINT Z1;G7(Z1);H7;S8: SELECT P6: SELECT P0
830 H4(Z1)=H7: N4(Z1)=N7
840 Z2=Z2+1
850 IF Z2=1 THEN Z1=2: IF Z2=1 AND Z1=2 THEN GOTO 520
860 K2=K2+1: IF K2=15 THEN 1020
870 G8=G7(2): G9=G7(1)
880 G6(Z1)=H4(Z1)-S8
890 IF ABS((H4(Z1)-S8)/S8*100)<.5 THEN 1020
900 IF SGN(G6(1))+SGN(G6(2))=0 THEN 940
910 IF SGN(G6(Z1))=1 THEN 920: GOTO 930
920 G7(Z1)=1/2*G7(Z1): IF Z1=1 THEN G7(2)=G7(1): Z1=2 : GOTO 520
930 G7(Z1)=2*G7(Z1): IF Z1=2 THEN G7(1)=G7(2): Z1=1: GOTO 520
940 IF  ABS(H4(1)-S8)<ABS(H4(2)-S8) THEN GOTO 950: GOTO 960
950 G7(2)=G7(1)-(G7(1)-G7(2))/2: GOTO 970
960 G7(1)=G7(2)+(G7(1)-G7(2))/2
970 K1=K1+1: IF K1=10 THEN GOTO 1020
980 IF ABS((H4(Z1)-S8)/S8*100)<.5 THEN 1020: REM CONVERGENCE CRI
-TERIA
990 IF G9=G7(1) THEN GOTO 1000: GOTO 1010
1000 Z1=2: GOTO 520
```

APPENDIX C. Program "DIFFUSE1" continued.

```
1010 IF G8=G7(2) THEN Z1=1: GOTO 520
1020 D(M)=G7(Z1): X1(M)=X: S3(M)=H4(Z1): S5(M)=N4(Z1): IF X>=X9
THEN GOTO 1050
1030 M=M+1
1040 GOTO 490
1050 SELECT PRINT 216
1060 SELECT PRINT /216(80)
1070 PRINT "  X         T/S                    REL.AREA DIFF.  "
1080 PRINT "  ft     sqft/s                    TO ";S8
1090 SELECT PRINT /216(80)
1100 PRINT "======================================================"
1110 FOR I=1 TO M
1120 PRINTUSING 1130, X1(I);D(I);S3(I)
1130 %####      ##.##                  ####.##
1140 NEXT I
1150 PRINT " ": PRINT "NUMBER OF TIME STEPS: ";P
1160 PRINT "LENGTH OF TIME INTERVAL:";D9
1170 PRINT "INITIAL CHOICES FOR T/S:";T7;",";T8
1180 PRINT "FILE NAME OF FIRST WELL :";S$
1190 PRINT "FILE NAME OF SECOND WELL:";S1$
1200 GOTO 1270
1210 DEFFN'1(B): REM ********  CALCULATE ERFC   *******
1220 IF B<4 THEN 1230: S=0: RETURN
1230 B3=1/(1+A0*B)
1240 S=(A1*B3+A2*B3↑2+A3*B3↑3)*EXP(-B↑2)
1250 RETURN
1260 DEFFN'0: GOTO 530
1270 END
```

APPENDIX C. Program "FIXIT", used to edit numeric files.

```
10 REM PROGRAM FIXIT
20 REM USE THIS TO CORRECT NUMERIC VALUES IN A FILE
30 DIM A(370)
40 PRINT HEX(03)
50 PRINT : PRINT
60 PRINT "                         PROGRAM FIXIT"
70 PRINT : PRINT
80 PRINT "USE THIS PROGRAM TO EDIT DATA FILES STORED ON THIS DIS
K": PRINT
90 INPUT "WHAT IS THE FILE YOU WANT TO CORRECT",A$
100 D$=A$
110 DATA LOAD DC OPEN F A$: DATA LOAD DC A()
120 INPUT "FROM WHAT WATER DAY TO WHAT WATER DAY WOULD YOU LIKE
TO VIEW,   ENTER 0 TO STOP",I,J
130 IF I=0 OR J=0 THEN 280
140 FOR L=I TO J
150 PRINT L;A(L),
160 NEXT L
170 PRINT
180 INPUT "WOULD YOU LIKE TO ENTER A CONSTANT CORRECTION",C$
190 IF C$="Y" OR C$="YES"THEN 340
200 INPUT "WHAT DAY WOULD YOU LIKE TO CORRECT, ENTER 0 TO STOP",
I
210 IF I=0 THEN 280
220 PRINT I;A(I)
230 INPUT "WHAT IS THE NEW VALUE",B: A(I)=B
240 PRINT "NEXT DAY";I+1: INPUT Y$
250 IF Y$="Y" THEN I=I+1: IF Y$="Y" THEN GOTO 220
260 IF Y$="N" OR Y$="NO" THEN 200
270 GOTO 120
280 INPUT "ARE YOU SURE YOU UPDATED CORRECTLY",H$: IF H$="Y" OR
H$="YES" THEN SCRATCH F A$: IF H$="N" OR H$="NO" THEN 120
290 DATA SAVE DC OPEN F(D$) D$
300 DATA SAVE DC A()
310 DATA SAVE  DC END: DATA SAVE DC CLOSE
320 GOTO 420
330 REM ***APPLYING A CORRECTION****
340 INPUT "FROM WHAT WATER DAY TO WHAT WATER DAY DO YOU WISH TO
ADD A CORRECTION",K,L
350 INPUT "WHAT IS THE CORRECTION",K1
360 FOR I=K TO L
370 A(I)=A(I)+K1
380 NEXT I
390 PRINT : PRINT
400 PRINT "                        CORRECTION APPLIED"
410 GOTO 120
420 END
```

APPENDIX C. Program "SORT", to sort data largest to smallest.

```
10 REM  PROGRAM SORT
20 REM USE THIS PROGRAM TO SORT YOUR DATA LARGEST TO SMALLEST
30 DIM A(370)
40 PRINT HEX(03): PRINT
50 PRINT "USE THIS PROGRAM TO SORT YOUR DATA LARGEST TO SMALLEST
": PRINT
60 INPUT "WHAT IS THE FILE YOU WANT TO SORT",A$
70 INPUT "HOW MANY ENTRIES IN THE DATA SET",N
80 DATA LOAD DC OPEN F A$: DATA LOAD DC A()
90 N=N-1
100 N1=N-1
110 FOR J=1 TO N1
120 PRINT AT(5,5);"DATA  NOW BEING SORTED": PRINT J+2
130 PRINT HEX(0A)
140 K=J
150 L=K+1
160 FOR I=L TO N
170 IF A(K)>=A(I) THEN 190
180 K=I
190 NEXT I
200 T=A(J)
210 A(J)=A(K)
220 A(K)=T
230 NEXT J
240 PRINT : INPUT "DATA SORTED DO YOU WANT A PRINTOUT",Y$
250 IF Y$="N" THEN 400
260 PRINT "DO YOU WANT AN EDITED PRINTOUT"
270 F=1
280 INPUT "THAT IS, EVERY 2nd,3rd,5th ENTRY, ENTER #",F
290 SELECT PRINT 215
300 FOR I=1 TO N STEP F
310 D=0
320 FOR J=0 TO F-1
330 R=I+J
340 D=D+A(R)
350 NEXT J
360 PRINTUSING 370,D/F+.005
370 % ###.##
380 NEXT I
390 SELECT PRINT 005
400 INPUT "DO YOU WANT TO SAVE THE SORTED DATA, THE ENTIRE FILE"
,W$
410 IF W$="N" OR W$="NO" THEN 460
420 INPUT "WHAT IS GOING TO BE THE FILE NAME",E$
430 DATA SAVE DC OPEN F(E$) E$
440 DATA SAVE DC (A)
450 DATA SAVE  DC END: DATA SAVE DC CLOSE
460 END
```