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# Interpretation of the thermal behavior of groundwater in an alluvial terrace : Bonneville Dam, Columbia Gorge, Oregon

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AN ABSTRACT OF THE THESIS OF Richard Stephen Malin for the Master of Science in Geology:Hydrogeology presented May 2, 1991.

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Groundwater temperature data, collected at an alluvial terrace located on the Oregon shore of the Columbia River downstream from Bonneville Dam, was

analyzed in order to characterize and formulate a conceptual model of the thermal data for the groundwater system in the terrace. There is concern that an unlined entrance channel for a new navigation lock, to be located down the middle of the terrace, will widen the range of temperatures in the fish hatchery-groundwater supply. The analysis of temperature behavior in the terrace supports the hydraulic observations derived from analysis of pump test data, but with greater definition of the more subtle behavior of the groundwater system not readily discernable in the pump test data. The thermal behavior of the terrace groundwater system is governed by: 1) the stratigraphy of the terrace, 2) its groundwater recharge characteristics, 3) thermal influence from the Columbia River, and 4) stress placed on the aquifer system due to pumping of fish hatchery wells located in the terrace.

Analysis of the temperature data for the terrace groundwater system is consistent with the following behavior: 1) pumping of fish hatchery wells is the driving force controlling the thermal character of the downstream terrace and that each hydrogeologic unit exhibits its own unique thermal behavior, 2) a six month lag time exists between the groundwater temperature in the main aquifer of the terrace with respect to temperature in the Columbia River, 3) a preferential east-west flow direction influenced by the fluvial stratigraphy of the terrace alluvium with recharge occurring dominantly from the western end of the terrace, and 4) the presence of a lower aquifer partially isolated from the hydraulic impact of the hatchery wells.

Information produced from this study will assist in the development of a three-dimensional numerical groundwater model of the terrace area that will take into account groundwater temperature changes occurring in the system. This model will be used to assess the thermal impact produced by the construction and operation of a downstream-entrance channel for the new navigation lock at Bonneville Dam.

# INTERPRETATION OF THE
# THERMAL BEHAVIOR OF GROUNDWATER
# IN AN ALLUVIAL TERRACE:
# BONNEVILLE DAM, COLUMBIA GORGE,
# OREGON

by

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# CHAPTER I

# INTRODUCTION

## GENERAL

Groundwater temperature has been used in hydrogeologic investigations to analyze the nature of groundwater movement, recharge and discharge characteristics (Cartwright, 1974; Lapham, 1988; Parsons, 1971; Schneider, 1962; Simpson, 1952). The simultaneous conduction and convection of heat in an aquifer is affected by the velocity of groundwater. Conversely, the variation of temperature in an aquifer is an indication of the magnitude of the groundwater velocity in the saturated zone. Temperature changes at various levels, in groundwater systems not geothermally impacted, depend on the groundwater flow velocity and increase with increased velocity.

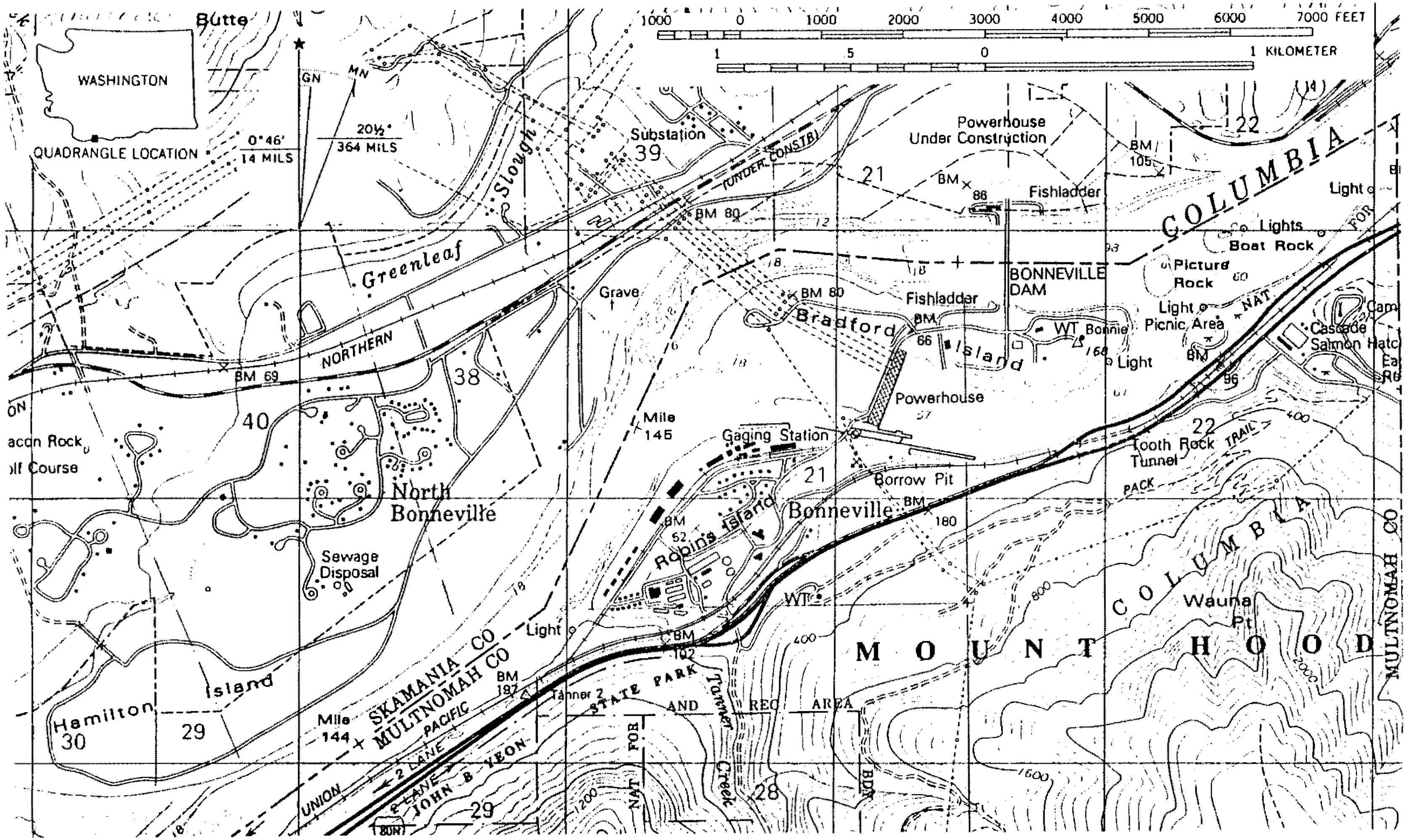
Construction of a downstream entrance channel by the U.S. Army Corps of Engineers (USACE) for a new navigation lock on an alluvial aquifer is expected to impact the thermal character of the groundwater system to some degree due to construction dewatering, dredging, and operation. This study was undertaken to develop a greater understanding of the thermal behavior and characteristics of the groundwater system located in the downstream terrace near Bonneville Dam on the Oregon shore of the Columbia River. The U.S. Geological Survey topographic map of the Bonneville, Oregon 15 minute quadrangle (Figure 1) refers to this terrace as Robins Island. The geomorphic character of Robins Island is that of a river alluvial terrace rather than an actual island.

Since the Bonneville Fish Hatchery utilizes water from the main aquifer of the terrace in its salmon fingerling-rearing ponds, it is necessary to develop an understanding of the thermal behavior of the groundwater in this area. Groundwater from this aquifer has proven to be ideal water in which to raise fish. One of the valued qualities is water temperature. Groundwater pumped from the terrace maintains a consistent narrow temperature range that minimizes the spread of disease and promotes maximum growth. This study examines groundwater-temperature data collected from piezometers located in the terrace in order to characterize and formulate a conceptual model of its thermal behavior.

Data presentation and interpretation from this study was used by the USACE in their assessment of the impact created by construction and operation of the new navigation lock. Consequently, due to the reports intended usage, the units employed in this study are a mixture of standard and metric. Units in the text are reported in both metric and standard.

## BACKGROUND

The pre-slide alluvium (PSA) is the dominant hydrogeological unit in the Bonneville Dam downstream terrace. During normal fish hatchery operational pumping, the annual 17°C (62.6°F) temperature variation of the Columbia River



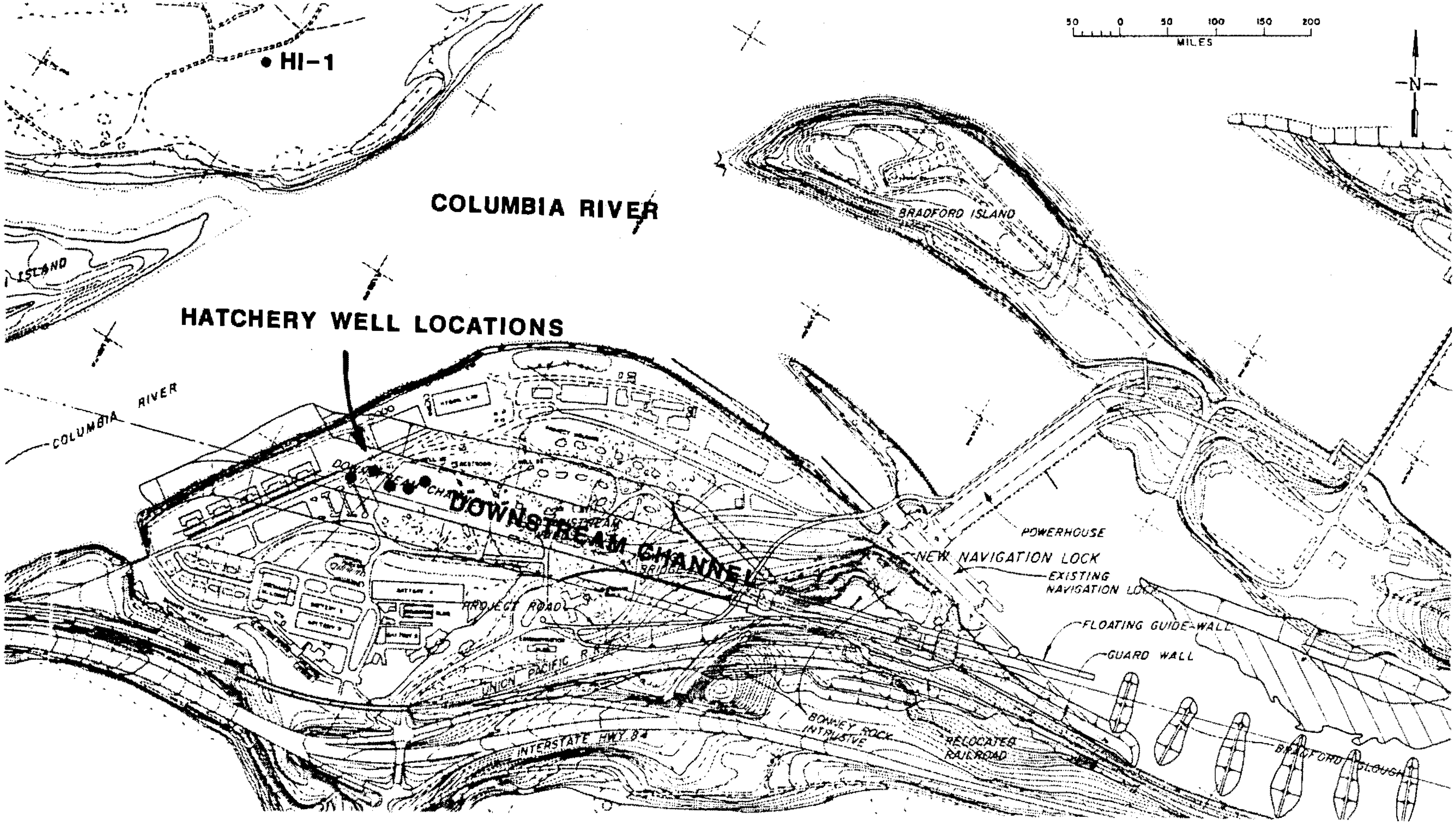

<u>Figure 1.</u> Location of the Bonneville Dam ownstream errace. Map from U. S. Geological Survey Bonneville Dam 15' quadrangle, 1979.

is moderated to less than a five degree Centigrade variation at the point where the groundwater is pumped to the fish hatchery. The fish hatchery wells supply water that is on average 10°C (50°F) with a maximum of 12.5°C (54.5°F) and a minimum of 8.8°C (47.8°F). Groundwater temperature is of concern since temperatures above 11.7°C (53°F) create an environment that stresses fingerlings producing a greater susceptibility to pathogens; temperatures below 8.3°C (47°F) greatly decreases fish growth.

Construction of the proposed navigation lock on the south side of the Bonneville Dam requires relocation of the existing fish hatchery wells because the location of the downstream entrance channel and the hatchery wells conflict (Figure 2). During channel construction dewatering, due to increase pumping stress on both shallow and deep aquifers, groundwater temperature variation is expected to increase. Thermal influence from Columbia River water occupying the entrance channel is also expected to produce greater thermal variation of the terrace's groundwater temperature.

## PURPOSE AND SCOPE

A computer model of the terrace groundwater system (Baron, 1990) utilizing a three-dimensional heat and solute groundwater code (HST3D; Kipp, 1987) will aid in predicting the thermal impact associated with construction dewatering and operation of the entrance channel to the navigation lock. To accurately predict future temperatures, the HST3D groundwater model




<u>Figure 2</u>. Location and orientation of the new navigation lock at Bonneville Dam. General plan map, U.S. Army Corps of Engineers, 1984.

requires calibration with field measurements of groundwater temperature. Direct temperature measurements in time and space offer the best means of estimating the parameters needed in the model.

A groundwater study of the terrace hydrogeology by Cornforth Consultants (1987) recommended that accurate temperature data over time was needed to confirm groundwater temperature variations throughout a yearly pumping cycle. Collection of temperature data for the U.S. Army Corps of Engineers began on September 26, 1986 and continued on an irregular basis through 1987; becoming more consistent in 1988. Eight piezometers in the downstream terrace were initially selected as data sources (see Figure 3): BDH-1610, BDH-1611, BDH-1612, BDH-1614, BDH-1615, BDH-1624, BDH-1629 and BDH-1632. Several gaps exist in the temperature record. The most noteworthy gap is between late May 1987 and mid-October 1987. Another gap exists from December 1987 to June 1988; a few piezometers having temperature data during April 1988. Temperature measurements at regular intervals (about seven days) have been recorded since June, 1988. The number of piezometers used for temperature measurements has increased from eight to seventeen locations. The addition of four deep piezometers (DH-1946, DH-1949, DH-1953, DH-1958) (see Figure 3), in the winter of 1987 greatly expanded the temperature data base.

Groundwater temperature is measured by lowering a thermistor down a piezometer and measuring at 1.5 meter (5 feet) increments above -15.2 meters (-50 feet) elevation and at 3.05 meter (10 feet) increments at depths below -15.2

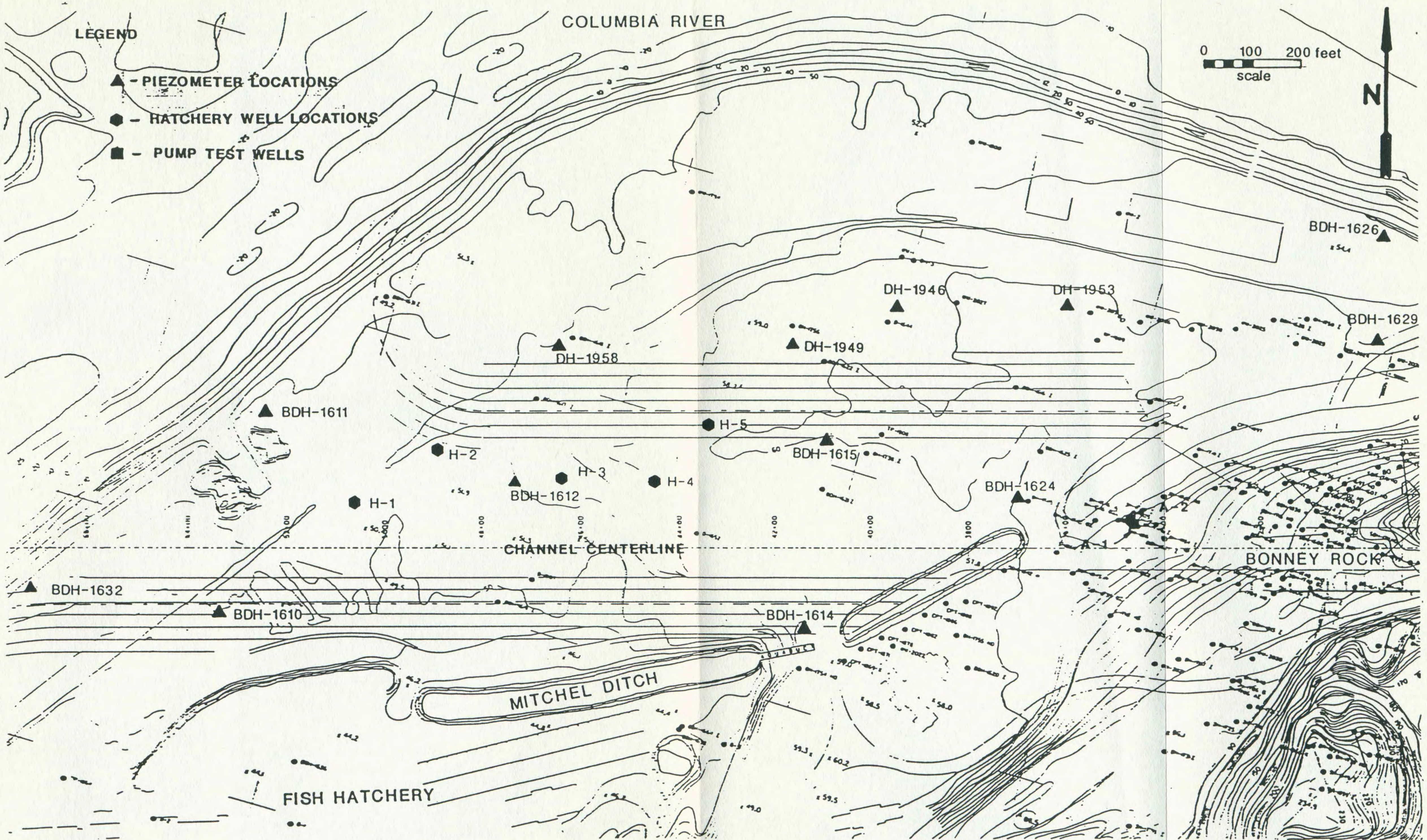



Figure 3. Locations of peizometers in the Bonneville Dam downstream terrace.

meters (-50 feet) elevation. The piezometers are located in borings with a diameter of 16.82 centimeter (6-5/8 inch). A 3.81 centimeter (1-1/2 inch) diameter polyvinyl chloride (PVC) pipe, open at the bottom, back-filled with pea gravel up to a bentonite seal, constitutes a piezometer. Temperature variations occurring within the piezometer are due to thermal conductance through the PVC pipe. Early data tend to be subject to sudden large variations in temperature change that was not observed in later data. In the assessment of this early data, there is difficultly, in some cases, in determining whether or not suspect data (sudden large temperature changes) is due to faulty readings (possible leakage down the outside of the piezometer from rain water or just bad instrumentation), or actual variations due to well pumping influence.

The HST3D groundwater model of the downstream terrace area includes groundwater temperature changes that occur in the system. In order to properly model thermal behavior of the groundwater, this study was undertaken to determine: 1) the degree and distribution of the seasonal temperature variations that occur, 2) the influence of the geology of the downstream terrace on observed thermal variations, 3) the factors influencing groundwater temperature behavior in the downstream terrace, and 4) potential locations on the terrace for the new fish hatchery well field.

# CHAPTER II

# METHOD OF INVESTIGATION

## TEMPERATURE DATA

Assessment of the thermal behavior of the groundwater system required investigation of all sources that could potentially impact the temperature of the groundwater in the terrace. The two major sources of thermal impact on terrace groundwater are the Columbia River and the pumping activity of the hatchery wells. Thermal impact due to geothermal sources was not observed or minimal in comparison to river and pumping impacts. Considered less of an influence on groundwater thermal behavior are Tanner Creek (see Figure 1), Mitchell Ditch (see Figure 3), and atmospheric heating and cooling. The large temperature data set required the development of graphical presentations to assess the thermal behavior of the groundwater system in the terrace. The following describes the information collected and the various methods employed to present the data for model calibration.

Temperature measurements of water in the Columbia River were taken in the scroll casing of the Bonneville Dam powerhouse generators (see Figure 2). Data from October 1986 to December 1988, indicate that the river temperature

(Figure 4) varies from a low of 3.3°C (38°F) in mid-January, to a high of 22°C (72°F) in August to early September. The mean river temperature during this period was 13.2°C (55.7°F). The Columbia River has a longer warming period relative to a shorter cooling period. River-temperature data indicates that, on average, it takes from mid-January to September to go from the minimum to the maximum, or about 230 days (7.5 months). Cooling occurs in 135 days (4.5 months).

Tanner Creek forms the southwest boundary of the terrace (see Figure 1) and serves as a secondary water source for the fish hatchery. The fish hatchery, at times, mixes Tanner Creek water with terrace groundwater for its rearing ponds (salmon are both released and captured from Tanner Creek as part of fish hatchery operations). Bonneville Fish Hatchery records of the temperature of Tanner Creek in 1986, 1987 and 1988 (Table I) indicate an average temperature of 8.3°C (47°F). The low temperature recorded during this time was 3.5°C (38.3°F) and the high temperature was 11.9°C (53.4°F). The average Tanner Creek temperature is 5°C cooler than the average for the Columbia River. Water temperatures during three cold months were not measured (Table I) and are excluded from this average. The average temperature for Tanner Creek with this data would be lower.

The maximum measured range of groundwater temperature in the downstream terrace alluvium is from 3.7° to 18.2°C (38.7° to 64.8°F). The Bonneville Fish Hatchery pumps water from the upper section of the PSA-aquifer

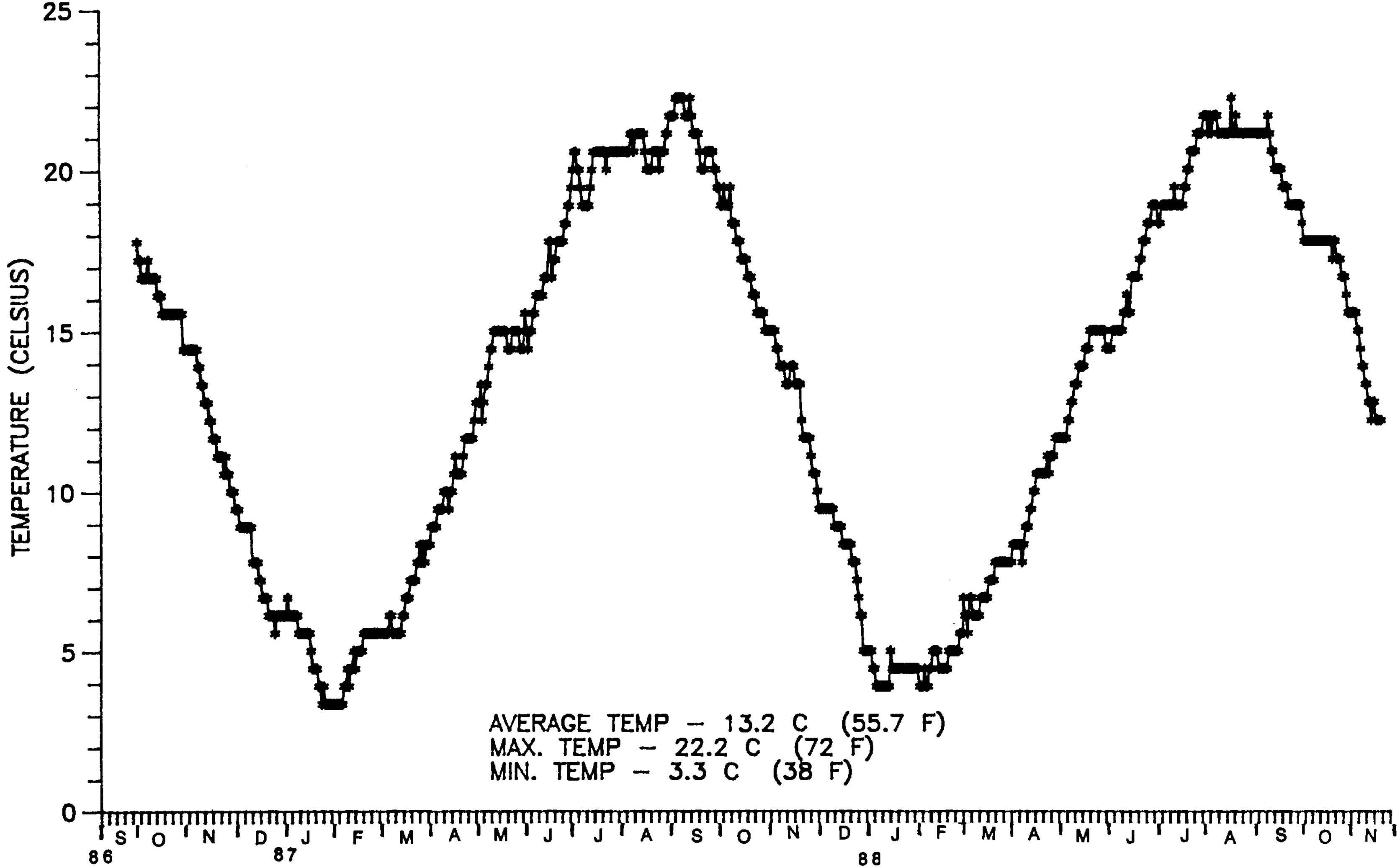



Figure 4. Columbia River temperature from October 1986 to December 1988.

TABLE I

TANNER CREEK AVERAGE
MONTHLY WATER TEMPERATURE (°C)

| Yr | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| '86 | - | 5.6 | 6.2 | 6.7 | 8.3 | 10.9 | 10.8 | 11.6 | 9.9 | 8.7 | 7.1 | 3.9 |
| '87 | - | 5.2 | 6.1 | 7.6 | 9.6 | 10.1 | 10.8 | 11.5 | 10.9 | 8.7 | 7.2 | 4.7 |
| '88 | 3.5 | 4.7 | 5.6 | 7.1 | 7.7 | 10.3 | 11.0 | 11.1 | 10.2 | 9.4 | 6.0 | - |

which has a maximum measured groundwater temperature range of 4° to 16.2°C (39.2° to 61.2°F). Fish hatchery records of water temperature measured at the well pumps (Figure 5) indicate a temperature range of 7.8° to 12.5°C (46° to 54.5°F) with an average water temperature of 10.1°C (50.2°F).

## DATA REDUCTION AND PRESENTATION

Several approaches were investigated in order to interpret groundwater temperature. A variety of graphical presentations and isotherm maps in conjunction with pump test analysis were found to best characterize the thermal behavior of the terrace groundwater system.

One of the most useful graphical presentations of groundwater temperature data is as a temperature-depth profile (Figure 6) or thermal profile. This graph depicts groundwater temperature versus elevation. Points on the graph represent data collected at a specific time. Composite diagrams of temperature versus depth profiles at different times for the same piezometer allows a presentation of groundwater temperature as a function of depth and time. The addition of stratigraphic boundaries (hydrogeologic units) on the profile produces a clearer graphical presentation of temperature behavior and its association with stratigraphy and time. Water yields, measured during drilling, are labeled on the right side of the graph indicating observed relative availability of water.

Another graphical presentation is the temperature-time graph (Figure 7). Temperature measurements over time at selected elevations are plotted in such a

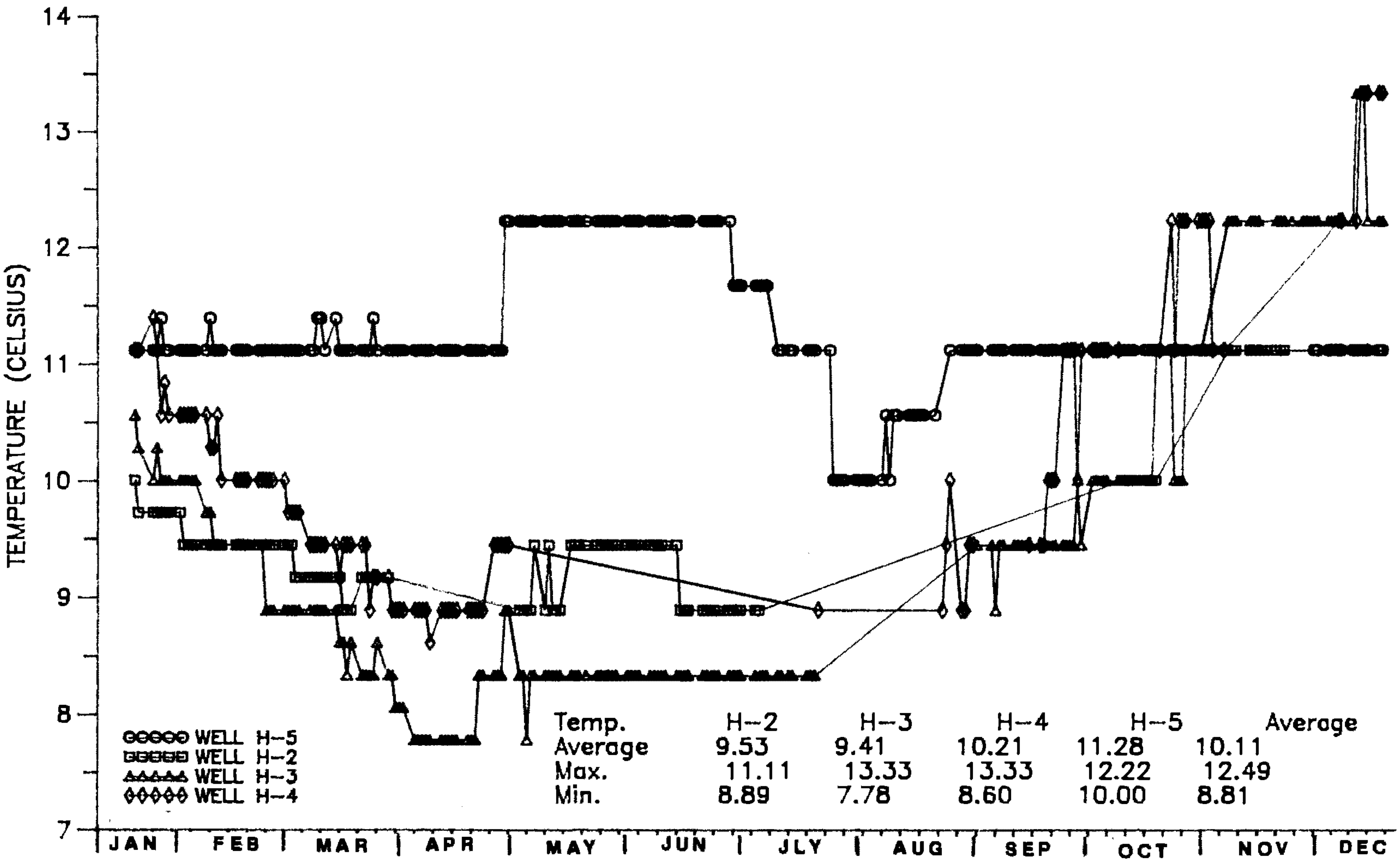



Figure 5. Bonneville Dam fish hatchery well temperatures for 1988. See Figure 3 for hatchery well locations.

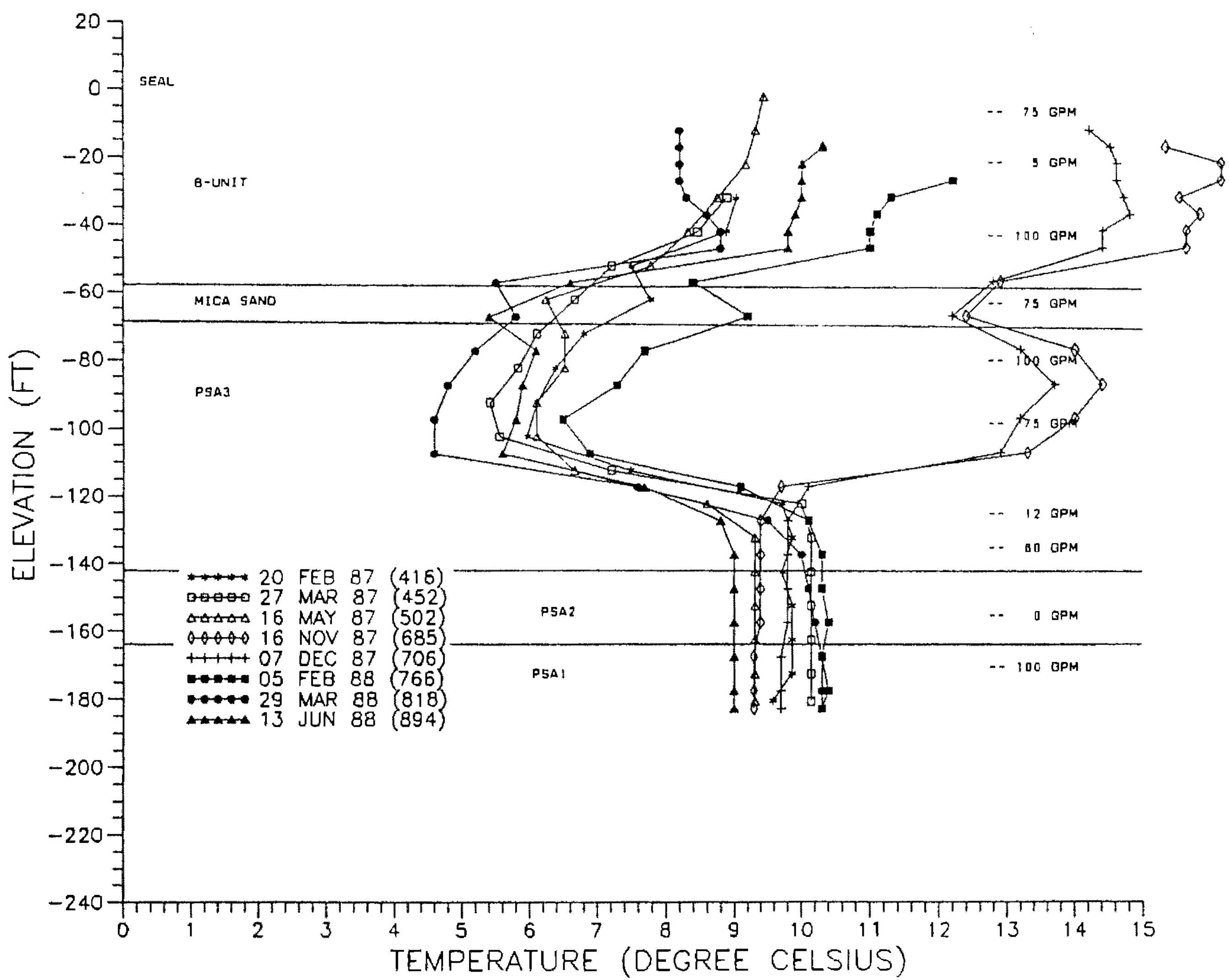



**Figure 6**. Temperature-depth profile.

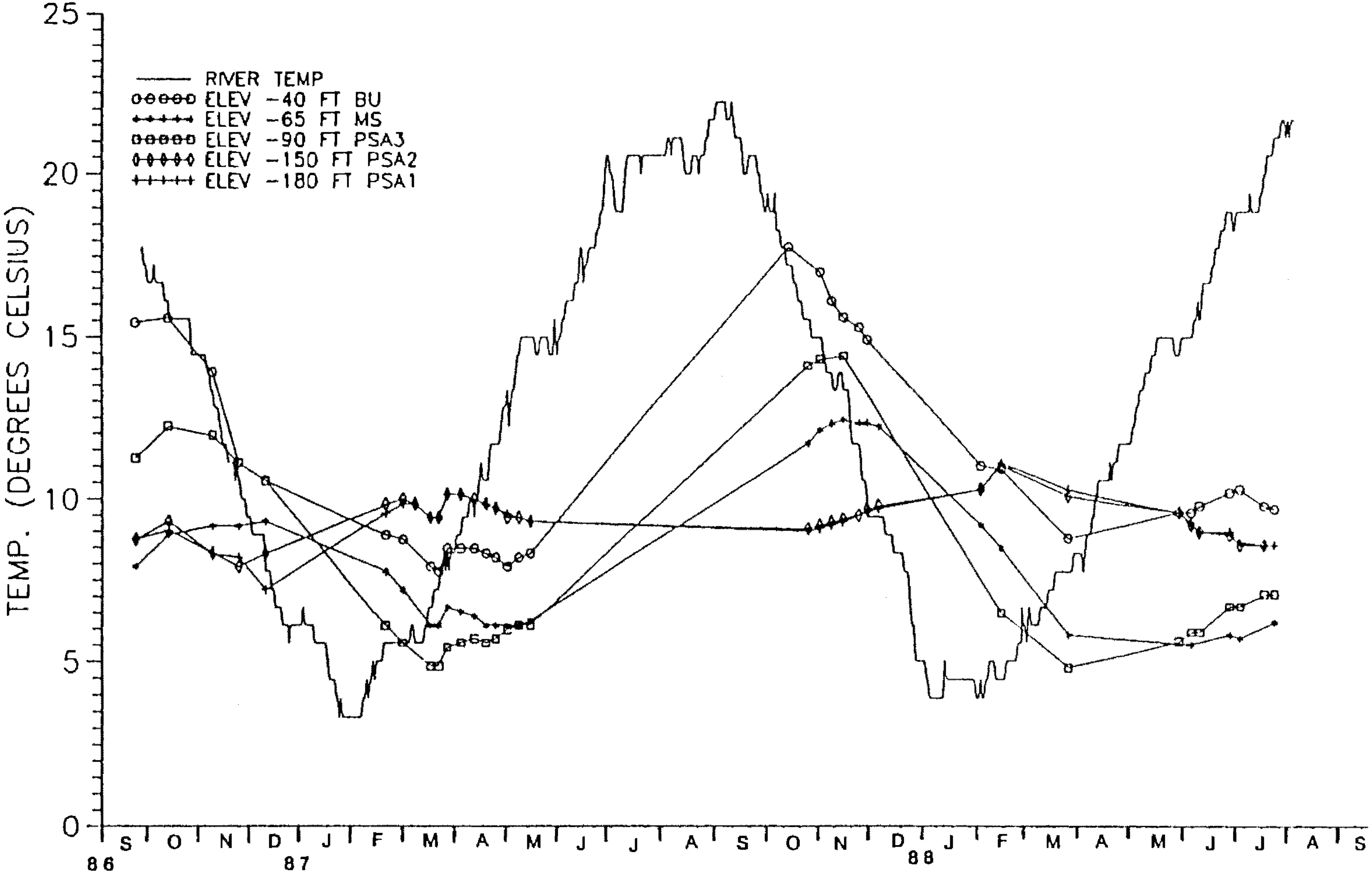



Figure 7. Temperature-time graph.

manner that the thermal behavior of a piezometer in each of the hydrogeologic units at the piezometer's location can be observed. The temperature of the Columbia River is also plotted for comparison with groundwater temperature. Smoothed temperature-time graphs were created by adding an interpretative hand-smoothed line through the data points to produce a generalized graphical presentation of the heating and cooling trends of the hydrogeologic units of the piezometer over time. This graph can be used to estimate lag times and attenuation between groundwater temperature at a specific location in the terrace and water temperature in the Columbia River.

Each of these graphical presentations focus on the temperature behavior at a specific piezometer. Two presentations were developed to analyze temperature behavior on a terrace-wide basis. These presentations are a temperature-time graph (see Figure 7) using groundwater temperature of the same hydrogeologic unit at several locations and isotherm maps (see Appendix C) of the terrace also using groundwater temperature of the same hydrogeologic unit.

# CHAPTER III

# GEOLOGY OF THE DOWNSTREAM TERRACE

## GENERAL

Groundwater flow in the terrace is highly influenced by how the material was deposited. The bulk of the alluvial material found in the terrace was deposited in a fluvial regime flowing in an east to west direction (RZA, 1988). This type of depositional regime would potentially produce deposits that are oriented in the east-west direction. The depositional history of the terrace represents a very short geologic time period (USACE, 1976; USACE, 1984; RZA, 1988). Terrace sediment deposition is characterized by the activities associated with the Pleistocene Epoch; glacial meltwaters (torrential outwashes due to ice dam failure), changes in sea level, and the addition of volcanic ash and debris produced by Cascadian volcanic eruptions (Cornforth Consultants, 1987). The high energy floodwaters of the Missoula Floods scoured the channel of the Columbia River and concurrently deposited the basal alluvial material in the terrace area (RZA, 1988).

# STRATIGRAPHY

There are four Pleistocene stratigraphic units that have been defined and correlated within the terrace area whose deposition are associated with distinctive events (USACE, 1984; RZA, 1988). Each of these stratigraphic units (Figure 8) form separate and unique groundwater aquifers and aquitards -- hydrogeologic units. These stratigraphic units have not been formerly recognized. The following type of nomenclature will be used throughout the text to identify these units. These units are known as the pre-slide alluvium (PSA), the mica sand (Mica Sand) unit, the b unit (B unit), and the fill/recent river deposits (F/RD) (RZA, 1988).

The oldest alluvial unit in the downstream terrace area is the PSA consisting of coarse gravel with abundant cobbles and boulders along with lesser amounts of sand and silt. The origin of this unit is associated with Missoula floodwaters. These floodwater events scoured the channel of the Columbia River during the Pleistocene into the relatively non-resistant weigle formation, an Eocene-Oligocene fine-grained volcanic-clastic sedimentary unit. Deposition occurred in and above the scour. The clasts found in the terrace PSA are well rounded and represent deposition in a very high energy environment of a plunge pool produced by floodwaters spilling over the resistant Bonney Rock intrusive (USACE, 1984). The PSA material rests on top of the bedrock consisting of the weigle formation. The material fills an eroded channel cut into the weigle formation (Figure 9) by the plunge pool. The scour channel trends southwesterly across the terrace area

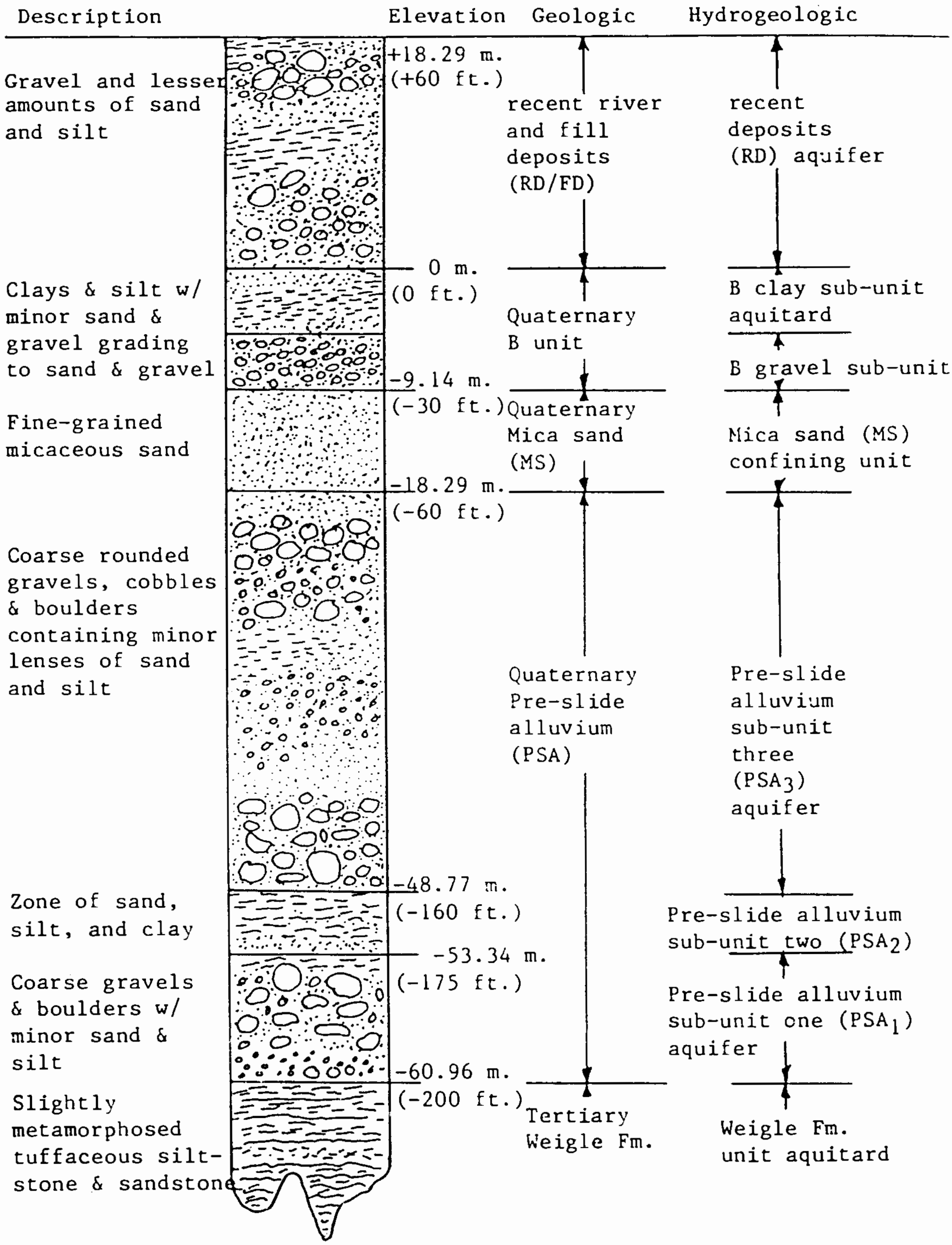



Figure 8. Stratigraphic column of the Bonneville Dam downstream alluvial terrace. Based on information from RZA, 1988 and USACE, 1984.

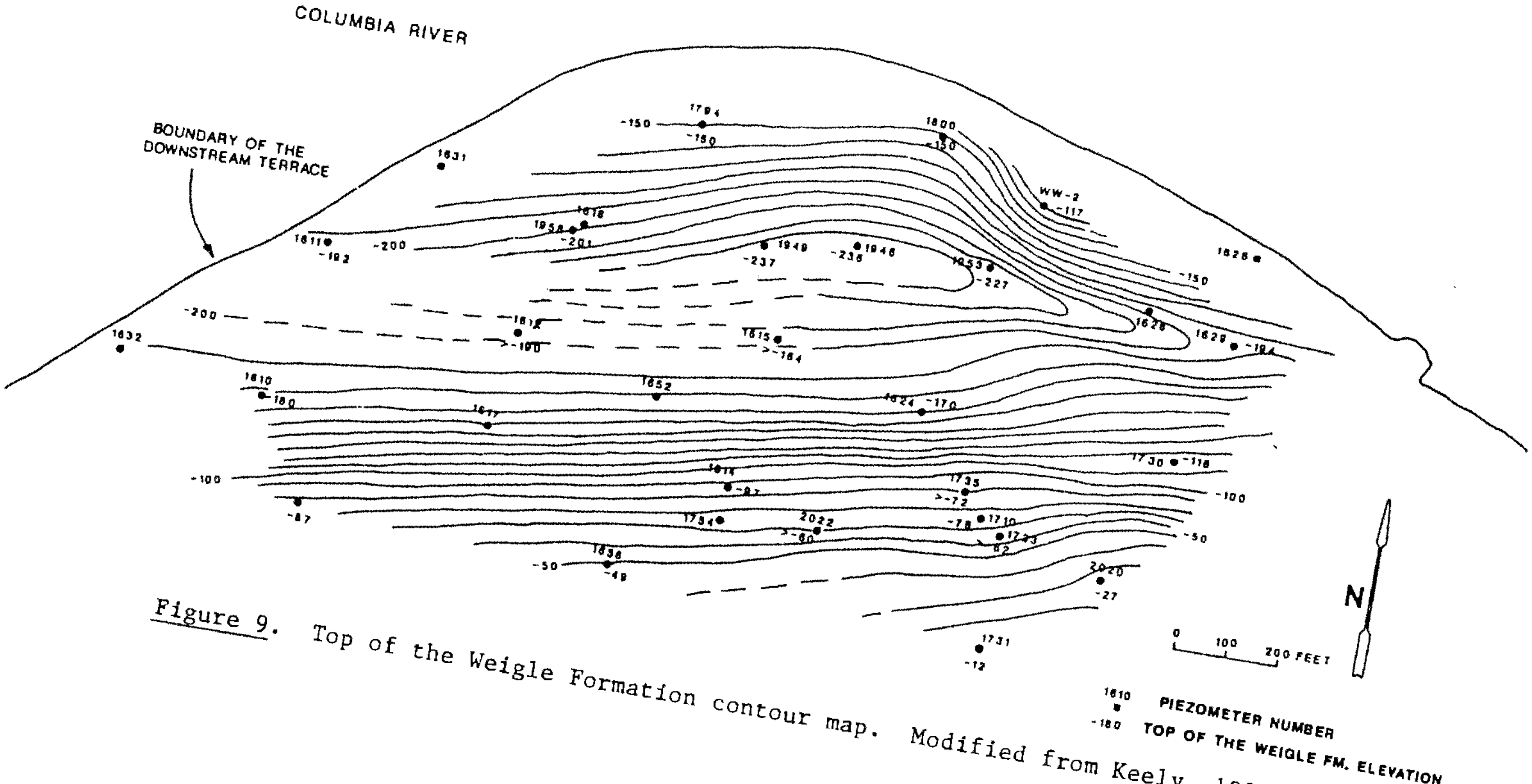



Figure 9. Top of the Weigle Formation contour map. Modified from Keely, 1989.

becoming shallower to the north. The PSA is bounded on the eastern and southeastern sides by the Bonney Rock intrusive, a diabase. In addition to filling the terrace scour channel, the PSA forms a layer of sand, gravel, cobbles and boulders to a thickness greater than 51.8 meter (170 feet) in the terrace area. Deposition of the PSA has been described (RZA, 1988) as aggrading with minimal cut-and-fill features.

The top of the PSA is approximately 18.3 meters (60 feet) below sea-level. Bathymetric maps of the Columbia River in the terrace area indicate river bottom elevations of -15.2 meters (-50 feet) and possibly deeper in isolated areas. A depression in the southeast section of the terrace, where the top of the PSA drops down to -26.8 meters (-88 feet, Figure 10), may have formed during a smaller later episode of the Missoula Floods. Towards the north, the PSA appears to thin and extend beneath the Columbia River (USACE, 1976). The western portion of the PSA interfingers with alluvium from Tanner Creek where sediment has angular clasts smaller in diameter than PSA clasts and includes fresher clasts of the Eagle Creek and weigle formations (RZA, 1988). Figure 11 indicates the location of two diagrammatic cross-sections (Figure 12) oriented east-west and north-south through the downstream terrace. The PSA has been divided into three hydrogeologic sub-units (RZA, 1988; see Figure 8 and Figure 12). The pre-slide alluvium sub-unit one ($PSA_1$), the lowest sub-unit, is present only in the terrace scour channel. This sub-unit consists of coarse gravel, cobbles and boulders with

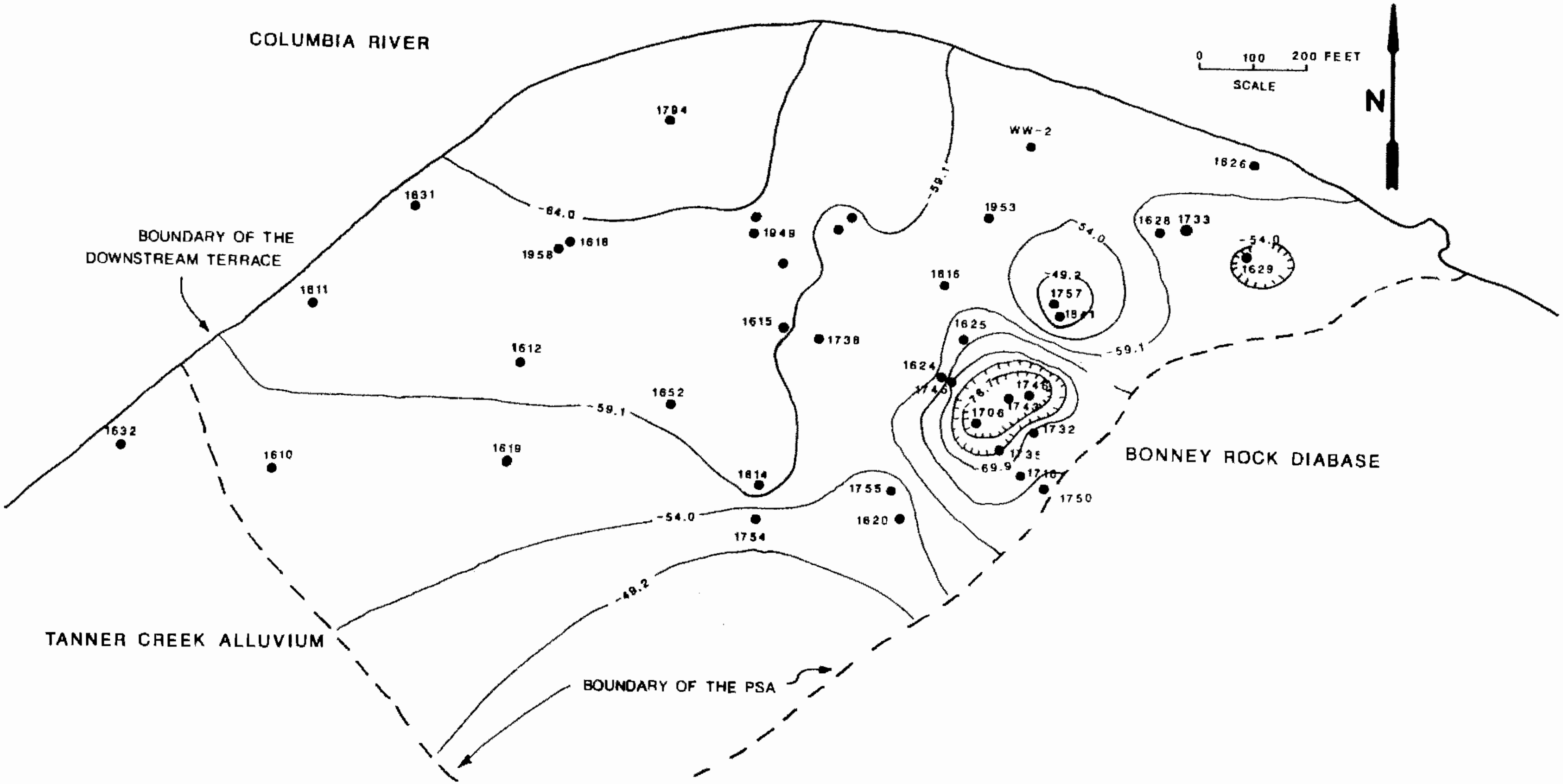



Figure 10. Top of the pre-slide alluvium hydrogeologic unit. Modified from Baron, 1990.

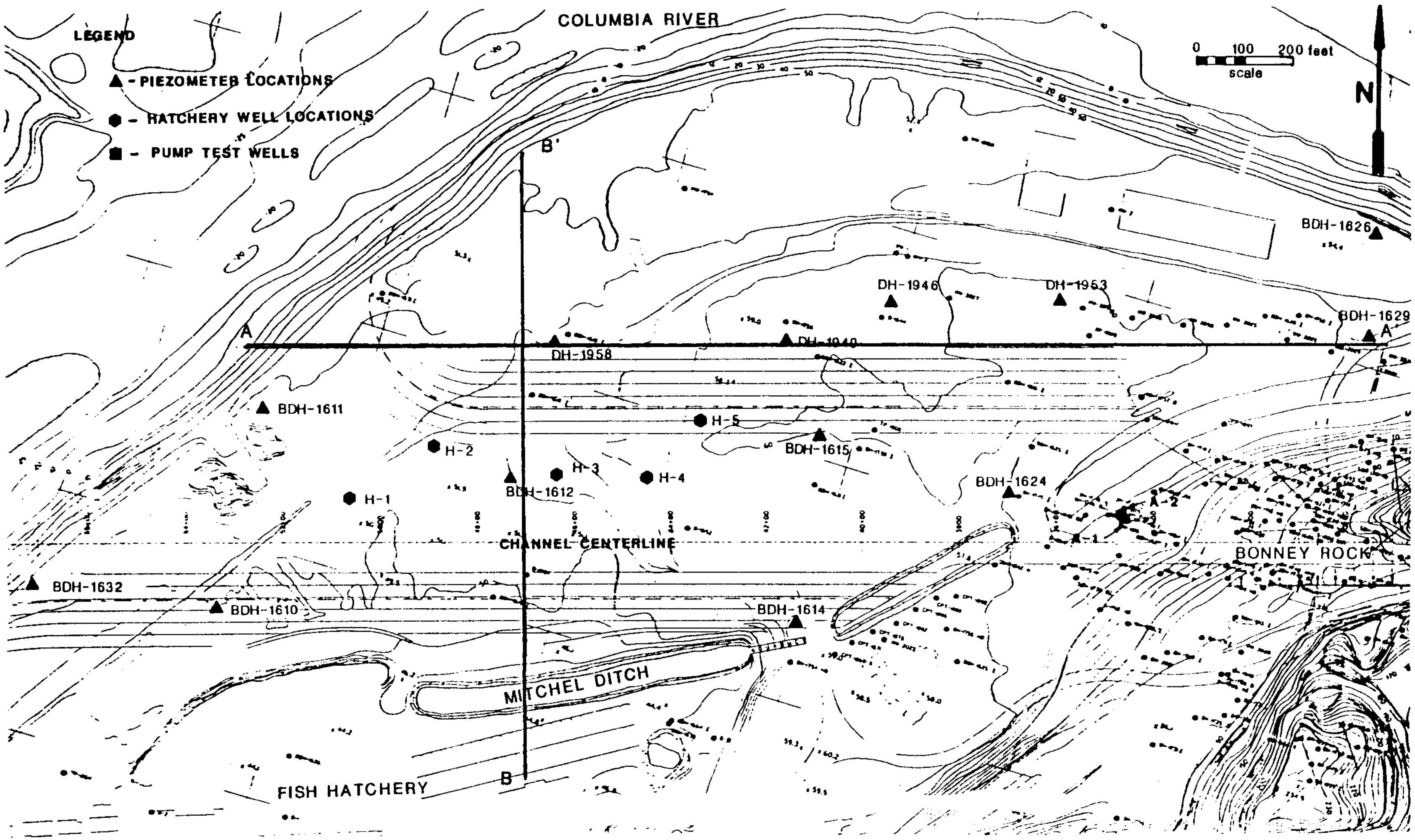



Figure 11. Diagrammatic cross-section locations for the downstream terrace at Bonneville Dam.

minor sand and silt zones. It is a highly permeable aquifer present from -51.8 meters (-170 feet) to bedrock in the terrace scour channel (see Figure 12, section B-B'). Thickness varies from 0 to 68 meters (0 to 223 feet). The pre-slide alluvium sub-unit two ($PSA_2$) is a relatively thin sand, silt and clay zone 3.1 to 9.1 meters (10 to 30 feet) in thickness overlying the $PSA_1$. Generally, the $PSA_2$ is found only in the terrace scour channel area but has been detected north of the scour area (RZA, 1988). Drilling logs (USACE, 1984) in the terrace describe this layer as a blue-gray clay with some loose coarse gravel. The $PSA_2$ has some lateral discontinuity. Since it is a less permeable water-bearing zone, it functions as an aquitard allowing for only partial hydraulic connection between the overlying pre-slide alluvium sub-unit three ($PSA_3$) and the $PSA_1$.

The uppermost sub-unit, $PSA_3$, is the predominant PSA sub-unit which extends over most of the downstream terrace area and extends under the Columbia River (Baron, 1990; USACE, 1976). $PSA_3$, a high-permeability aquifer, contains rounded coarse gravels, cobbles and boulders as well as variously sized lenses of sand and silt. Some of these sand and silt lenses are located downstream from a slide block (PSA-SB) encased in the $PSA_3$ and appear to be material derived from the slide block (RZA, 1988). In general, there is an increase in the amount of sand in this sub-unit up-section; a coarse sand separates the $PSA_3$ from the overlying Mica sand unit. The $PSA_3$ is the sub-unit from which water for the Bonneville Dam Fish Hatchery is produced.

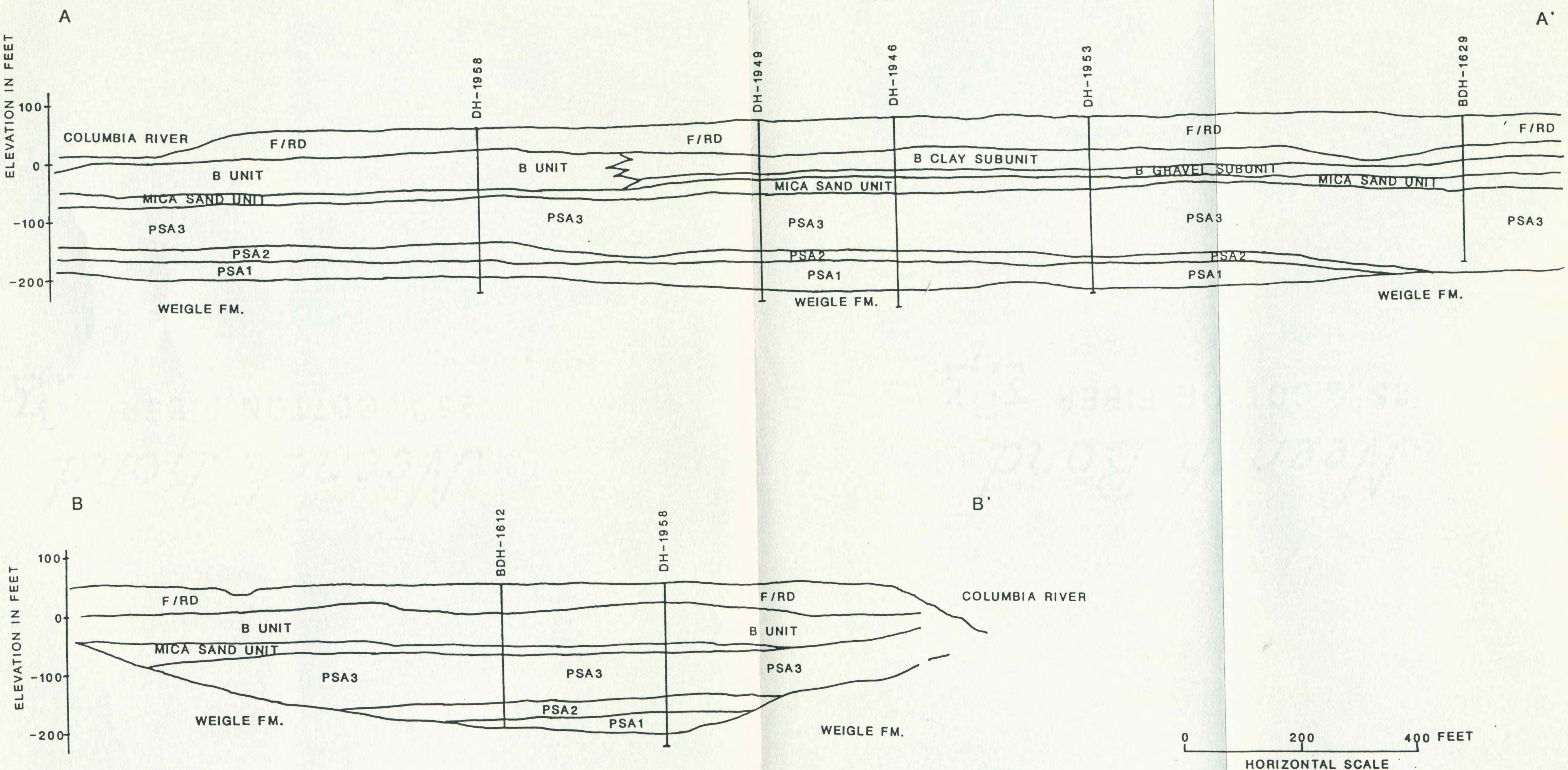



Figure 12. Diagrammatic cross-sections east-west and north-south through the downstream terrace at Bonneville Dam. Geology modified after RZA (1988) and USACE (1984).

The extent of the PSA-aquifer toward the north and west is unknown. The Bonney Rock intrusion provides a natural groundwater cut-off between the upstream channel area where groundwater level is controlled by the Bonneville Pool and the varying river levels below Bonneville Dam. To the south, the bedrock rises in elevation forming a natural boundary. Gravel similar to the terrace PSA-aquifer was encountered in the second powerhouse excavation (USACE, 1984) located 3.2 kilometers (two miles) northwest across the Columbia River (see Figure 1). At both locations the PSA overlies tufaceous sandstones and siltstones of the weigle formation. Several variations in the PSA occur in the terrace area other than vertical changes. A slide block or slide debris (PSA-SB) is encased in the $PSA_3$ west and northwest of the Bonney Rock intrusive. The block consists of brown silts, clays and angular rock fragments (RZA, 1988). It lacks exotic rocks, angular clasts, and large quantities of water. In the area south of Mitchell Ditch (see Figure 3), the upper section of the $PSA_3$ consists of sand. This material has been termed sand-rich $PSA_3$ (RZA, 1988) and is described as a sand with mica similar to the mica sand unit or a lithic sand containing abundant basalt and mafic rock fragments.

Overlying the PSA is the Mica Sand, a fine-grained micaceous, brown sand (see Figure 8 and Figure 12). This hydrogeologic unit contains minor amounts of silt, clay, lithic sand and layers of fine gravel. It is moderately permeable, but in comparison with the PSA-aquifer, it is considered an aquitard. The Mica Sand unit is usually 3.1 to 12.2 meters (10 to 40 feet) thick and thickens southward partially filling the depression in the southeast section of the upper PSA. Towards the western section of the terrace the mica sand interfingers with Tanner Creek alluvium (TCA). Mica Sand was encountered during exploration and construction of the second Bonneville powerhouse (USACE, 1976) suggesting that the unit also occurs across the Columbia River.

The B unit overlies the Mica Sand (see Figure 8 and Figure 12). The B unit, formerly called the blue clay unit (USACE, 1984), does not always contain abundant clay and was hence renamed (RZA, 1988). A portion of the B unit is gravel and sand with only locally abundant clay and silt. The B unit varies greatly both vertically and laterally and can be locally divided into two hydrogeologic sub-units -- the B unit clay ($B_c$) and B unit gravel ($B_g$) (see Figure 8 and Figure 12, section A-A'). The undivided sections of the B unit represent areas that are not dominated by a thick sequence of clay or silt and consist of interbedded layers of gravel and sand with clay and silt layers. The area south of Mitchell Ditch and west of the fish hatchery is undivided. Along the southern boundary of the terrace, sand is predominant over gravel.

The $B_g$ sub-unit contains abundant sand, silt and gravel in a clay-bearing matrix. It can be a prolific producer of water and has been defined (RZA, 1988) as the zone in which sands and gravel are more abundant than clays and silts. The $B_c$ is the upper sub-unit containing abundant blue clays and silts with minor amounts of sand and gravel. The $B_c$ may act as an aquitard in some areas of the terrace. The thickest clay zone is located directly west of the Bonney Rock intrusive and north of Mitchell Ditch (see Figure 3). Adjacent to this thick clay layer, clay layers are interbedded with thin sand and gravel layers (RZA, 1988). Further to the west, the $B_c$ is interbedded with more sand and gravel. West of well H-4 (see Figure 3), the B unit contains interbedded clay/silt and sand/gravel layers making subdivision into $B_c$ and $B_g$ sub-units difficult (see Figure 12, section A-A').

The uppermost hydrogeologic unit in the terrace is designated the F/RD (see Figure 8 and Figure 12). This unit consists of fill material (construction debris, wood, sand, silt and gravel) and recent river deposits (coarse gravel, cobble, sand and silt) which have been deposited by the Columbia River or through human modification of the terrace. The thickness of this unit varies; the river deposits are usually less than 9.1 meters (30 feet) and fill deposits are usually less than 15.2 meters (50 feet) (RZA, 1988).

A local depositional unit in the terrace area is the Tanner Creek alluvium. This depositional unit consists of material deposited by Tanner Creek. The Tanner Creek alluvium has cut into or is interbedded with other alluvial units in the terrace area. In the area of the Tanner Creek alluvium, other alluvial terrace units are either partially or totally absent. The Tanner Creek alluvium contains rounded to sub-angular gravel with sand, silt and clay as layers that may be lenses. The clast size tends to be smaller and the shapes are more angular than the gravel in the PSA.

The alluvial units in the terrace are generally continuous laterally and fairly uniform in thickness. However, there are depositional zones that exist within the terrace area which do not have definite boundaries but have gradational contacts. These zones (Figure 13) have been named the Bonneville alluvial sequence zone, the Tanner Creek zone, the sand zone and a talus zone by RZA (1988). The Bonneville alluvial sequence zone covers a major portion of the terrace area. In this zone, the major alluvial units are fairly uniform both vertically and laterally. The major variations are the PSA-SB sub-unit, the thick PSA section that fills the scour channel area, and the thick clay zone in the $B_c$ sub-unit. In the Tanner Creek zone, sediment from Tanner Creek dominate or are interbedded with the units of the Bonneville alluvial sequence. The B unit, that increases in thickness near Tanner Creek, has been impacted the greatest by Tanner Creek alluvium deposition with less influence on the PSA unit (RZA, 1988). The sand zone, in the area south of Mitchell Ditch, sand predominates over gravel in the PSA and B units. In the talus zone, talus from Bonney Rock and bedrock slide blocks are abundant (RZA, 1988).

The nature, distribution and thermal behavior of the aquifers and confining units in the downstream terrace are controlled by the lithology and stratigraphy of the alluvial deposits. Each alluvial unit in the terrace has its own unique thermal behavior. The thermal behavior of each alluvial unit is influenced by the hydraulic parameters that are unique to the unit. Parameters that influence the hydraulic character of the alluvial units located in the terrace are: where the unit

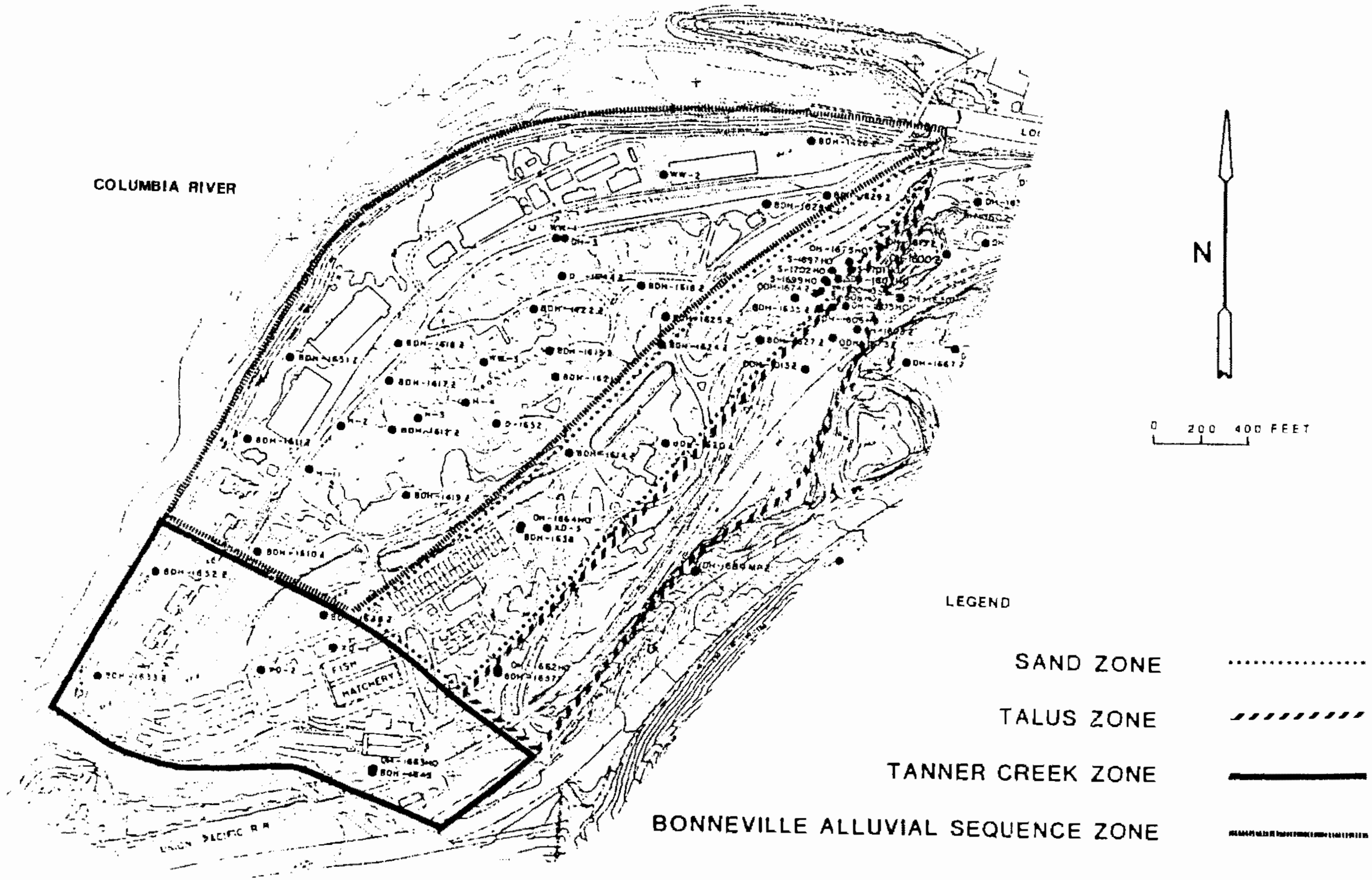



Figure 13. Bonneville Dam downstream alluvial terrace depositional zone map. From Rittenhouse-Zeman and Associates, 1988.

is located in the terrace (stratigraphically and spatially), its porosity (hydraulic conductivity), the degree to which it is influenced by fish hatchery pumping, and its thermal conductivity.

## HYDROGEOLOGY

This section examines the hydraulic properties and parameters of the terrace hydrogeologic units. Hydraulic behavior of the terrace hydrogeologic system has been assessed by several investigations (Baron, 1990; Cornforth Consultants, 1987; Cornforth Consultants, 1986b; USACE, 1984) by analysis of pump test data. Thermal behavior of the terrace groundwater system can be directly related to its hydraulic behavior since simultaneous flow of heat and groundwater is treated as a coupled process. Accordingly, it is of benefit to outline the hydraulic observations made by the above investigators.

Four constant-rate pump tests have been performed to evaluate the specific hydraulic parameters of the PSA and the Mica Sand aquifers. Of these four pumping tests, three were performed on the PSA-aquifer (well A-2, also known as WW 1805, and hatchery wells H-3 and H-4) and one on the Mica Sand aquifer (A-1, also known as WW 1816) (see Figure 3 for pump locations). Analysis of pump test data by different investigators has lead to a range of values for the hydraulic parameters of the terrace aquifers. Difficulties encountered with pump tests on the terrace aquifers are produced by complexities created by Columbia River level variations occurring during the test and interference from concurrent pumping of existing hatchery wells. Differences in results can be partially attributed to how interference created by variation of the river elevation during the pump test was evaluated. Columbia River elevation variation along the north boundary of the terrace is influenced by the amount of water being spilled from Bonneville Dam. In the following tables, the presentation of more than one value or range of values is a reflection of this difference in analysis.

The results of pump tests indicate that the PSA-aquifer has a static water level of about 15.2 meters (50 feet) below ground surface depending on pumping rates. It is a confined, highly transmissive and an extensive aquifer capable of providing 95,375 cubic meters per day (17,500 gallons per minute) of water to the fish hatchery on a continuous basis. The reported interpretations of Cornforth Consultants (1987) and Baron (1990) from pump tests performed on terrace aquifers are given in Tables II through IV. Table II outlines the pump test results on the PSA-aquifer.

Flattening of the drawdown curve during PSA pump tests (A-2, H-3, and H-4) suggests that a large portion of the recharge to the PSA-aquifer is from the Columbia River. However, Baron (1990) observed that a response occurred in a piezometer (H-1) located on the Washington shore of the Columbia River, (see Figure 2) 975.4 meters (3200 feet) from the fish hatchery wells, due to changes in hatchery well pumping rate. This indicates that influence from the fish hatchery wells extends beneath the river supporting the hypothesis that the PSA-aquifer is not totally connected to or recharged from the Columbia River. A response beyond

TABLE II

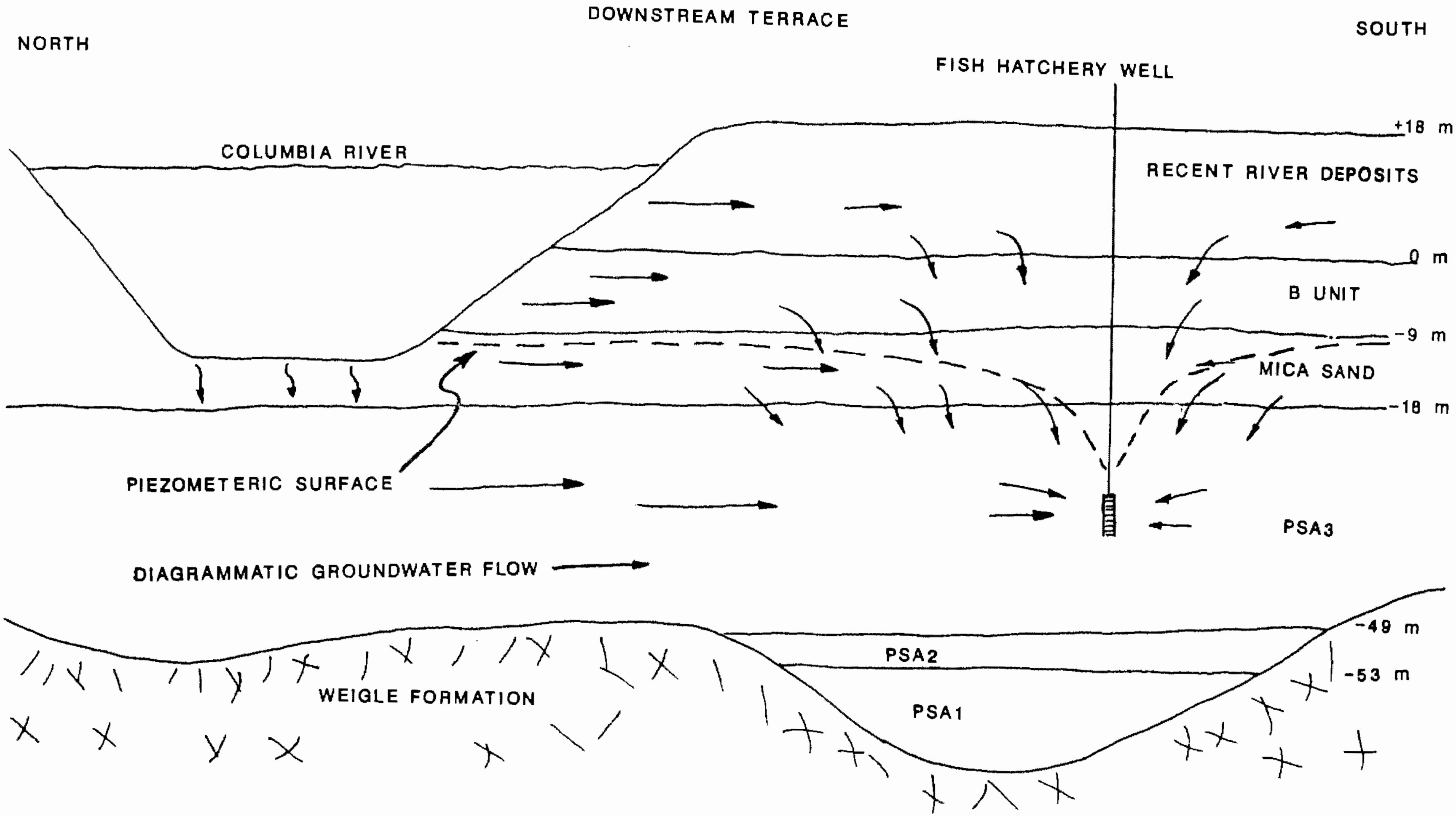
PUMP TEST RESULTS ON THE PSA-AQUIFER
AT BONNEVILLE DAM DOWNSTREAM TERRACE
(Cornforth Consultants, 1987; Baron, 1990)

| Test: | A-2 | H3 & H4 |
|---|---|---|
| Permeability | 0.2 - 0.3 meters/min<br>(0.5 - 1.0 ft/min) | -<br>- |
| Hydraulic Conductivity | 38 - 240 meters/day<br>(920 - 5,900 gpd/ft$^2$) | 38 - 122 meters/day<br>(920 - 3,000 gpd/ft$^2$) |
| Transmissivity | 1,366 - 3,974 meters$^2$/day<br>(110,000 - 320,000 gpd/ft) | 1,366 - 2,422 meters$^2$/day<br>(110,000 - 195,000 gpd/ft) |
| Storativity: (unitless) | $2*10^{-3}$ - $3*10^{-5}$ | $3*10^{-3}$ - $3*10^{-5}$ |
| Radius of Influence | 488 meters<br>1,600 ft | -<br>- |

the Columbia River would not occur if there was direct recharge by the river (Baron, 1990).

Prior to the observations at the H-1 piezometer, several analytical techniques had been applied to determine whether the Columbia River was a recharge boundary for the PSA-aquifer in the terrace area. Pump tests of the PSA-aquifer encounter a recharge boundary within the first 200 minutes of a test. The results of these analyses eliminated the Columbia River as a direct recharge boundary (Cornforth Consultants, 1987).

Analysis of pump test data by Cornforth Consultants (1987) along with limited temperature data, and terrace lithologies lead to the conclusion that the PSA-aquifer is primarily recharged by a far-field source (assumed to be the Columbia River), and locally recharged by near-field sources and by downward leakage from overlying aquifers. Pumping of the PSA-aquifer results in significant drawdowns at some piezometers screened in the shallower overlying aquifers, indicating their leaking behavior (Cornforth Consultants, 1987). Leakage into the PSA-aquifer was thought to be produced by a large cone of depression within the aquifer creating a hydraulic gradient between the PSA-aquifer and the overlying deposits. Cornforth Consultants (1987) speculated that even though the vertical hydraulic conductivity of the confining beds are low, specifically in the Mica Sand, the large area over which flow is induced supplies sufficient recharge to the PSA-aquifer to constantly yield large quantities of water to the wells. Baron (1990)




<u>Figure 14</u>. Conceptual model of the flow behavior in the Bonneville Dam downstream hydrogeologic units.

also noted that downward leakage was not significant when observed on a localized level, but substantial when examining the terrace as a whole.

The amount of water recharging the PSA through downward leakage is not known. Part of the conceptual hydraulic model (Figure 14) of the terrace is that water leaking downward into the PSA is replaced by water from the Columbia River flowing into the transmissive fill/recent deposits and B units that overlie the Mica Sand. There are primarily two areas that show the greatest impact from drawdown due to pumping (Baron, 1990). These areas are the region of the downstream alluvium/Bonney Rock contact (a boundary condition) and the western region of the terrace (a recharge boundary) (see Figure 3). Preliminary stream depletion calculations made by Cornforth Consultants (1987) lead to the estimation that it would take less than 30 minutes for a hatchery well to pump 75 percent of its water as near-field infiltration from the Columbia River. If this were the case, wide groundwater temperature variations such as those observed in the Columbia River would be observed in water pumped from the hatchery wells. Hatchery well temperature varied less than 4°C (7.2°F) during 1988.

Deep dewatering drilling indicated the existence of lithologic differences in the PSA from area to area that affect the PSA characteristics. Drawdown behavior in the terrace area, as determined from distance-drawdown curves, illustrate the lithologic variations in the area west of fish hatchery wells compared to the area east of fish hatchery wells. Cornforth Consultants (1987) observed different degrees of drawdown with respect to direction in the terrace area. This variable drawdown behavior indicated possible horizontal anisotropy and/or a pronounced recharge source to the west. Areas observed to be affected by pumping were the downstream alluvium/Bonney Rock contact, and the western end of the terrace. Drawdown analysis by Baron (1990) is consistent with the observations of variable drawdown behavior in the terrace area made by Cornforth Consultants (1987). Horizontal anisotropy is probably due to variations in lithologic content and fluvially produced streamlined sedimentary depositional structures.

The wide range of transmissivities observed in the PSA-aquifer are due to zones of higher and lower transmissivities occurring within the aquifer. Pump test analysis by Baron (1990) indicates a zone of very high transmissivity and conductivity in the southeastern section of the alluvial terrace. This zone coincides with the depression in the top of the PSA-aquifer filled by sand-rich PSA material. The northeast region of the terrace shows relatively low transmissivity that is associated with the influence of the slide block located in that region of the terrace.

The western area of the terrace, lacking the internal variability created by encasement of slide-block material, has higher hydraulic conductivity than that of the eastern section. The hydraulic conductivity of the Tanner Creek alluvium is similar to that of the PSA-aquifer.

Analysis of pump test data (pump test A-1) from WW-1816 (see Figure 3), in the Mica Sand aquifer, indicated that the unit is confined and moderately productive (Cornforth Consultants, 1987). Both Baron (1990) and Cornforth

Consultants (1987) indicate that a large portion of the recharge to the aquifer comes from the Columbia River. Cornforth Consultants (1987) noted, during a pump test on the Mica Sand, that drawdown in piezometers located in the deeper PSA-aquifer was greater than that observed in the Mica Sand indicating that recharge also occurs from the PSA into the Mica Sand. Table III outlines the hydraulic parameters of the Mica Sand aquifer as determined from the pump test.

The Mica Sand has been described (RZA, 1988) as compact to dense and moderately permeable. Pump test evidence indicates that the unit is confined with considerable direct leakage into the aquifer from the Columbia River (Cornforth Consultants, 1987). Early stabilization of the drawdown curve at approximately 4.6 meters (15 feet) after five minutes of pumping suggests a nearby zone of recharge probably from the underlying PSA-aquifer. A general correlation between pump test data and nearby river stage variation also indicates a large portion of the recharge to the aquifer appears to come from the Columbia River (Cornforth Consultants, 1987).

The shallower aquifers (Mica Sand and $B_g$ sub-unit) experience significant recharge from the Columbia River. The hydraulic gradient produced by pumping in the lower $PSA_3$ allows for recharge to occur as leakage from these shallow aquifers into the PSA-aquifer (see Figure 14). Baron (1990) observed that the preferred direction of flow in the overlying alluvial deposits is horizontal due to their layered nature. The actual percentage that vertical leakage represents as recharge into the PSA-aquifer is unknown.

TABLE III

PUMP TEST RESULTS ON THE MICA SAND AQUIFER
AT BONNEVILLE DAM DOWNSTREAM TERRACE
(Cornforth Consultants, 1987)

| Test: | A-1 |
|---|---|
| Permeability | 0.003 meters/min.<br>(0.01 ft/min.) |
| Hydraulic Conductivity | 2.9 meters/day<br>(70 gpd/ft$^2$) |
| Transmissivity | 41 - 68 meters$^2$/day<br>(3,300 - 5,500 gpd/ft) |
| Storativity | - |
| Radius of Influence | 488 meters<br>(1,600 ft) |

# CHAPTER IV

# HEAT TRANSPORT IN POROUS MEDIA

## BACKGROUND

The utilization of temperature data to investigate the nature of groundwater movement, recharge and discharge is not a new concept in groundwater science. Schneider (1962) studied the relationship between the seasonal fluctuation of temperature in an influent lake and the seasonal fluctuation of water temperature in nearby wells. A similar type of study was made by Simpson (1952) examining the water temperature of wells pumping near the Mohawk River in New York. Parsons (1971) studied the relationship between groundwater movement and subsurface temperatures in a glacial complex in Canada and made comparisons between thermal profiles measured in the field and thermal profiles simulated by digital computer.

In conjunction with field studies has been advances in the theory of simultaneous conductive and convective heat transfer. The flow of water is controlled by the pattern of hydraulic gradients, but there may also be additional flow induced by the presence of a thermal gradient (Gurr et al., 1952; Philip and de Vries, 1957). Therefore, the simultaneous flow of heat and groundwater must be treated as a coupled process. Heat flow through aquifers results from two mechanisms: conduction and convection. Heat flow by conduction is in response to temperature gradients within the saturated material and is directly proportional to the thermal conductivity of the geologic formations. Conductive transport is most important in static groundwater situations. Convective transport occurs as heat moves from place to place as the liquid moves. Conductive transport is proportional to the velocity of the liquid (Brown et al., 1983; Freeze, 1979; Ene, 1987). In most groundwater systems, convective transport exceeds conductive transport.

There are two limiting types of convective heat transfer commonly distinguished; forced convection and free convection. Under forced convection, fluid inflows and outflows are present and fluid motion is due to the hydraulic forces acting on the boundaries of the system. Under free convection, fluid cannot enter or leave the system. The motion of the fluid is due to density variations caused by temperature gradients. In the analysis of forced convection, density gradients are ignored and buoyancy effects are considered negligible (Freeze, 1979; Domenico, 1973). In free convection, fluid motion is controlled by buoyancy effects. The transport of heat by natural groundwater-flow systems is an example of forced convection.

If conduction alone was responsible for underground heat flow, the temperature distribution within any given volume could be determined knowing the temperature distribution on the surface of that volume (Brown et al., 1983). The difference between temperature measured under known boundary conditions, including the moving liquid and temperature computed under the assumption that the heat flow is only conductive, is relatable to the velocity of groundwater flow (Brown et al., 1983). This is the basic concept underlying the computation of groundwater velocities from observed temperatures.

The relationship between conduction and convection of heat in aquifers is affected by the velocity of groundwater. Therefore, the distribution of temperature in an aquifer can be an indication of the magnitude of the groundwater velocity in the saturated zone. The temperature variations at various levels in a hydrogeologic system depend on the groundwater flow velocity and increase with increased velocity. The greater the velocity of water movement through a porous medium and the resulting larger mass movement in the system, the greater the effect of the fluid movement on the aquifer temperature and the less time required to observe the temperature changes (Cartwright, 1974; Brown et al., 1983).

## HEAT AND FLUID ANALYTICAL SOLUTIONS

Stallman (1963) presented the basic equation for the simultaneous transfer of heat and water, and suggested that the equation might be useful in determining the rates of groundwater movement and the permeability of formations. The general differential equation for simultaneous non-steady heat and fluid flow through isotropic, homogeneous, and fully saturated porous media is

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} - \frac{c_o \rho_o}{K}\left[\frac{\partial (V_x T)}{\partial x} + \frac{\partial (V_y T)}{\partial y} + \frac{\partial (V_z T)}{\partial z}\right] = \frac{c\rho}{K}\frac{dT}{dt} \quad (1)$$

where:

T = temperature at any point at time t,

$c_o$ = specific heat of fluid,

$p_o$ = density of fluid,

c = specific heat of solid-fluid complex,

p = density of solid-fluid complex,

k = thermal conductivity of solid-fluid complex,

$v_x, v_y, v_z$ = components of fluid velocity in x,y, and z direction,

t = time since flow started (Stallman, 1963).

Stallman (1963) solved equation (1) to estimate groundwater velocity in the horizontal direction, $v_x$, the down-gradient velocity. The solution assumes that the aquifer has a dip, that the dip of the aquifer is known, that the flow of groundwater is down-dip, groundwater flow is steady, and that the temperature regime is not modified at depth due to topographic control. The solution is

$$\frac{T_1 + T_3 - 2T_2}{(\Delta Z)^2} = \frac{c_o p_o V_x}{K} (\sin \alpha) \frac{(T_1 - T_3)}{2 \Delta Z} \qquad (2)$$

where:

$T_1$, $T_2$, $T_3$ = temperature, absolute, measured at points 1, 2, and 3;

z = depth interval between temperature-measurement points;

= dip of the aquifer.

Figure 15 is an illustration of the system for solving groundwater velocity in the horizontal direction. An estimation of transmissivity can be derived by combining Darcy's law with an observed value of the head gradient and the aquifer thickness.

Bredehoeft and Papadopulos (1965) presented a solution to Stallman's general equation for the case of steady-state vertical flow of both groundwater and heat. Their solution allows for a means of calculating vertical rates of groundwater movement or the hydraulic conductivity of a leaky confining bed. They constructed type response curves for the case of steady parallel flow of heat and water along the z-axis. A configuration of the system is shown on Figure 16. Bredehoeft and Papadopulos (1965) found that velocity through a confining bed may be expressed as

$$V_z = KB/c_o p_o L \tag{3}$$

where L is the vertical distance between ends of the selected measurement interval and B is a dimensionless parameter defined by equation (3). The value of B is found by comparing observed values of z/L versus $(T_z - T_0)/(T_L - T_0) = f(B, z/L)$ with the type curves (Figure 17).

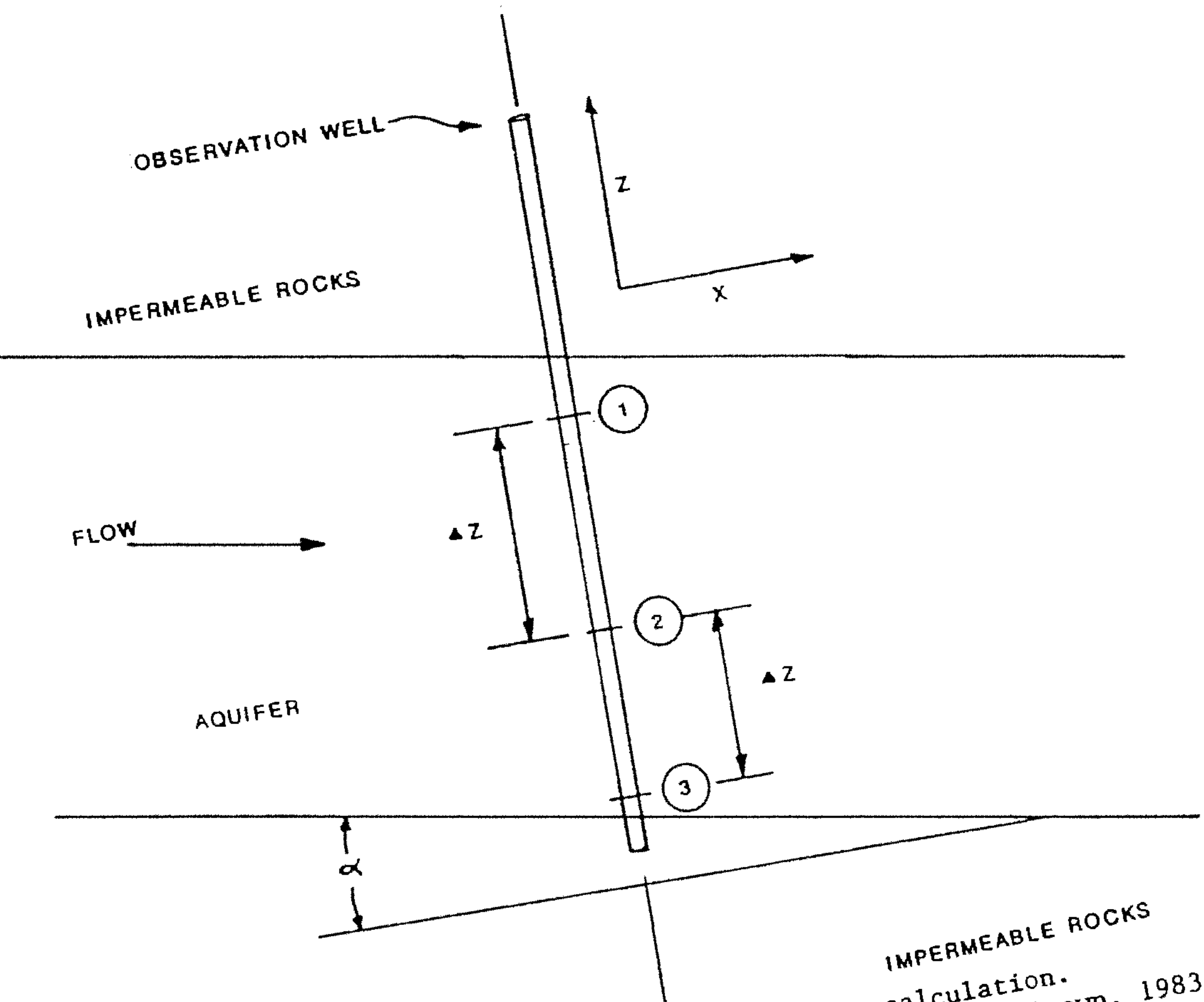



Figure 15. Configuration of horizontal velocity calculation. Diagrammatic section of a dipping aquifer. Modified from Brown, 1983.

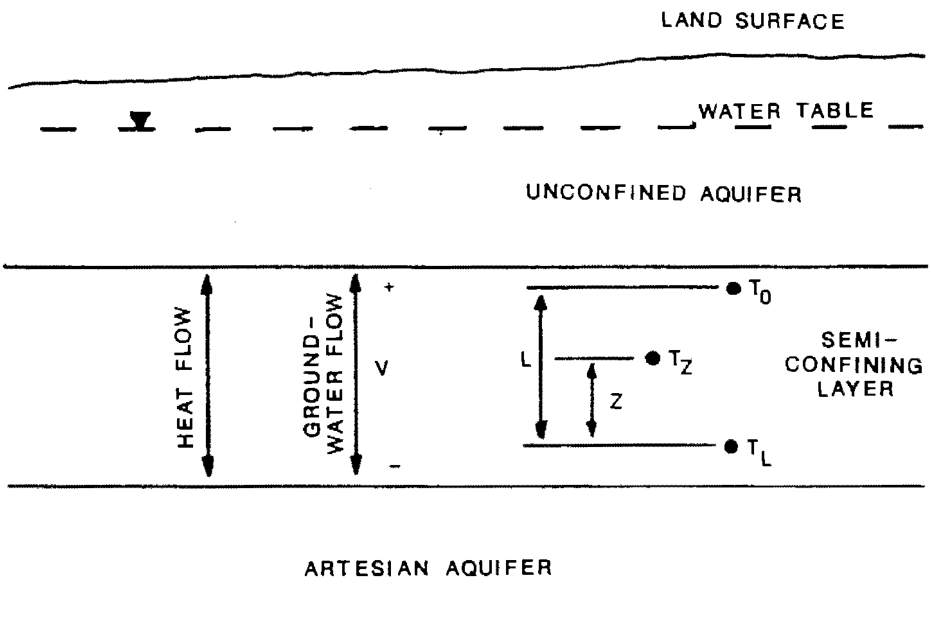



Figure 16. Configuration of vertical velocity calculation. Diagrammatic sketch of a leaky aquifer. Modified from Bredehoeft and Papadopulos, 1965.

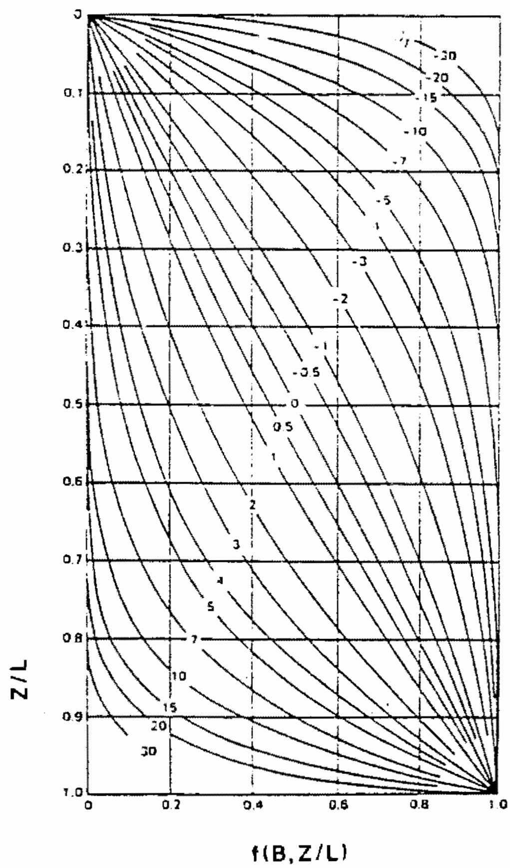



Figure 17. Vertical flow type response curves. Type curves of the function f(B,z/L). From Broedehoeft and Papadopulos, 1965.

## HORIZONTAL AND VERTICAL GROUNDWATER VELOCITY

Groundwater flow in the downstream alluvial terrace at Bonneville Dam, controlled primarily by hatchery well pumping, appears to move groundwater dominantly in the horizontal direction in the $PSA_3$-aquifer and produce potentially significant downward leakage from the Mica Sand. The equations presented therefore can be used as a basis for analyzing downstream terrace temperature data and allowing for some rough estimates of groundwater velocities in the terrace groundwater system.

Calculating the horizontal groundwater velocity for the Bonneville Dam downstream terrace using equation (2) introduces several constraints and violates some assumptions upon which the equation is based. Equation (2) assumes groundwater movement is only in the horizontal direction with the aquifer confined by two impermeable layers, one above and one below. In the downstream terrace groundwater system, thermally variable groundwater is leaking downward from the Mica Sand unit into the PSA-aquifer due to a decrease of pressure in the aquifer from hatchery pumping. The volume of water entering the PSA-aquifer due to leakage may be significant and would introduce error in horizontal velocity calculations. Stallman's model also assumes a steady flow whereas flow conditions in the downstream terrace are variable due to pumping. Finally the PSA-aquifer lacks a definitive dip and groundwater flow in the terrace PSA-aquifer is not consistently parallel to a dip.

Calculations of horizontal velocity in the $PSA_3$-aquifer were made with an understanding that several assumptions upon which equation (2) is based do not hold true in the downstream terrace. Horizontal flow in the PSA-aquifer for the terrace is assumed to flow toward the hatchery wells. A very low dip of one degree was used in the calculations. Leakage into the PSA-aquifer from the Mica Sand unit decreases the calculated groundwater velocity in the $PSA_3$. This leakage effect produces a lower thermal gradient in the top section of the aquifer than would occur if the unit was impermeable. Consequently, horizontal velocity calculations represent orders of values and give an indication of horizontal flow rates.

Horizontal velocity calculations for the $PSA_3$ were made on the following piezometers; BDH-1610, BDH-1611, BDH-1615, BDH-1624, and DH-1953. The thermal conductivity of the water/solid mixture, K, of the $PSA_3$-aquifer is assumed to be $5.0 \times 10^{-3}$ cal/cm sec°C. This value was selected since work by previous investigators on similar material (Lapham, 1988; Birch, 1947) indicates that this value would be representative of the $PSA_3$-aquifer material. The specific heat of water, $c_0$, times the density of water, $p_0$, is equal to 1 cal/cm$^3$/°C. The greatest temperature change across the $PSA_3$-aquifer for each piezometer based on thermal profiles located in Appendix A was selected for the horizontal velocity calculations. Horizontal velocity in the $PSA_3$ for these piezometers ranged from 100 to 300 cm/day. The average value being 212 cm/day. The highest values were produced at BDH-1610, the lowest at BDH-1611.

An example of a horizontal groundwater velocity using terrace temperature data is shown for BDH-1610; an area in which temperature data indicates high groundwater flow rates are occurring. The following temperature readings were selected to represent a relatively even distribution of temperature-measurement points. Temperature measurements representing $T_1$, $T_2$, and $T_3$ in equation (2) were selected at -74.5 feet, -124.5 feet, and at -183.5 feet representing depth intervals of 1,661.2 centimeters. The temperature measured at these elevations on February 3, 1987 were 7.22°C, 10.0°C, and 7.78°C, respectively. Using these values in equation (2) produces a horizontal groundwater velocity of approximately

$$\frac{(-5.0^\circ C)}{(2{,}759{,}452.6\ cm^2)} = \frac{(1\ cal/cm^3/^\circ C)(\sin 1^\circ)(-0.56^\circ C)V_x}{(5 \times 10^{-3}\ cal/cm\ sec\ ^\circ C)(3{,}322.3\ cm)}$$

$V_x$ = 0.0031 cm/sec or approximately 266 cm/day.

Calculation of vertical groundwater velocity through the Mica Sand unit, which acts as a leaky confining unit to the PSA-aquifer, for the downstream terrace was also attempted. Several factors produce complications and limit the number of calculations that could be made. These limiting factors are erratic temperature readings across the Mica Sand unit that do not allow for a type curve fit, temperature measurements that are made too far apart for the generally thin Mica

Sand unit which does not allow for enough data points for velocity calculations, and many cases where there is no temperature change within the Mica Sand unit.

Most of the piezometers in the downstream terrace do not have enough data points or a thermal gradient that allows for vertical velocity calculations. Calculations were completed on BDH-1615, BDH-1614 and BDH-1629 using equation (3). The thermal conductivity of the water/solid mixture, K, of the Mica Sand unit is assumed to be $4.0 \times 10^{-3}$ cal/cm sec °C. This value was selected since work on similar material (Birch, 1947; Cartwright, 1974) indicates that this value would be most representable for the Mica Sand unit. The specific heat of water, $c_o$, times the density of water, $p_o$, is equal to 1 cal/cm$^3$/°C. Temperature data of the Mica Sand from BDH-1614 for July 7, 1988 best fits the type curve B = -2.7. The vertical distance, L, between ends of the selected measurement interval is 609.6 cm. The Mica Sand vertical groundwater velocity at BDH-1614 for July 7, 1988 is approximately:

$$V_z = (4.0 \times 10^{-3} \text{ cal/cm sec °C})(-2.7)/(1 \text{ cal/cm}^3/\text{°C})(609.6 \text{ cm})$$

$$= -1.8 \times 10^{-5} \text{ cm/sec or approximately } -1.5 \text{ cm/day.}$$

The negative sign indicating that flow is in the downward direction.

Vertical groundwater velocities for the Mica Sand made from the other selected piezometers for the same time of the year range from 1.1 to 2.0 cm/day. The average value being 1.6 cm/day. All calculations indicated a downward flow.

Groundwater velocity calculations for the horizontal flow of the $PSA_3$-aquifer (an average of 212 cm/day) and the vertical flow (leakage) of the Mica Sand unit (1.6 cm/day) indicate that an order of two magnitudes of difference exists between the two directions of flow occurring in the groundwater system of the terrace. This supports the observation that groundwater flow is dominantly horizontal in the terrace, but that a notable amount of leakage into the productive PSA-aquifer does occur.

Temperature data presented in a temperature-depth profile can be used to estimate and evaluate the amount of water moving through the porous media. Areas that have the greatest temperature variations are also areas of higher groundwater velocities. This generalization is based on the hypothesis that for the case of no pumping activity, a static system, there would be an even temperature distribution throughout the temperature-depth profile of the piezometer. The greatest amount of temperature variation would occur near the land surface due to atmospheric influences and decrease downward. This assumption forms the basis of the temperature analysis in the following chapter to assess groundwater movement in the downstream terrace.

The terrace, on average, is supplying 10,738 gallons per minute (0.68 $m^3$/sec.) of water to the fish hatchery. Groundwater is pumped from wells that partially penetrate the PSA-aquifer. Temperature data presented in the temperature-depth profiles and in the form of isothermal contour maps can be used to further evaluate where groundwater is moving faster than in other sections in the terrace.

# CHAPTER V

# CHARACTERIZATION AND INTERPRETATION OF THERMAL BEHAVIOR

## GENERAL

Groundwater temperature behavior of the terrace is highly impacted by fish hatchery pumps operating at a combined pumping rate of 12,900 to 17,200 gpm. Figure 18 illustrates the relationship between fish hatchery well pumping and well temperature. A rough correlation exists between the total pumping rate of the fish hatchery wells and the temperature at each hatchery well. Hatchery well H-5, which is located closest to the Columbia River, shows the greatest influence from pumping.

To interpret and formulate a conceptual model of the temperature behavior in the terrace, the hydraulic parameters that influence the groundwater system must be examined. The more important factors of the system are: 1) the porosity of the material in the groundwater system, 2) the depositional nature of the material, 3) the temperature of the groundwater in storage, 4) the temperature of the river, 5) the amount of mixing that occurs as a result of pumping, and 6) the specific heat of the rocks and mineral grains in the hydrogeologic units.

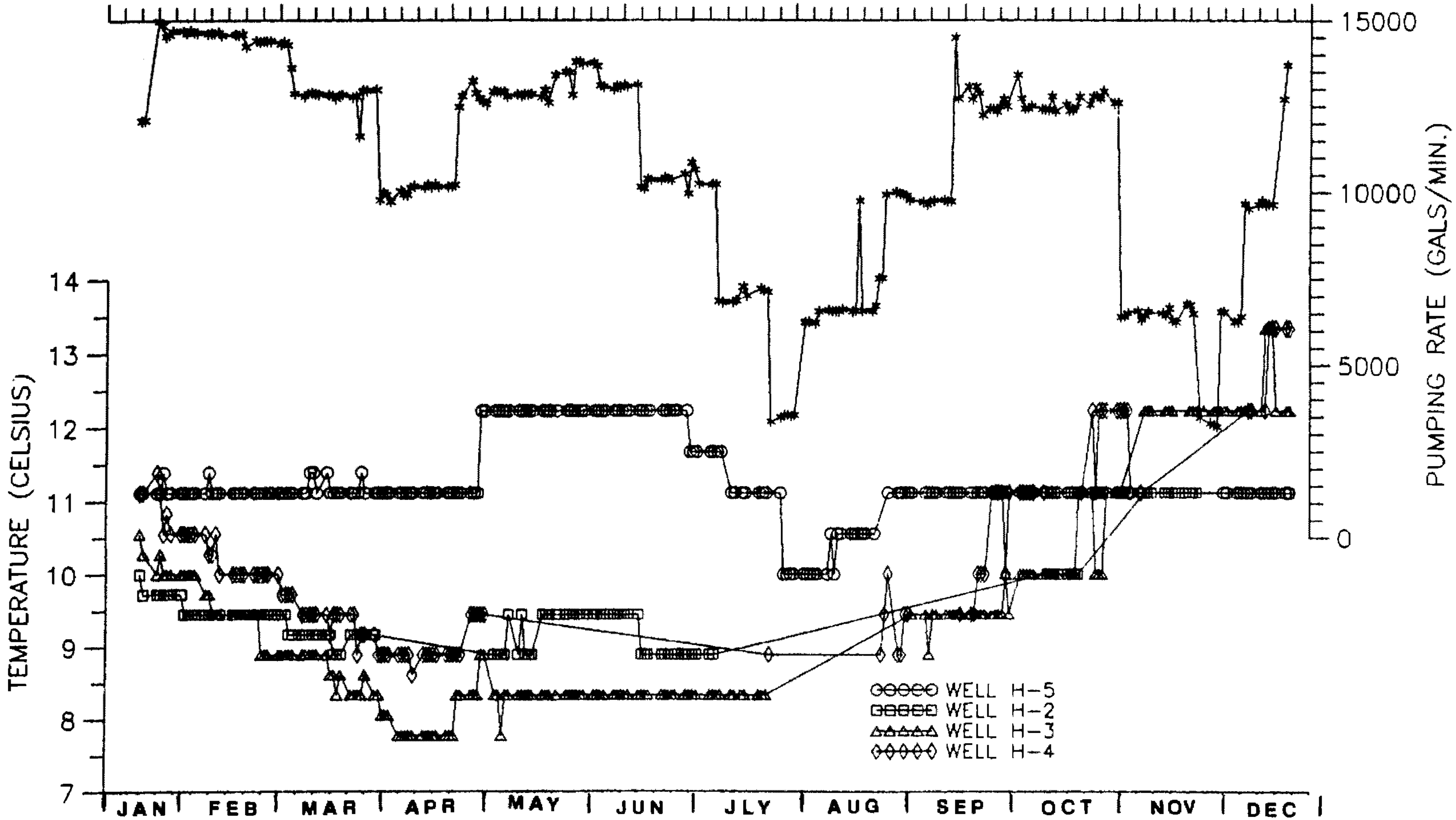



Figure 18. Total hatchery well pumping rate and hatchery well temperatures for 1988. See Figure 3 for hatchery well locations.

The amount of mixing of river and groundwater is dependent upon: 1) the distance between the well and the river, and 2) the volume of groundwater available from storage. Other factors and dependencies that could potentially influence temperature behavior are: lateral and upward flow of heat in the aquifer, and the rate of flow of groundwater which varies inversely with the viscosity. Schneider (1962) noted that in the normal temperature range of groundwater in the United States, an increase of $1^{o}$F in the groundwater temperature lowers the viscosity sufficiently to increase the rate of flow by about 1.5 percent.

Table IV summarizes the thermal behavior of the hydrogeologic units from October 1986 to August 1988 with respect to the Columbia River at each piezometer. Included are the maximum and minimum observed temperatures of the hydrogeologic units at each piezometer. Temperature range information are derived from two sources: analysis of temperature-depth profiles and temperature-time graphs of each piezometer (Appendix A and Appendix B, respectively).

Detailed examination and interpretation from various thermal profiles of piezometers in the terrace form the core of the analysis presented in this chapter. Observations made from the thermal profiles were used to guide the development of other graphs and maps that allowed for further analysis of the temperature behavior of the terrace groundwater system. Appendix A contains the thermal profiles of each piezometer. Data used to produce the graphs and maps in this chapter were selected by examination of the thermal profile of each piezometer.

# TABLE IV

## TEMPERATURE VARIATION AND LAG TIME FOR THE STRATIGRAPHIC UNITS OF THE BONNEVILLE DOWNSTREAM TERRACE

Lag time is in days = difference between peak temperature of river in comparison with peak temperature of the piezometer.
H = heating peak  C = cooling peak
Low temp./high temp. in celsius from generalized smoothed temperature time graphs and low/high temperatures from thermal profiles.
(-) = indicates data was not available or insufficient for entry.  (*) = indicates time lag is possibly a whole year out of synch.

| PIEZOMETER NUMBER | DISTANCE FROM RIVER | B-UNIT TEMP RANGE | B-UNIT TIME LAG | MICA SAND TEMP RANGE | MICA SAND TIME LAG | PSA3 TEMP RANGE | PSA3 TIME LAG | PSA2 TEMP RANGE | PSA2 TIME LAG | PSA1 TEMP RANGE | PSA1 TIME LAG |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1632 | 22.9 METERS | 4.25/12 | - H | 7/10 | - H | 7/12 | - H | | | | |
| | (75 FEET) | (4.2/12) | 15 C | (7.4/10) | 120 C | (7.1/11.8) | 45 C | | | | |
| | | | 40 H | | 100 H | | 55 H | | | | |
| | | | 75 C | | - C | | 140 C | | | | |
| 1611 | 22.9 METERS | 8/18 | 50 H | 4.75/14.75 | 65 H | 5.4/12.5 | 115 H | 8.3/11 | - H | SAME AS PSA2 | |
| | (75 FEET) | (7.3/16) | 65 C | (5.4/12.8) | 50 C | (4.6/14.4) | 85 C | (9/10.4) | - C | | |
| | | | 40 H | | 70 H | | 80 H | | - H | | |
| | | | 85 C | | 80 C | | 120 C | | 200 C | | |
| | | | | | | | | | 180 H | | |
| 1610 | 121.9 METERS | 4/11.5 | - H | 4/11.5 | - H | 4/12.7 | - H | | | | |
| | (400 FEET) | (4.8/11.4) | 32 C | (4.6/11.1) | 32 C | (4.5/12.8) | 50 C | | | | |
| | | | 35 H | | 38 H | | 55 H | | | | |
| | | | 30 C | | 30 C | | 45 C | | | | |
| | | | - H | | | | - H | | | | |
| 1612 | 182.9 METERS | 4/12 | - H | 4/12 | SAME | 4/12 | SAME | 8.5/10.5 | - H | 8.5/10.5 | SAME |
| | (600 FEET) | (6.8/13.8) | 75 C | (5.7/11.1) | AS | (5.8/12.0) | AS | (8.6/10) | 70 C | (8.6/10.0) | AS |
| | | | 135 H | | B-UNIT | | B-UNIT | THICK CLAY | 210 H | | PSA2 |
| | | | - C | | | | | | 225 C | | |
| 1615 | 243.8 METERS | - | - H | 11/12.5 | - H | UPPER PART | - H | - | - H | - | - H |
| | (800 FEET) | (11.3/13.0) | - C | (11/12.6) | 10 C* | 9.5/12.7 | - C | (8.7/9.4) | - C | (8.7/9.4) | - C |
| | | | - H | | 20 H* | (10.2/12.9) | 55 H | | - H | | - H |
| | | | - C | | - C | LOWER PART | 140 C | | - C | | - C |
| | | | | | | - | 110 H | | | | |
| | | | | | | (8.6/12.9) | | | | | |
| 1624 | 256.0 METERS | 10.7/14 | - H | SAME AS | SAME | SAME AS | SAME | SAME AS | SAME | 8.7/10 | - H |
| | (840 FEET) | (11.1/15) | 85 C | B-UNIT | AS | B-UNIT | AS | B-UNIT | AS | (8.3/9.6) | - C |
| | | | 45 H | (10.8/13.4) | B-UNIT | (10.3/14.7) | B-UNIT | (9.4/14.2) | B-UNIT | | 285 H |
| | | | 145 C | | | | | VERY SANDY | | | 210 C |
| | | | 100 H | | | | | | | | 205 H |
| 1629 | 91.4 METERS | Bg | 85 H | 7.2/14.5 | SAME | UPPER PSA3 | 100 H | SLIDE BLOCK | SAME | | |
| | (300 FEET) | 7.2/14.5 | 80 C | (7.5/13.8) | AS | 9.5/15.2 | 95 C | 9.5/15.2 | AS | | |
| | | (7.5/17.5) | 85 H | | Bg | (9.9/15) | 65 H | (9.9/14.1) | PSA3 | | |
| | | | 100 C | | | | 135 C | | | | |
| | | | | | | LOWER PSA3 | | | | | |
| | | | | | | 9.5/11.7 | - H | | | | |
| | | | | | | (9.6/13.2) | - C | | | | |
| 1626 | 30.5 METERS | 5.2/15.5 | 90 H | 8.5/15.7 | 105 H | 9.5/16.2 | 104 H | | | | |
| | (100 FEET) | (4.5/16.8) | 50 C | (5.5/15.9) | 80 C | (10.0/16.0) | 120 C | | | | |
| | | | 95 H | | 75 H | | 90 H | | | | |
| | | | 60 C | | 110 C | | 150 C | | | | |

Piezometric thermal profiles were used as a means by which elevations could be selected that best represented the thermal behavior of a specific hydrogeologic unit at a particular piezometer. Selected elevations could then be used to evaluate the temperature behavior of a hydrogeologic unit for the whole terrace.

## ANALYSIS OF THE PSA-AQUIFER

Piezometers that extend into the $PSA_1$ sub-unit indicate groundwater with the least amount of temperature change as illustrated by temperature profile of BDH-1624 (Figure 19). Thermal isolation of the sub-unit is the result of the confining influence of the overlying $PSA_2$ and the location of the $PSA_1$ within the scour channel cut into the weigle formation. Piezometers (BDH-1611, BDH-1612, BDH-1615, BDH-1624, DH-1946, DH-1949, and DH-1958) that penetrate into the $PSA_1$ indicate groundwater with temperatures ranging from 8.3° to 11°C (46.9° to 51.8°F).

Thermal influence from the Columbia River is highly moderated and groundwater temperature lags behind river temperature by an estimated 215 days -- a little more than seven months. A temperature comparison graph of the $PSA_1$ (Figure 20) illustrates the behavior of the hydrogeologic unit with respect to the river. The piezometers used in the graph were selected because they penetrate the $PSA_1$ aquifer and have lengthy temperature records. It is difficult to select groundwater temperature peaks for the $PSA_1$ because of the small variations in temperature. Lag time and thermal moderation indicate that thermal influence on

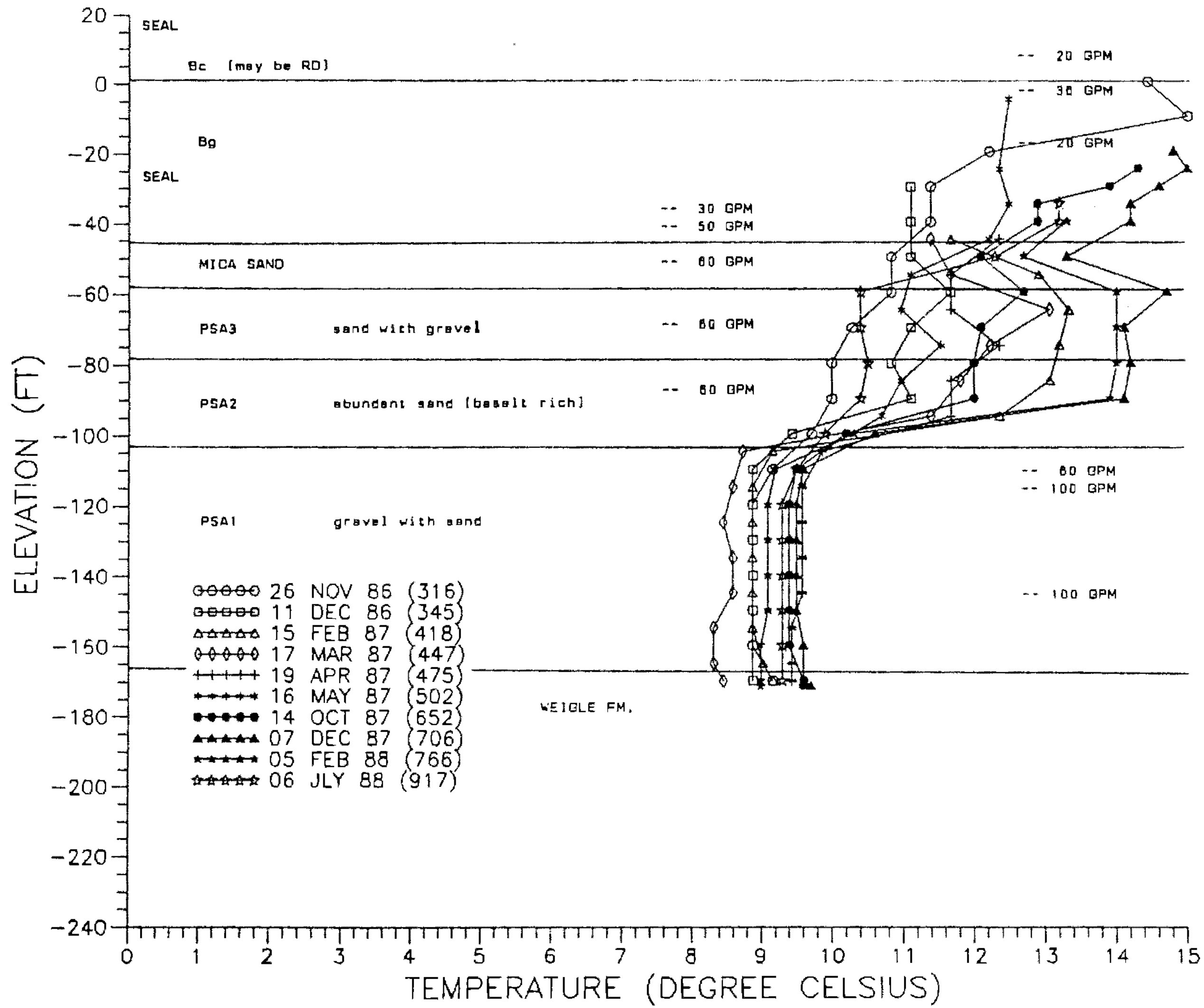



**Figure 19**. Temperature-depth profile of BDH-1624.

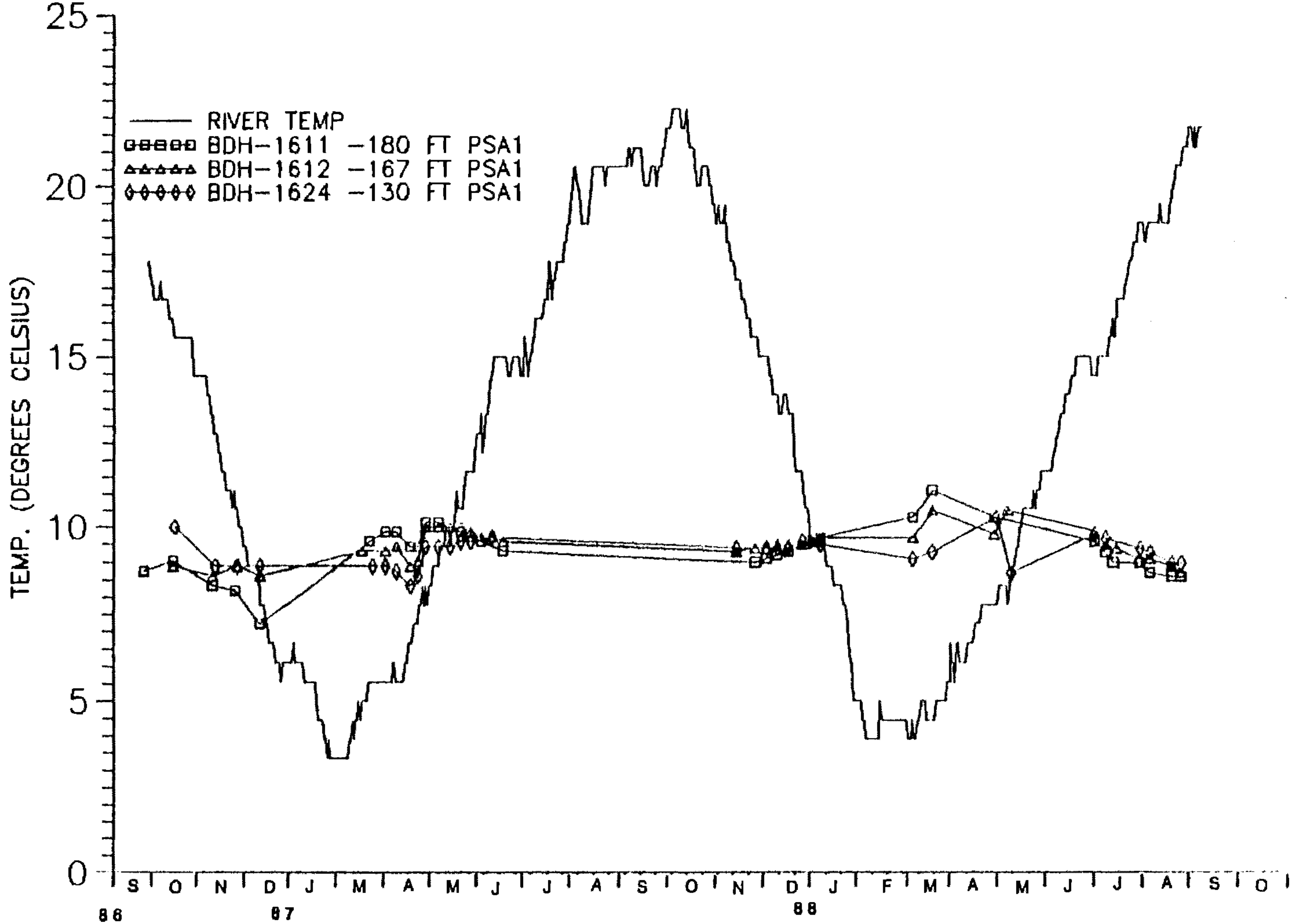
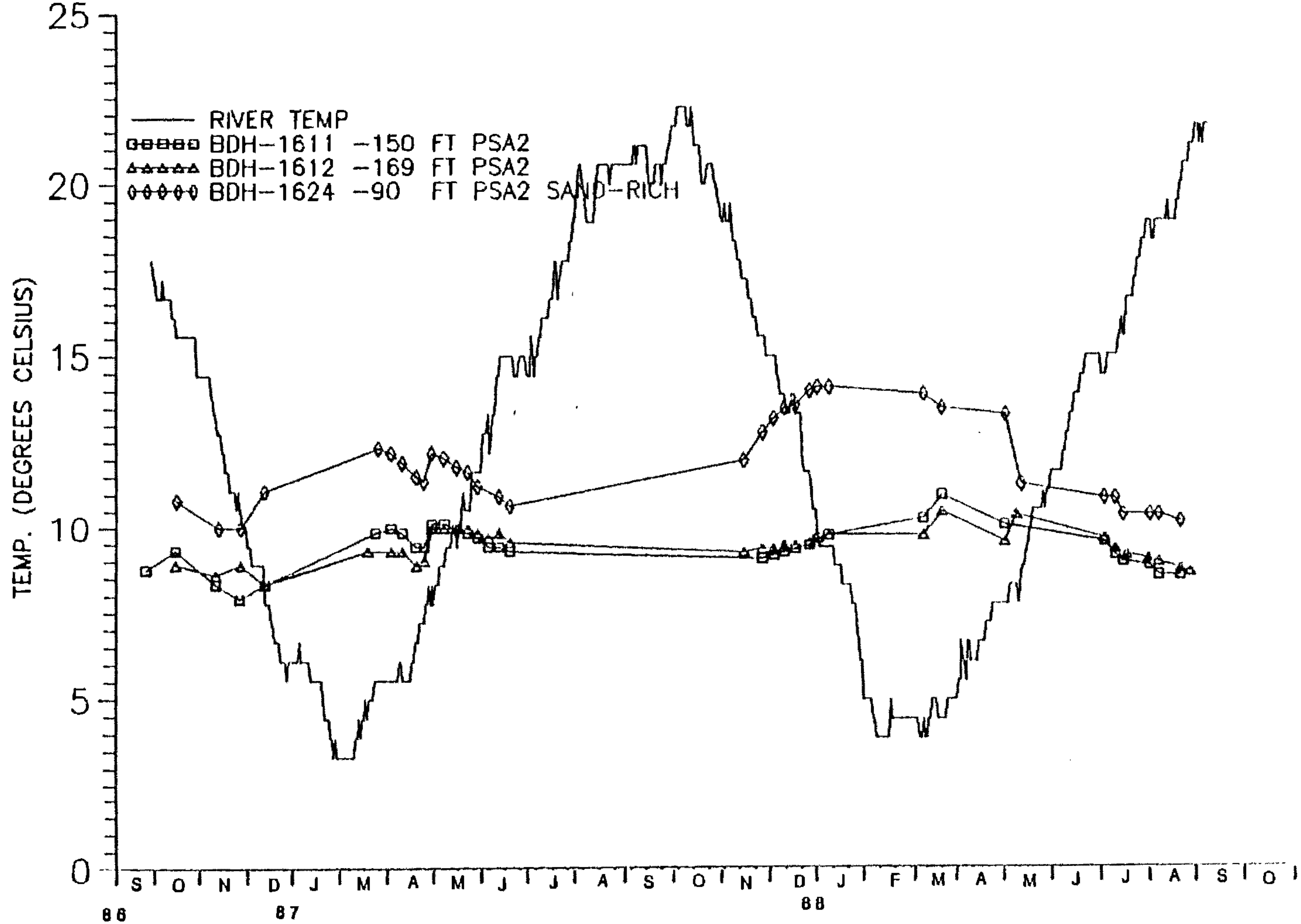



Figure 20. Temperature comparison graph of the $PSA_1$.

the $PSA_1$ from the Columbia River is dominantly from a conductive form of heat transport. This would also suggest that groundwater velocities in the unit are low compared to the upper PSA-aquifer, as indicated from the long lag times and small temperature changes, even though the aquifer is highly permeable.

The $PSA_2$ functions as an aquitard in most of the terrace area, behaving dominantly as a thermal buffer isolating the $PSA_1$ from the upper PSA-aquifer. The downstream terrace temperature comparison graph of the $PSA_2$ (Figure 21) depicts a thermal behavior similar to the behavior observed in the $PSA_1$. Thermal behavior of the $PSA_2$ is characterized by temperature moderation and long lag times. Less thermal moderation occurs at BDH-1624 (see Figure 19) where the $PSA_2$ is sand-rich. Table V summarizes and groups the thermal behavior of the $PSA_2$ in the downstream terrace area.

In the $PSA_2$, the type of lithology and its corresponding thermal behavior is readily discernible. Group one locations penetrate a $PSA_2$ material described as a blue-gray clay with varying amounts of pebbles embedded in it. This same clay occurs at DH-1946, DH-1949, DH-1953 and DH-1958. These locations are characterized by narrow temperature ranges. At BDH-1615 and BDH-1624, the $PSA_2$ it is described as slightly more sandy and a basalt-rich sand, respectively. Consequently, wider temperature ranges are observed in the $PSA_2$ at BDH-1615 (limited data) and BDH-1624. The higher permeability of the $PSA_2$ at these locations allows for greater groundwater flow and ultimately greater thermal transport.




<u>Figure 21</u>. Temperature comparison graph of the $PSA_2$.

TABLE V

TEMPERATURE RANGE OF THE $PSA_2$
IN THE DOWNSTREAM TERRACE

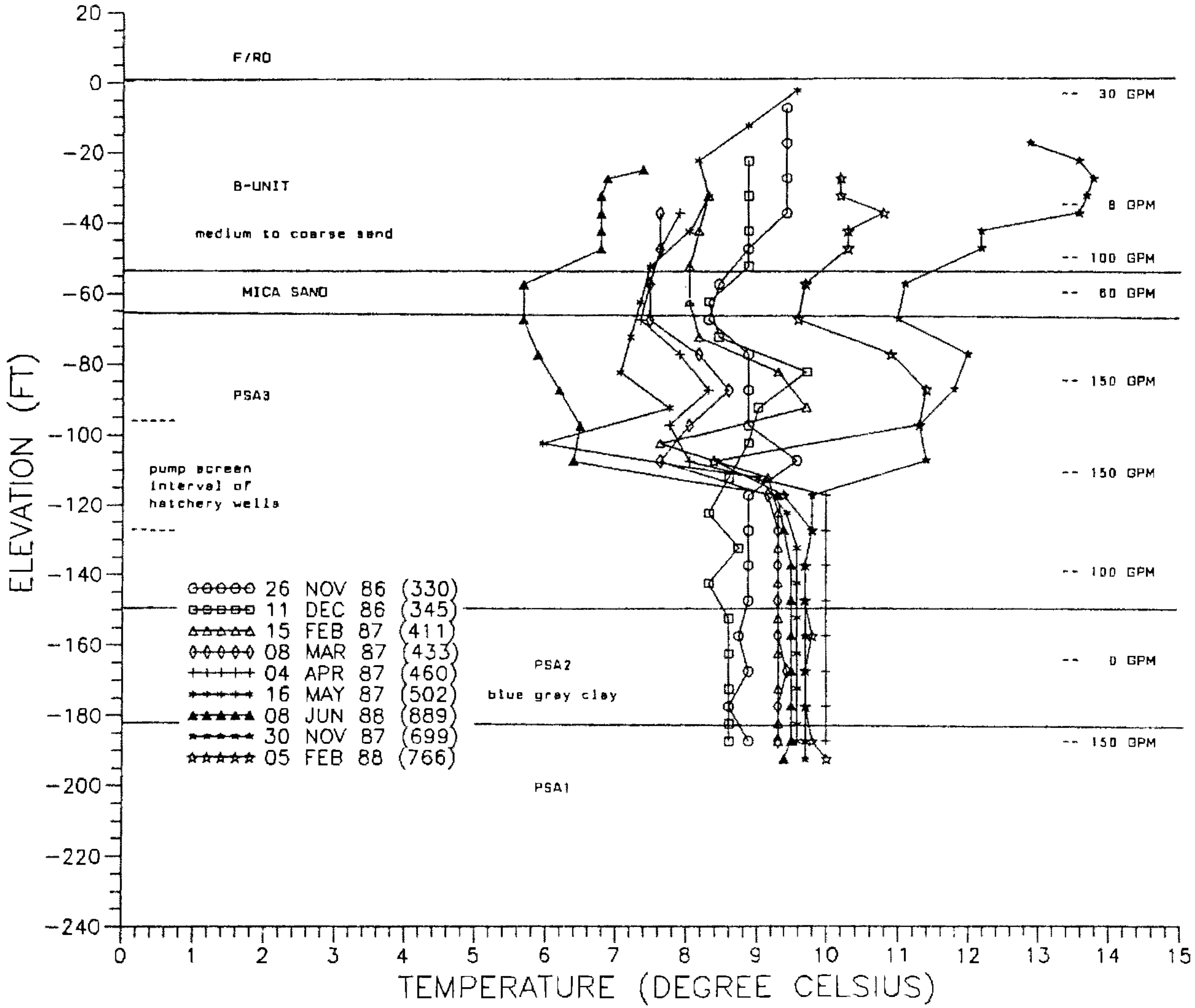
| Group | Piezometer | Temperature Range |
| --- | --- | --- |
| 1 | BDH-1611<br>BDH-1612 | 8° to 11°C (46° to 52°F) |
| 2 | BDH-1624<br>Sand-Rich PSA | 9.5° to 14.5°C (49° to 58°F) |

The thermal behavior of the $PSA_2$ is similar to the thermal behavior of the $PSA_1$. Both sub-units have similar temperature ranges and lag times with the exception of the $PSA_2$ at BDH-1624. The $PSA_2$, when consisting as a 9.1 meter (30 foot) thick layer of very stiff blue-gray clay with loose gravel and low water yield, functions as an efficient aquitard isolating the $PSA_1$ from both direct thermal influence of the Columbia River and hatchery well pumping influence.

The $PSA_3$ is the aquifer impacted by the partially penetrating fish hatchery wells. The temperature profile for BDH-1612 (Figure 22) is an example of this effect. This sub-unit has the most influence on groundwater temperature conditions in the downstream terrace due to pumping. Isothermal contour maps of the $PSA_3$ (Figure 23 and Appendix C) indicate that the fish hatchery wells draw groundwater from throughout the terrace area, but dominantly receive recharge from the eastern and western directions.

The area between DH-1953 and DH-1946 is a relatively low velocity zone. This zone appears to restrict groundwater flow and subsequent thermal influence from the northern direction. Figure 24 delineates areas of higher and lower transmissivity, produced by Baron (1990), and corresponds well with isotherm maps of the $PSA_3$ as areas with rapid or slow thermal change, respectively.

The thermal behavior of the $PSA_3$ based on isotherm maps also indicates two zones of temperature lag-time behavior -- an exterior zone and an interior zone (Figure 25). The exterior zone is monitored by piezometers BDH-1632, BDH-1610, DH-1958, BDH-1626, BDH-1629, BDH-1628 and DH-1953. The interior




**<u>Figure 22</u>. Temperature-depth profile of BDH-1612.**

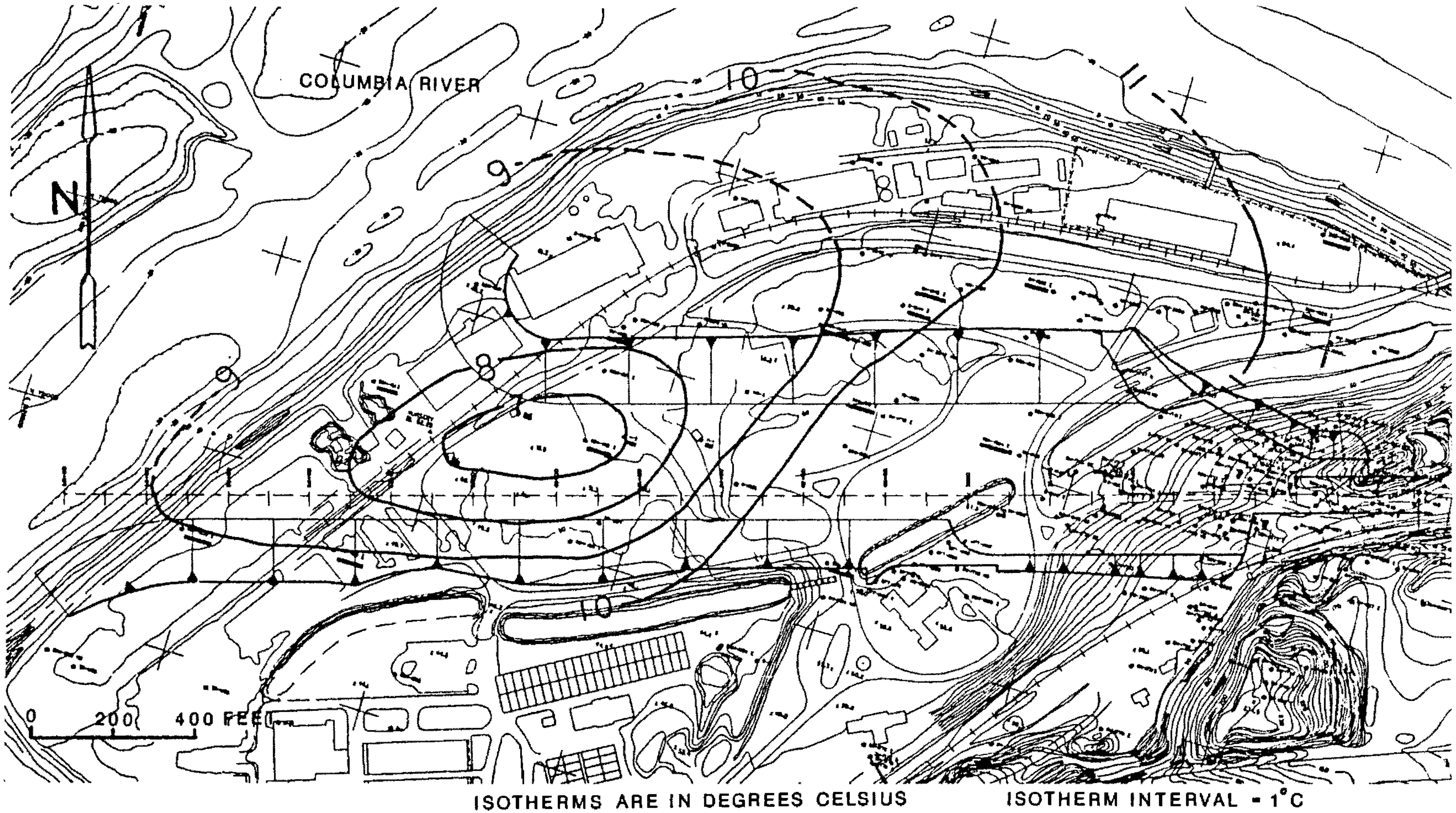
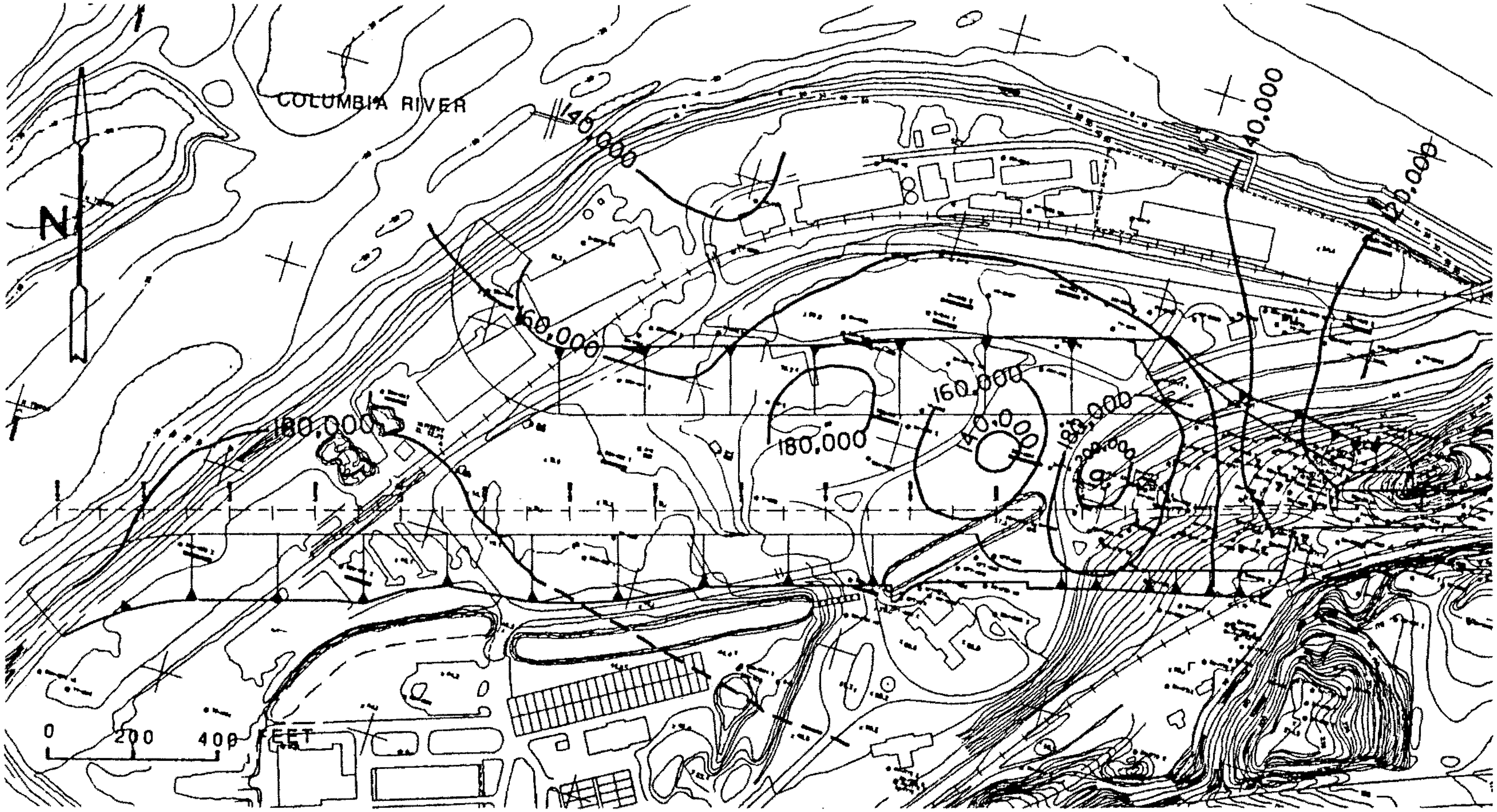



Figure 23. Isothermal contour map of the $PSA_3$ for September 8, 1988.




TRANSMISSIVITY CONTOURS ARE IN GPD/FT   CONTOUR INTERVAL - 20,000 GPD/FT

<u>Figure 24</u>. Transmissivity map of the $PSA_3$ for the downstream terrace. Modified from Baron, 1989.

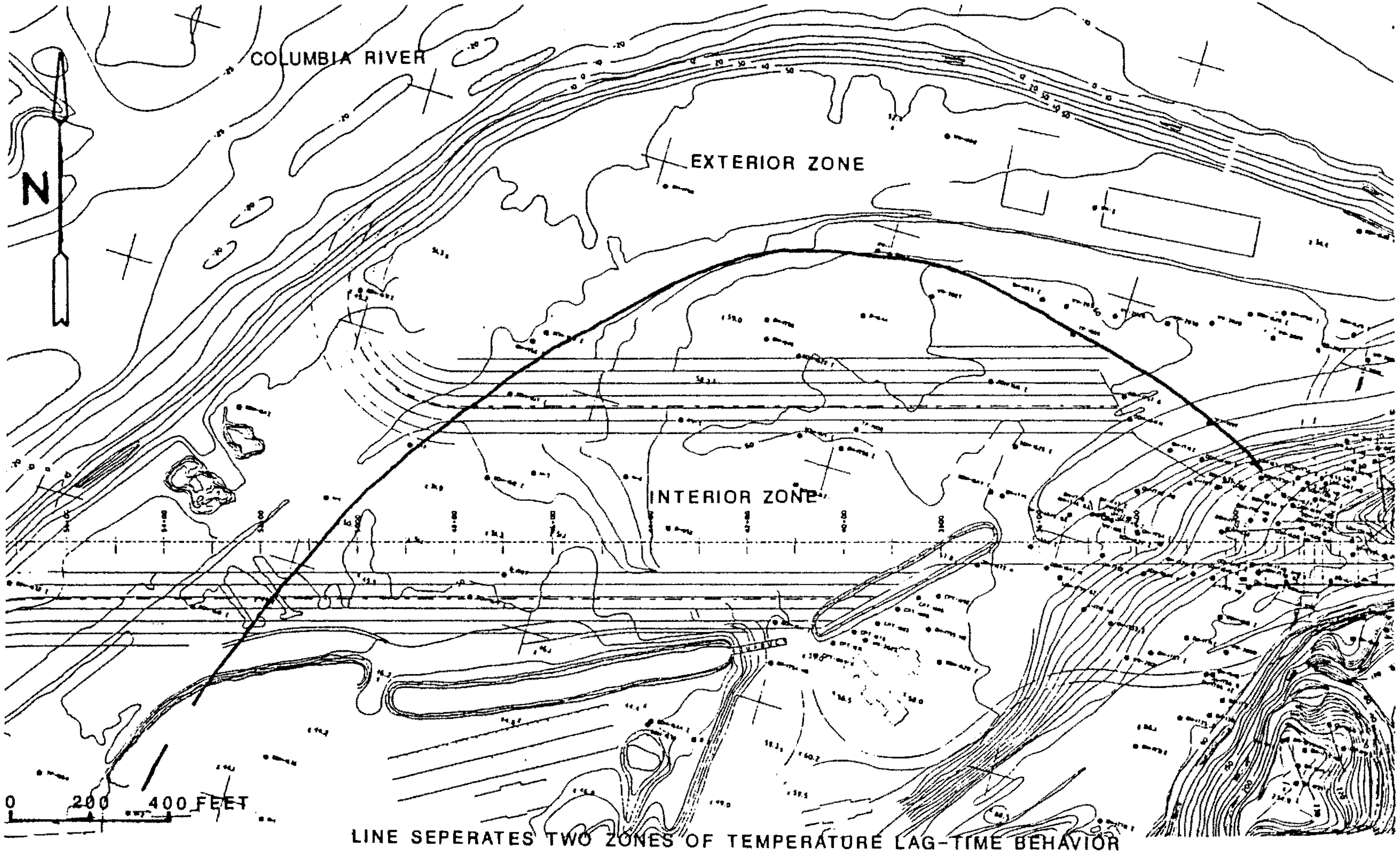



Figure 25. Thermal behavior map of the $PSA_3$. Based on isotherm maps of the $PSA_3$.

zone by piezometers BDH-1612, DH-1949, DH-1946, BDH-1615, BDH-1624, and BDH-1614. The exterior zone has a four month lag time difference with the Columbia River whereas the interior zone has a six month lag time.

The maximum temperature of the Columbia River for 1988 occurred in late September. The exterior zone of the $PSA_3$ reached its maximum groundwater temperature in mid-December 1988. The interior zone reached its maximum groundwater temperature in early March 1989. This indicates a little more than a three month difference in maximum temperatures between the two zones. The western end of the terrace reached its maximum temperature in mid-November 1988 whereas the east end of the terrace reached its maximum temperature in mid-December 1988.

Low temperature behavior in the $PSA_3$ is similar to its warm temperature behavior. The cold temperature peak of the $PSA_3$ groundwater for the exterior zone occurred in early June 1988 with the western end of the terrace being the first to attain minimum temperature. The interior zone reached its cold temperature peak in early August 1988. The cold temperature peak takes a slightly longer period of time to be attained than the high temperature peaks.

The downstream terrace temperature graph of the $PSA_3$ (Figure 26) indicates the existence of another form of thermal behavioral differentiation. Two groups of thermal behavior can be observed in Figure 26. Group one, consisting of piezometers BDH-1624, BDH-1626, BDH-1615, BDH 1629 and BDH-1614, are all located east of the fish hatchery well field (east of station 42+00; see

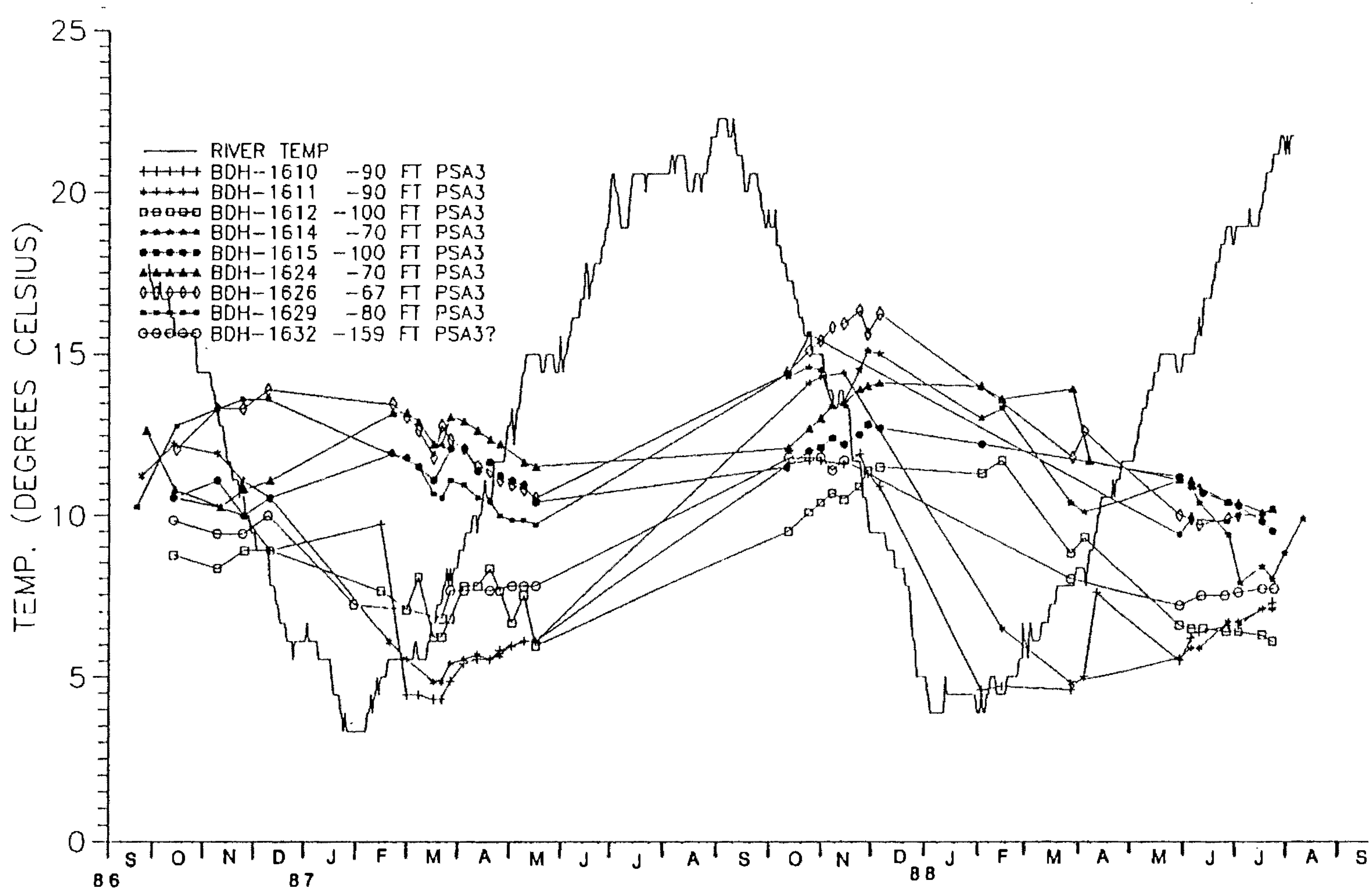



Figure 26. Temperature comparison graph of the $PSA_3$.

Figure 3). The thermal behavior of group one can be separated from group two piezometers by a narrower temperature range and generally warmer groundwater. Group two, consisting of piezometers BDH-1612, BDH-1632, BDH-1610 and BDH-1611, are all located west of station 42+00. The thermal behavior of group two has generally colder groundwater with a slightly greater temperature range. Table VI summarizes the overall temperature characteristics of the $PSA_3$ for the terrace area.

Groundwater east of station 42+00 has travelled, on an average, farther from the thermal influence of the Columbia River than groundwater located west of station 42+00. This extended terrace travel time would explain the narrower, more moderated groundwater temperature of the eastern terrace region which has undergone more thermal dispersion and mixing than that of the western terrace. A possible cause for colder groundwater in the western region of the terrace is that Tanner Creek water (see Table I) is infiltrating and mixing with $PSA_3$ groundwater. The average Tanner Creek temperature is $5^{\circ}$ cooler than Columbia River temperature. This effect could stimulate colder groundwater conditions. Possible Tanner Creek infiltration in conjunction with less moderated recharge from the Columbia River may be a reason for these observations.

Shorter lag times between thermal peaks for western terrace piezometers supports the hypothesis that the western region of the $PSA_3$ is receiving recharge from the Columbia River in a more direct manner than the eastern region of the terrace. The possibility that Tanner Creek water may also be infiltrating into

TABLE VI

TEMPERATURE RANGE OF THE $PSA_3$
IN THE DOWNSTREAM TERRACE

| Group | Piezometer | Temperature Range |
|---|---|---|
| 1 | BDH-1614<br>BDH-1615<br>BDH-1624<br>BDH-1626<br>BDH-1629 | 8° to 16°C (46° to 61°F)<br>average temperature - 12.0°C |
| 2 | BDH-1610<br>BDH-1611<br>BDH-1612<br>BDH-1632 | 4.5° to 14.5°C (40° to 58°F)<br>average temperature - 8.0°C |

the $PSA_3$ is consistent with the lithologic transition occurring in the $B_c$ sub-unit in the western end of the terrace. Decrease in the clay/silt content and the interstratification of Tanner Creek alluvium allows partial groundwater recharge from Tanner Creek.

Figure 27 compares the temperature behavior of BDH-1610, BDH-1611, and BDH-1632 at elevations where temperature-depth profiles indicate their greatest thermal variation. Figure 27 indicates graphically that a degree of correlation exists between groundwater moving through the upper sections of BDH-1611 and BDH-1632 and the lower gravel layer located at -35.7 to -42.1 meters (-117 to -138 feet) at BDH-1610 (see Appendix A for BDH-1610, BDH-1611, and BDH-1632 thermal profiles). The lower gravel layer of BDH-1610 can be correlated to the layer used by the hatchery wells (Figure 28). It appears that the removal of the Mica Sand unit and subsequent deposition by Tanner Creek alluvium west of BDH-1610 and BDH-1611 allows for a more direct route of groundwater flow into the $PSA_3$. If a strong eastward horizontal flow existed then the gravel/sand layer at BDH-1632 would be expected to have a greater thermal range.

## ANALYSIS OF THE OVERLYING HYDROGEOLOGIC UNITS

The Mica Sand is a moderately permeable unit varying in thickness and hydraulic conductivity throughout the downstream terrace area. The thermal behavior of this hydrogeologic unit reflects these variations. The Mica Sand functions as a thermal buffer between the hatchery well impacted groundwater of

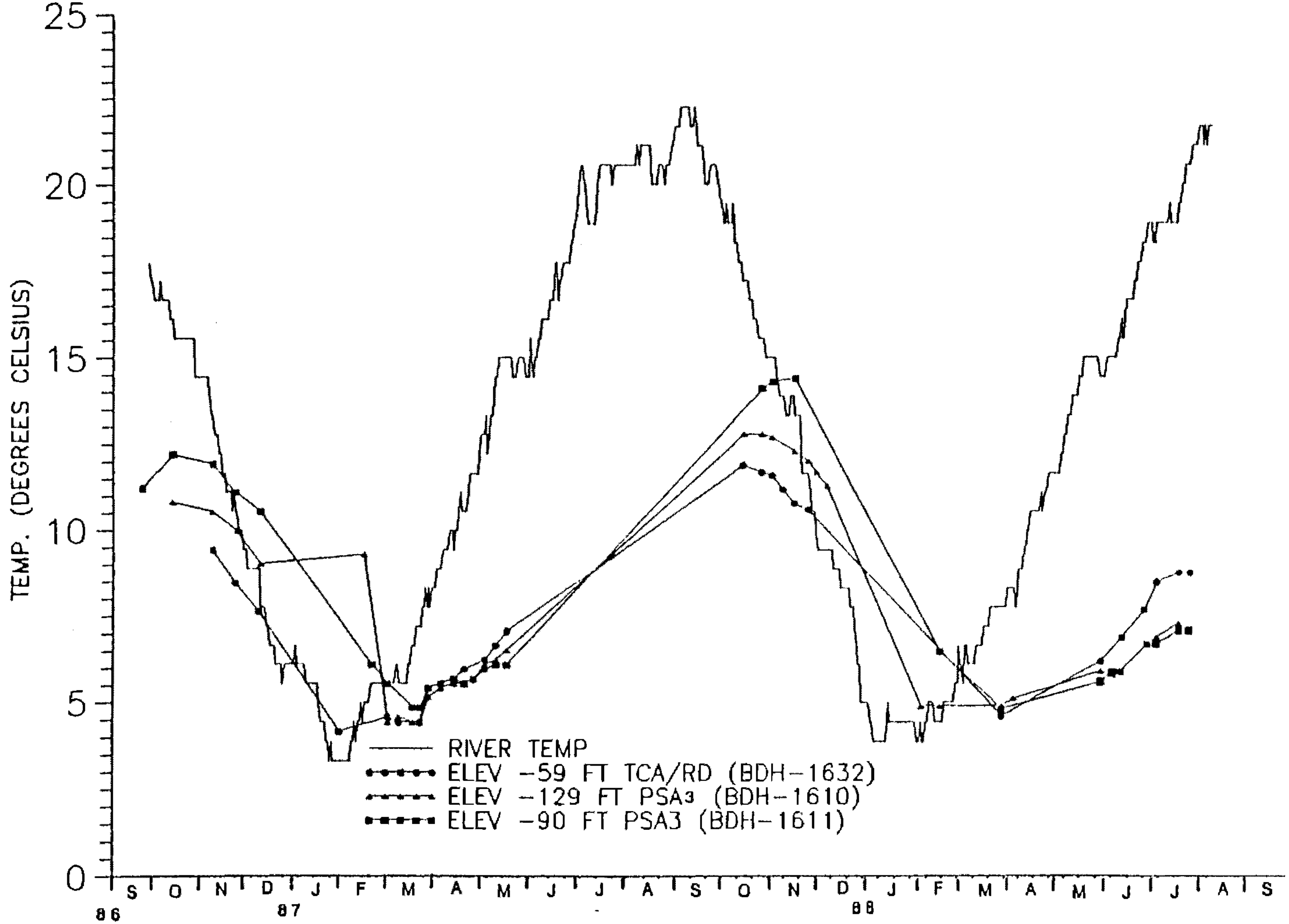
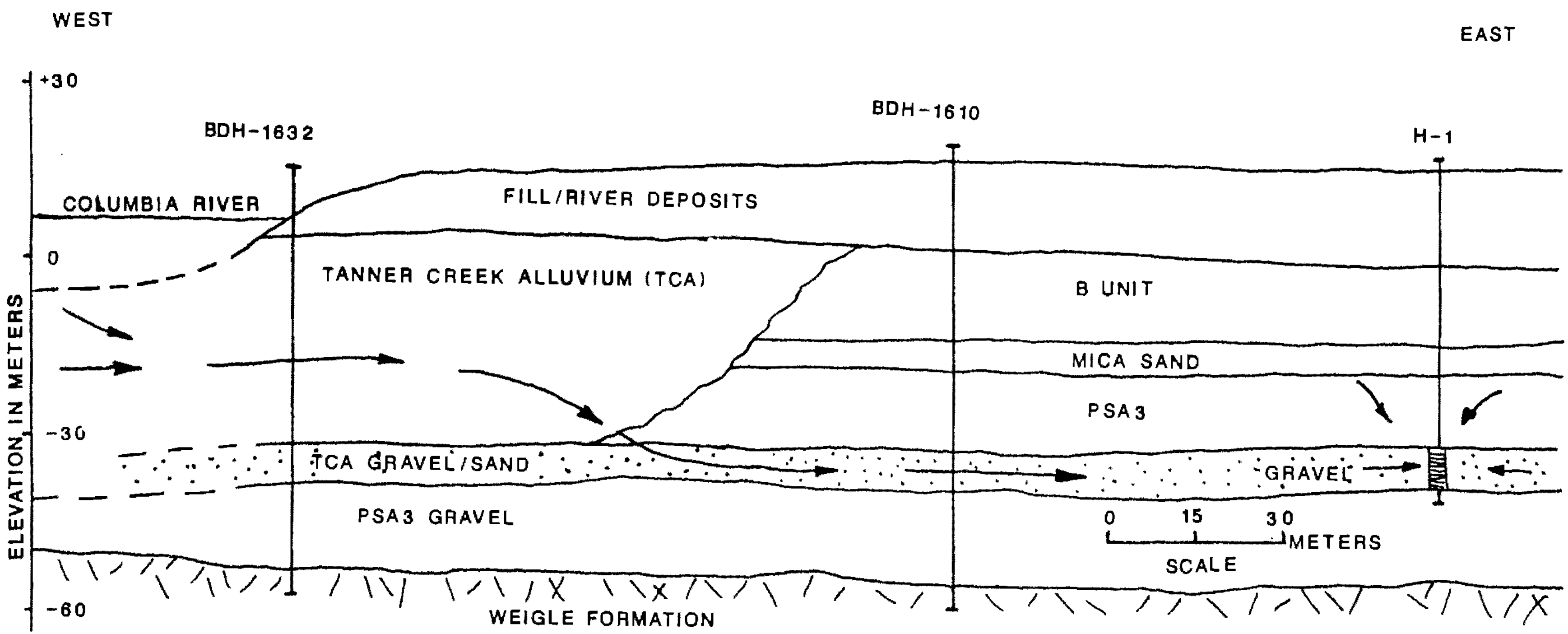



Figure 27. Temperature-elevation comparison graph indicating a potential recharge route.




<u>Figure 28</u>. Diagrammatic cross-section illustrating western recharge flow.

the upper PSA-aquifer and the overlying thermally variable $B_g$ sub-unit. Figure 29 is a temperature profile of BDH-1614 depicting this buffering behavior between the two hydrogeologic units by showing wide temperature ranges in the b-unit and $PSA_3$ in comparison to the temperature range in the Mica Sand.

The terrace temperature graph of the Mica Sand (Figure 30) indicates two groups of thermal behavior. The first group is characterized as having a narrow thermal groundwater range indicating that it receives the least amount of thermal impact from the Columbia River. Group one consists of piezometers BDH-1614, BDH-1615 and BDH-1624. These piezometers are located in the central southern area of the terrace, furthest from the Columbia River (see Figure 3 for location). Group two, consisting of BDH-1610, BDH-1611, BDH-1612, BDH-1626 and BDH-1629, have a greater thermal range indicating the group's closer location to the Columbia River. Table VII is a summary of the thermal differences for these two groups. Variation in the Mica Sand unit thickness and the location of the piezometer with respect to the river are the parameters that have the greatest influence on thermal behavior in the Mica Sand.

The downstream terrace temperature comparison graph of the B unit (Figure 31) indicates that the hydrogeologic unit is variable in its thermal behavior throughout the terrace area. All of the piezometers in Figure 31 indicate variable influence from the Columbia River. BDH-1615 appears to have the least amount of thermal impact from the river, BDH-1611 the greatest. BDH-1615 is located in the central area of the terrace whereas BDH-1611 is near the Columbia River.

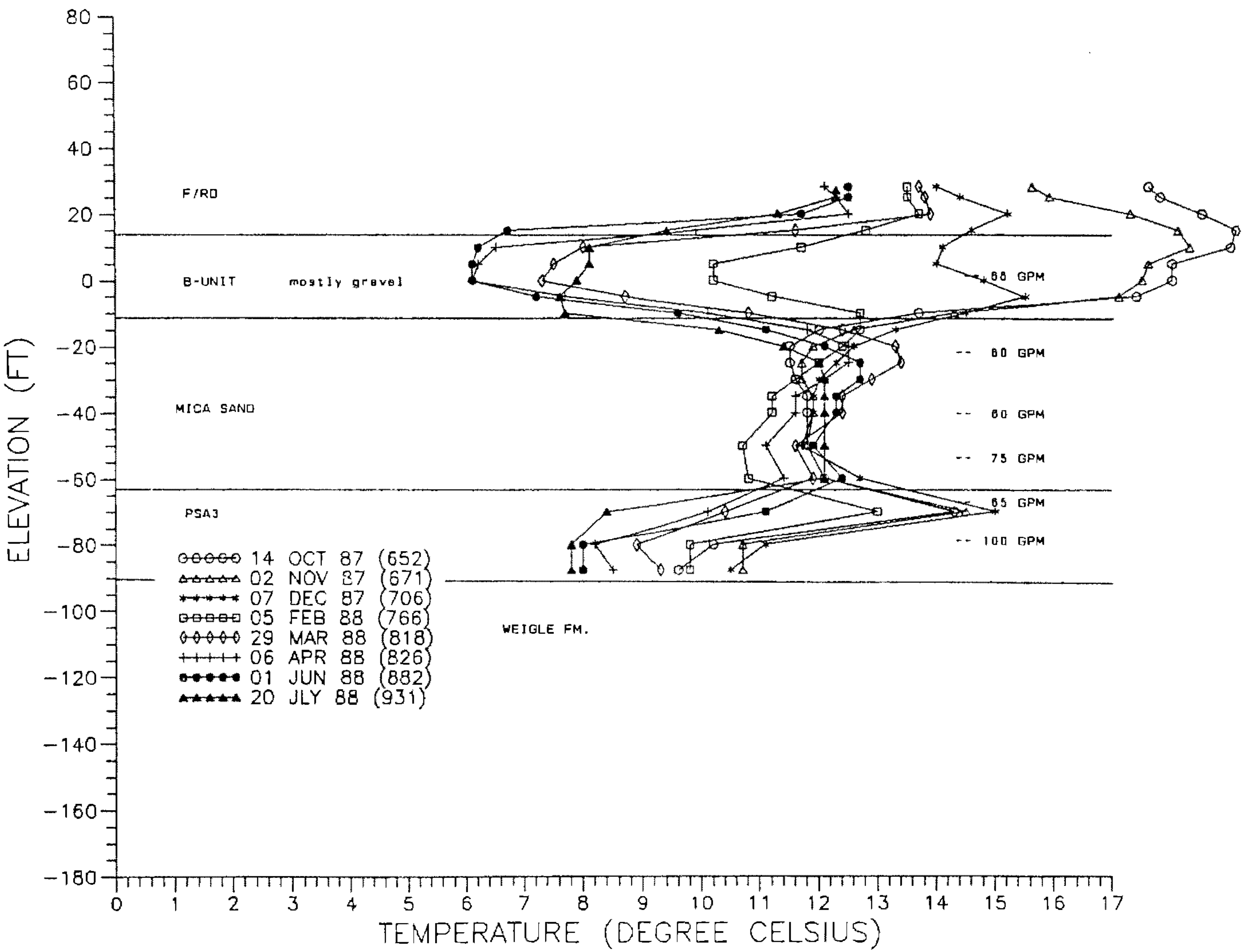



**Figure 29**. Temperature-depth profile of BDH-1614.

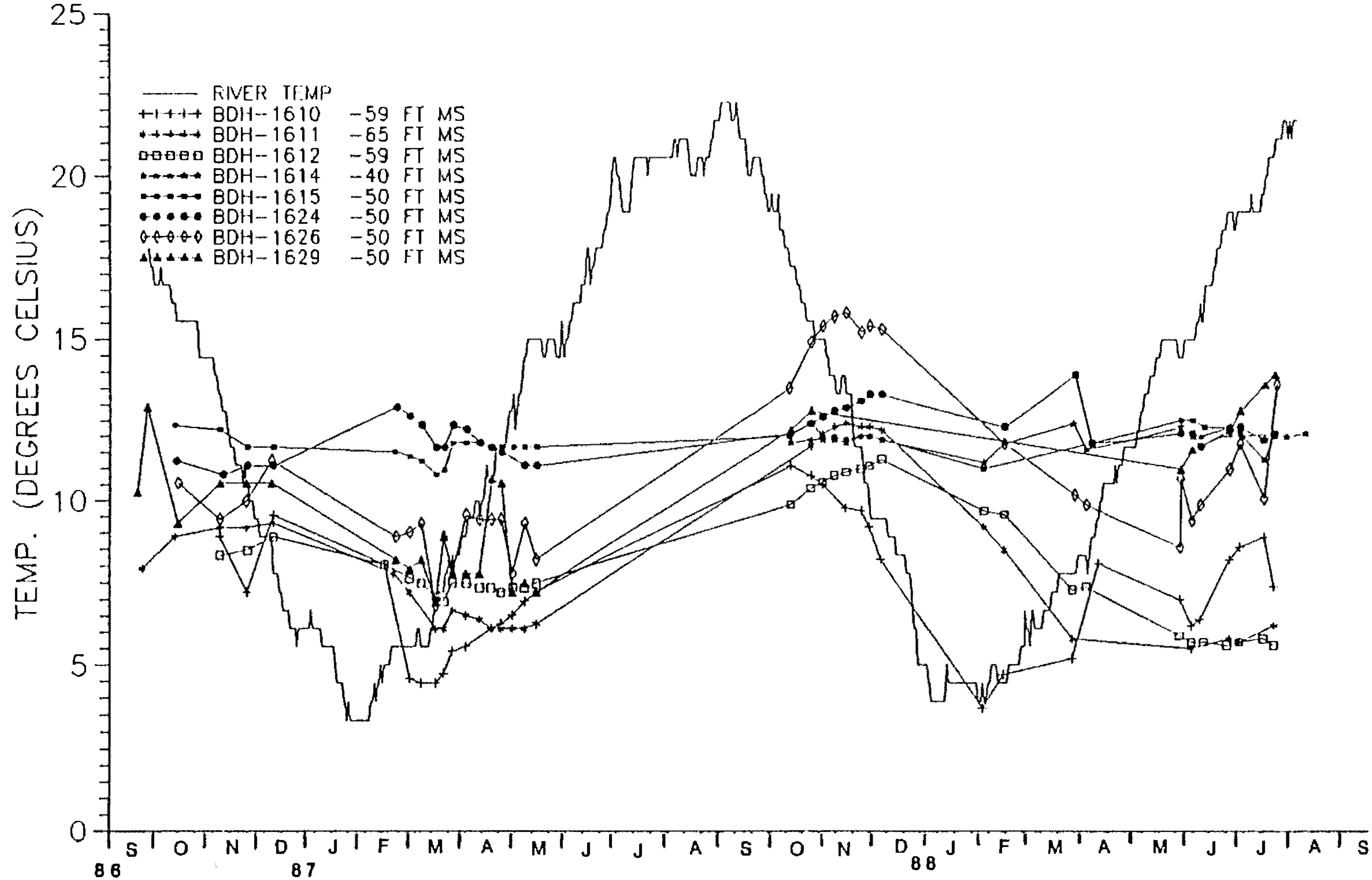



Figure 30. Temperature comparison graph of the mica sand.

TABLE VII

TEMPERATURE RANGE OF THE MICA SAND
IN THE DOWNSTREAM TERRACE

| Group | Piezometer | Temperature Range |
|---|---|---|
| 1 | BDH-1614<br>BDH-1615<br>BDH-1624 | 11° to 14°C (52° to 57°F) |
| 2 | BDH-1610<br>BDH-1611<br>BDH-1612<br>BDH-1629 | 4° to 16°C (39° to 61°F) |

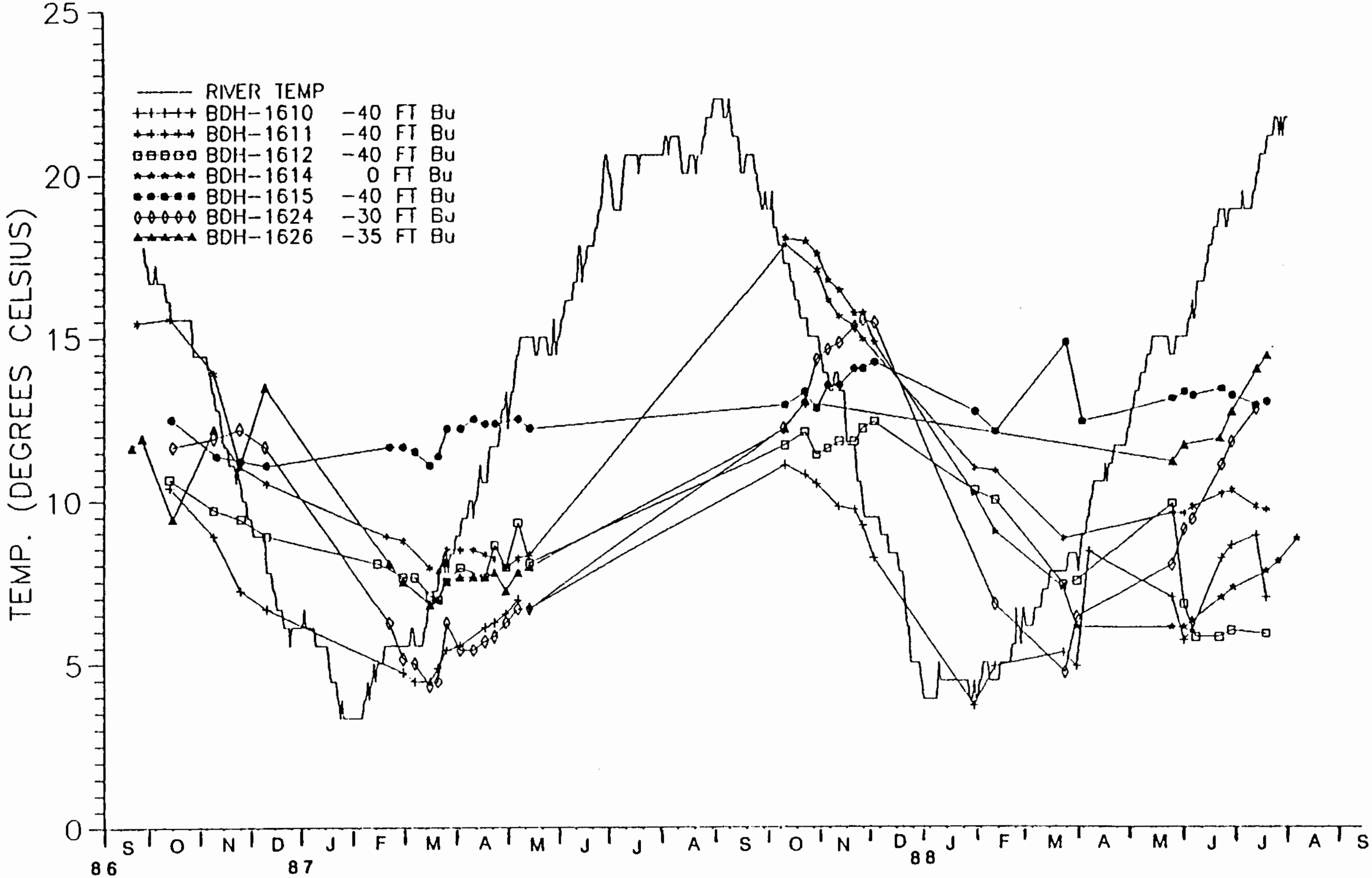



Figure 31. Temperature comparison graph of the b unit.

Over time there is no observable consistent temperature behavior between the piezometers in this hydrogeologic unit. Variation in the lithologic composition of the unit, impact from other thermal sources (i.e., Tanner Creek and Mitchell Ditch), and distance from the Columbia River influence the temperature behavior of the b-unit.

## CONCEPTUAL MODEL

The observed behavior of groundwater temperature in the terrace is associated with the large groundwater mass moving through the $PSA_3$ section of the PSA-aquifer. This movement, created by pumping of the hatchery wells, produces a strong disruption in the thermal profile of the terrace groundwater system. Disruption in the thermal profile continues in the upward direction where downward leakage from the overlying units, caused by a pressure decrease in the $PSA_3$ due to pumping, produces a mixture of groundwater drawn from two different sources: a far-field source (the extended PSA-aquifer) and a near-field source (the Mica Sand and B unit). Temperature data indicate groundwater from the near-field source has a more variable thermal nature even though the Mica Sand tends to moderate the more extreme temperatures of the B unit.

The hydraulic characteristics and parameters of the terrace were outlined in Chapter III and a brief description of a conceptual hydraulic model was introduced. Since the flow of heat and groundwater is a coupled process, the similarities observed in the pump test and thermal analyses is to be expected.

Incorporation of observations from both analysis produces the following conceptual model. The model relates depositional history and geology of the terrace to its groundwater recharge behavior.

Several observations based on temperature analysis can be made regarding the hydraulic characteristics of the PSA-aquifer. The stratigraphy of the alluvial terrace material produces a preferential flow direction in the hydrogeologic units of the terrace. This flow behavior is observed in the thermal movement and temperature distribution within the $PSA_3$ indicating that groundwater movement is mostly in an east-west direction. The $PSA_3$ is recharged dominantly from the western end of the terrace where the interfingering of Tanner Creek alluvium allows for a more direct and efficient route of groundwater recharge from the Columbia River. During the period of $PSA_3$ deposition, the introduction of a slide block in the northeastern section of the terrace produced an island-like feature within the ancestral Columbia River. Redistribution of flow in the ancestral Columbia River due to the slide block created conditions that allowed for deposition of finer, less permeable material downstream of the obstacle. The influence of the slide block on the depositional history of the terrace appears to have continued into the period of B unit deposition. A thick clay section in the B unit downstream of the obstacle in the northern section of the terrace has been noted during drilling exploration. This area is marked by lower transmissivity (see Figure 24) and accentuates the east-west preferential flow pattern as observed in the thermal behavior of the upper PSA-aquifer.

The Mica Sand separates the more thermally variable waters of the B unit (near-source) from the PSA-aquifer (far-source). The unit functions as a thermal buffer having a narrower temperature range than the B unit or upper PSA. Water in the Mica Sand is postulated to consist of a combination of water leaking down from the prolific $B_g$ sub-unit and water traveling in the unit directly or indirectly from the Columbia River. The Mica Sand varies spatially in thickness and conductivity over the terrace area, consequently its influence on the temperature of the groundwater system does likewise. Generally, the farther away the unit is from the river, the narrower its temperature range. It is difficult at some locations to separate the thermal behavior of the Mica Sand from that of the B unit except for the existence of a slight dampening in the thermal variation of the temperature profile that consistently occurs in the Mica Sand.

The B unit is directly influenced by the Columbia River since water from the river enters this unit directly. Based on this conceptual model of the terrace groundwater system, the less moderated Columbia River water is able to pass through the terrace in the B unit at various rates leaking down into the Mica Sand where it becomes thermally attenuated due to mixing from slightly different recharge sources before it is drawn into the upper PSA-aquifer. The central area of the terrace has the most moderated temperatures of the B unit in the terrace. This unit is difficult to characterize because it is not consistent in lithology and thickness. The area of the alluvial/Bonney Rock contact is an area of wide thermal variation in the hydrogeologic units of the terrace. The boundary condition of this contact produces a higher flow zone than the central part of the terrace. Consequently, greater thermal variability is observed in this area in comparison to the central region of the terrace. Possible trickling down into the PSA-aquifer through fractures and joints within the intrusive is another recharge route. This creates a condition where less thermally moderated water is introduced into the upper PSA in an area furthest away from the Columbia River.

# CHAPTER VI

## SUMMARY AND RECOMMENDATIONS

Construction of a navigation lock near Bonneville Dam on the Columbia River will affect the existing ground water supply used by the local fish hatchery. Change in the temperature characteristics of the ground water supply due to construction and operation of a downstream entrance channel is a primary concern. A three dimensional numerical ground water model that considers heat transport will be used to assess the thermal impact of the new downstream entrance channel. Analysis of direct temperature measurements is a means to formulate conceptual models of the thermal behavior of the terrace and also allows for calibration and verification of the numerical model.

Temperature data from the terrace was analyzed through the use of graphical presentations and isotherm maps. The depositional history and environment of the terrace strongly influences its groundwater hydraulics. Terrace temperature data indicates that thermal behavior of a groundwater system can be directly related to its hydraulic behavior and vice versa since simultaneous flow of heat and groundwater is treated as a coupled process. This is the fundamental concept that allowed for the development of a thermal conceptual model of the terrace.

Temperature data depict a narrow temperature range in the $PSA_1$ that extends up through the $PSA_2$ which is disrupted at an elevation similar to the well screen intervals of the partially penetrating fish hatchery wells. Hatchery well pumping draws groundwater both horizontally and downward from the overlying alluvial units. Temperature-depth profiles indicate that recharge of groundwater from below the level of hatchery well screen intervals is minimal. The deep PSA-aquifer, $PSA_1$, a highly permeable aquifer, is not impacted by the hatchery wells due to their lack of penetration into the $PSA_1$ and the low permeable nature of $PSA_2$ that caps the $PSA_1$. The $PSA_1$ is further protected from the thermal impact of the Columbia River by occupying a scour channel cut into the terrace bedrock. A lag time of a little more than seven months between $PSA_1$ and the Columbia River is observed. The $PSA_2$ has a similar thermal behavior as the $PSA_1$ when it consists of clay.

Thermally variable groundwater observed in the upper PSA-aquifer ($PSA_3$) is warmed and cooled indirectly by the Columbia River as recharge water is drawn into the terrace by the pumping activity of the hatchery wells. Several different temperature behavior characteristics exist for the $PSA_3$ based on location with respect to the river and the hatchery wells. An average lag time of four months for piezometers located near the river and six months for interior piezometers is observed for the $PSA_3$.

The overlying hydrogeologic units consisting of the Mica Sand and B unit have their own distinct thermal characteristics. The Mica Sand varies both in thickness and hydraulic conductivity throughout the terrace. The Mica Sand behaves as a thermal buffer between the B unit and the upper PSA-aquifer. The thermal range of groundwater in the Mica Sand is dominantly controlled by how far it is from the river. The B unit is thermally most variable at its boundaries; the Bonney Rock intrusion, Tanner Creek, and the Columbia River. The least amount of variation in temperature occurs in the interior area of the terrace.

The interstratification of Tanner Creek alluvium on the Bonneville alluvial sequence in the western end of the terrace has produced a more direct recharge route into the PSA-aquifer. The introduction of a slide block in the upper PSA during deposition allowed for depositional conditions that produced a lower permeability zone in the area at, and west, of the slide block. Fluvial deposition of terrace material has created an east/west preferential groundwater flow behavior in the terrace.

Relocation of the Bonneville Fish Hatchery Wells should consider utilizing the $PSA_1$ aquifer. This aquifer appears to have the potential of supplying groundwater with a desirable temperature range for fish hatchery usage. The influence of pumping will extend this temperature range as it has in the $PSA_3$. Wells utilizing the $PSA_3$ should be screened only in the lower portion of the hydrogeologic unit. Though this will decrease pumping efficiency it will produce less thermally variable groundwater than a full screen configuration. The development of a pumping strategy utilizing both aquifers will allow for greater flexibility in maintaining desirable groundwater temperature. To utilize the $PSA_1$, the wells should be located as close to the middle of the weigle formation scour channel as possible. It has been noted that PSA groundwater east of station 42+00 maintains a narrower temperature range than the groundwater located west of this station.

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# APPENDIX A

# TEMPERATURE PROFILES

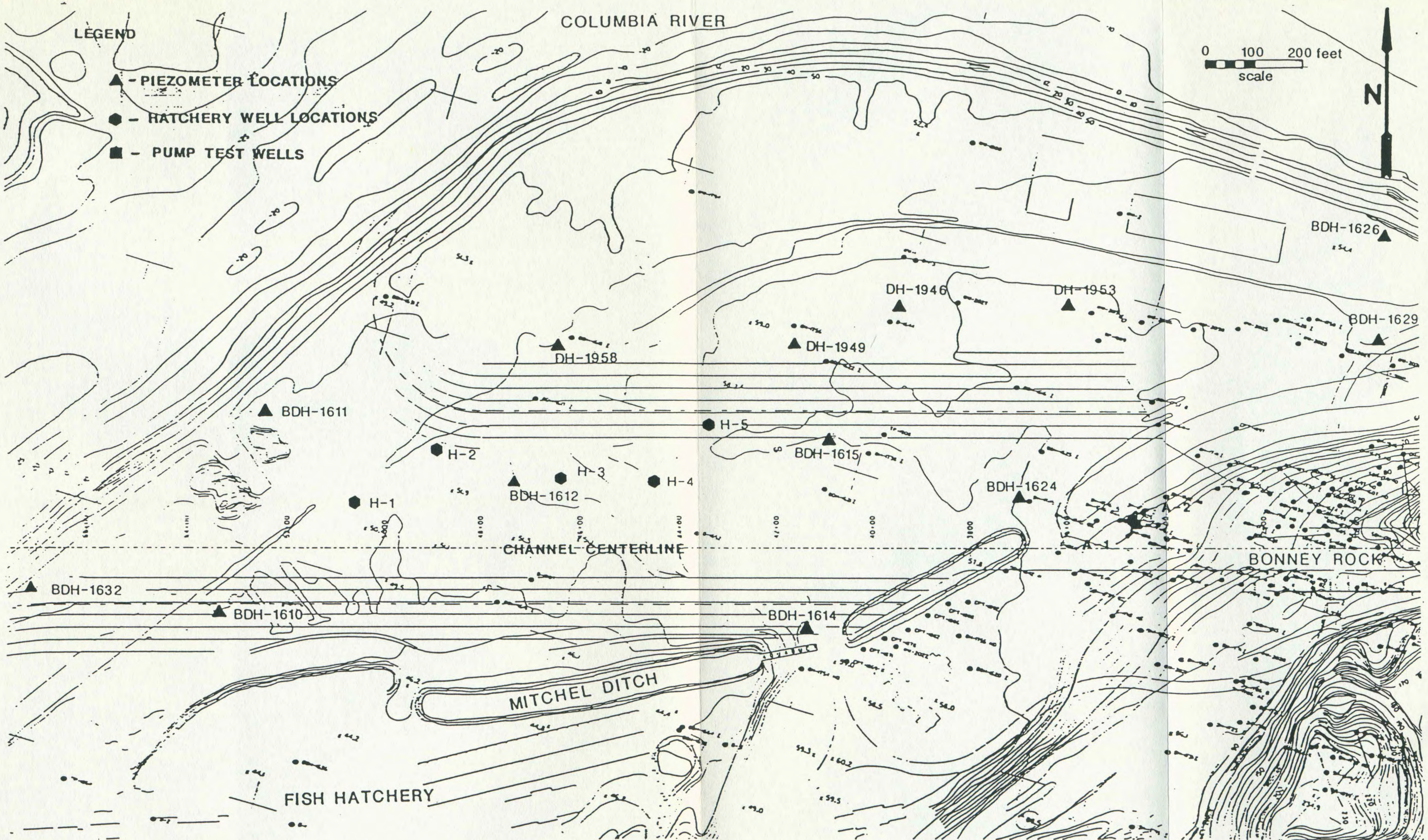
## TEMPERATURE PROFILES

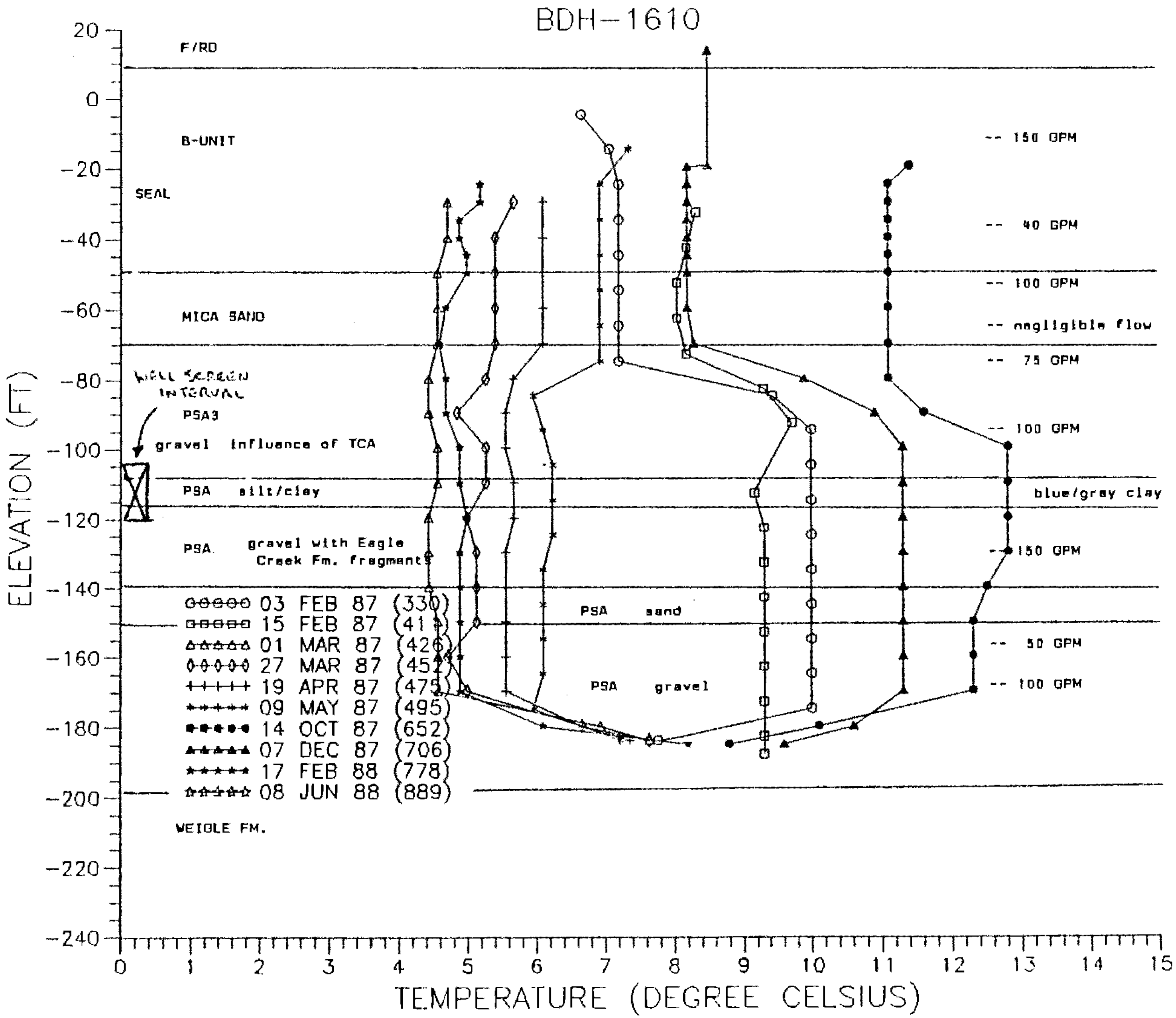
Appendix A presents the temperature-depth profiles for the following piezometers of the downstream terrace at Bonneville Dam: BDH-1610, BDH-1611, BDH-1612, BDH-1615, BDH-1624, BDH-1626, BDH-1629, BDH-1632, DH-1946, DH-1949, DH-1953, AND DH-1958. The locations of these piezometers are shown on the following map. The text for each temperature-depth profile includes a discussion on the thermal characteristics and interpretations of the piezometer.

### BDH-1610

The thermal profile for BDH-1610 is unique for the terrace region. The greatest amount of thermal variability occurs in the lower section ($PSA_3$). Both the wide range in groundwater temperature and the relatively quick response time with respect to Columbia River temperature variation indicate the existence of a large mass of groundwater moving through this section of the terrace. The thermal behavior of the upper section of the piezometer, in the Mica Sand and B unit, also indicates the movement of large amounts of groundwater but with a quicker, more moderated response time with respect to Columbia River temperature. A thermal gradient existing between the $PSA_3$ groundwater and the upper unit groundwater implies two different rates of groundwater movement and apparently two different areas of recharge.

The distinct thermal behavior of BDH-1610 is thought to be primarily due to two causes: the change in both stratigraphy and lithology in the western region


LEGEND
▲ - PIEZOMETER LOCATIONS
● - HATCHERY WELL LOCATIONS
■ - PUMP TEST WELLS
COLUMBIA RIVER
0 100 200 feet
scale
N
BDH-1626
BDH-1629
DH-1946
DH-1953
DH-1949
DH-1958
BDH-1611
H-5
BDH-1615
H-2
H-3
H-4
BDH-1612
H-1
BDH-1624
CHANNEL CENTERLINE
BONNEY ROCK
BDH-1632
BDH-1610
BDH-1614
MITCHEL DITCH
FISH HATCHERY

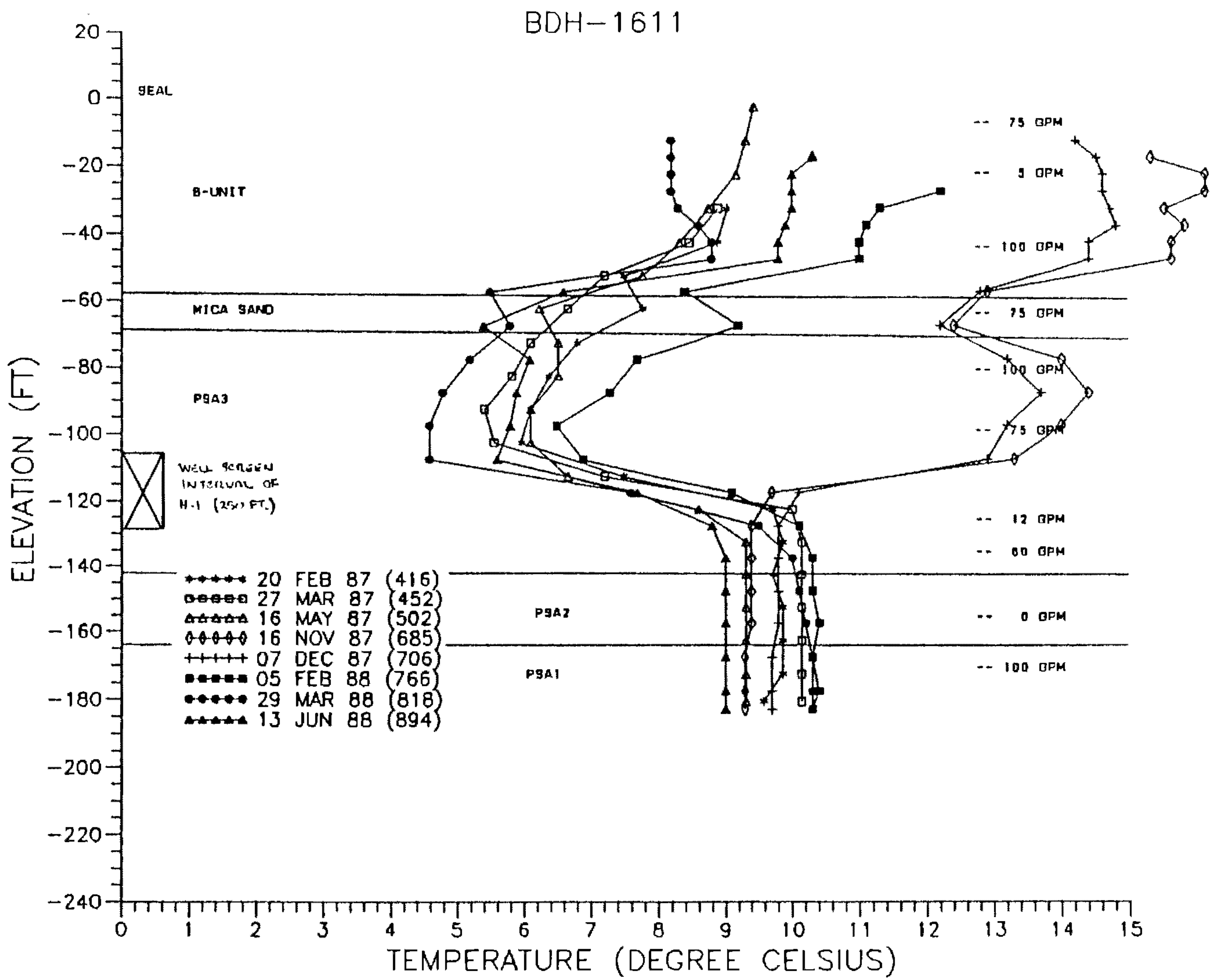

BDH—1610
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)
F/RD
B-UNIT
SEAL
MICA SAND
WELL SCREEN INTERVAL
PSA3
gravel influence of TCA
PSA silt/clay
PSA gravel with Eagle Creek Fm. fragments
PSA sand
PSA gravel
WEIGLE FM.
blue/gray clay
-- 150 GPM
-- 40 GPM
-- 100 GPM
-- negligible flow
-- 75 GPM
-- 100 GPM
-- 150 GPM
-- 50 GPM
-- 100 GPM
03 FEB 87 (330)
15 FEB 87 (411)
01 MAR 87 (426)
27 MAR 87 (452)
19 APR 87 (475)
09 MAY 87 (495)
14 OCT 87 (652)
07 DEC 87 (706)
17 FEB 88 (778)
08 JUN 88 (889)

of the terrace. West of BDH-1610, the Bonneville alluvial sequence is disrupted by Tanner Creek alluvium. Core samples of BDH-1610 indicate that Tanner Creek alluvium was encountered at this piezometer. Tanner Creek alluvium is highly transmissive. Further temperature analysis also indicates that this area of the terrace is the primary route of recharge for the terrace PSA-aquifer. The second apparent cause of BDH-1610's thermal uniqueness is its location in the area between the Columbia River, Tanner Creek, and the hatchery well field.

BDH-1611

Thermal profile of BDH-1611 illustrates the variation in thermal behavior that occurs within the terrace alluvial sequence produced by differences in groundwater velocity. The thermal profile illustrates that the Mica Sand functions as a thermal buffer between the upper $PSA_3$ and the B unit through its moderation of groundwater temperature.

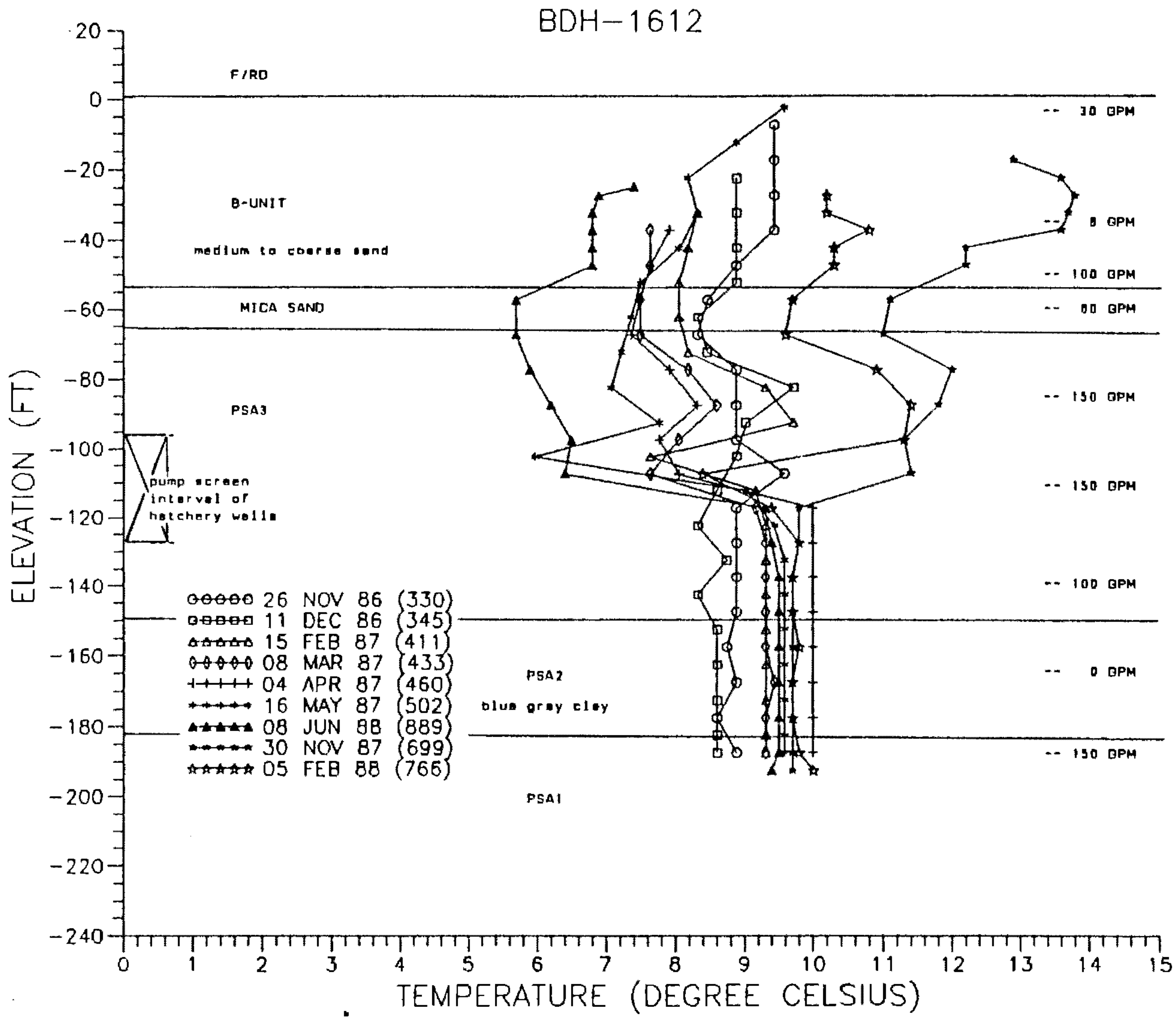
The observed thermal phenomena in the $PSA_3$ at BDH-1611 is associated with the pumping impact of the hatchery wells. Hatchery wells H-1 and H-2 are located 250 and 350 feet away, respectively. Recharge to these wells creates higher groundwater velocities in the upper section of the $PSA_3$ that produces a dramatic break in the thermal behavior of the lower section of the $PSA_3$ and lower PSA sub-units. The wide temperature range observed in the upper section of BDH-1611 is interpreted as indicating the presence of a proximal thermal influence due to near-field recharge from the Columbia River. This interpretation is based on the


BDH-1611
SEAL
B-UNIT
MICA SAND
PSA3
WELL SCREEN INTERVAL OF H-1 (250 FT.)
PSA2
PSA1
-- 75 GPM
-- 5 GPM
-- 100 GPM
-- 75 GPM
-- 100 GPM
-- 75 GPM
-- 12 GPM
-- 60 GPM
-- 0 GPM
-- 100 GPM
20 FEB 87 (416)
27 MAR 87 (452)
16 MAY 87 (502)
16 NOV 87 (685)
07 DEC 87 (706)
05 FEB 88 (766)
29 MAR 88 (818)
13 JUN 88 (894)
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)

low degree of thermal moderation and short lag time. The buffering influence of the Mica Sand separates the thermal behavior between the two hydrogeologic units. This also supports the existence of two different recharge areas for the two hydrogeologic units. The wider temperature range and shorter lag times indicates that the B unit has a closer recharge source.

BDH-1612

Thermal profile of BDH-1612 indicates a strong influence from hatchery well pumping. A wider temperature range occurs within the screen interval elevation of the hatchery wells. In the upper section of the BDH-1612 temperature profile, the coolest water is observed in June with the warmest water occurring in November through February indicating that increase in thermal variation at and above the well screens is a result of differences in groundwater velocity occurring within the $PSA_3$. Temperature data indicates that BDH-1611 has about a month quicker response time than BDH-1612, located 525 feet further away from the Columbia River. The momentum of wide temperature variations produced by seasonal river heating and cooling observed at BDH-1611 is moderated and becomes less distinguishable by the time the water reaches BDH-1612. Both the Mica Sand and B unit at this location appear to be six months out of phase with Columbia River temperatures.


BDH-1612
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)
F/RD
B-UNIT
medium to coarse sand
MICA SAND
PSA3
pump screen
interval of
hatchery wells
PSA2
blue gray clay
PSA1
-- 30 GPM
-- 8 GPM
-- 100 GPM
-- 80 GPM
-- 150 GPM
-- 150 GPM
-- 100 GPM
-- 0 GPM
-- 150 GPM
26 NOV 86 (330)
11 DEC 86 (345)
15 FEB 87 (411)
08 MAR 87 (433)
04 APR 87 (460)
16 MAY 87 (502)
08 JUN 88 (889)
30 NOV 87 (699)
05 FEB 88 (766)

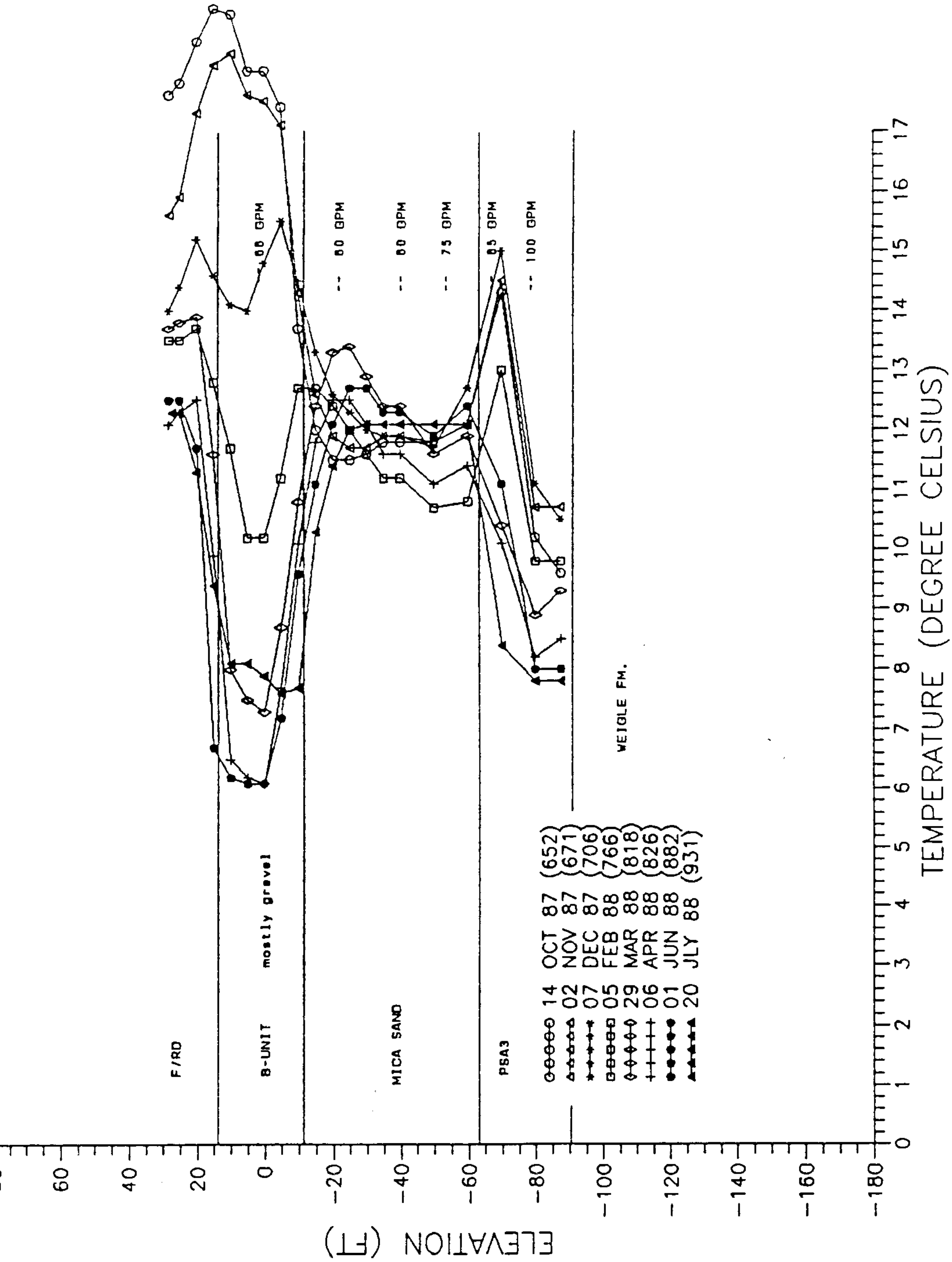
BDH-1614

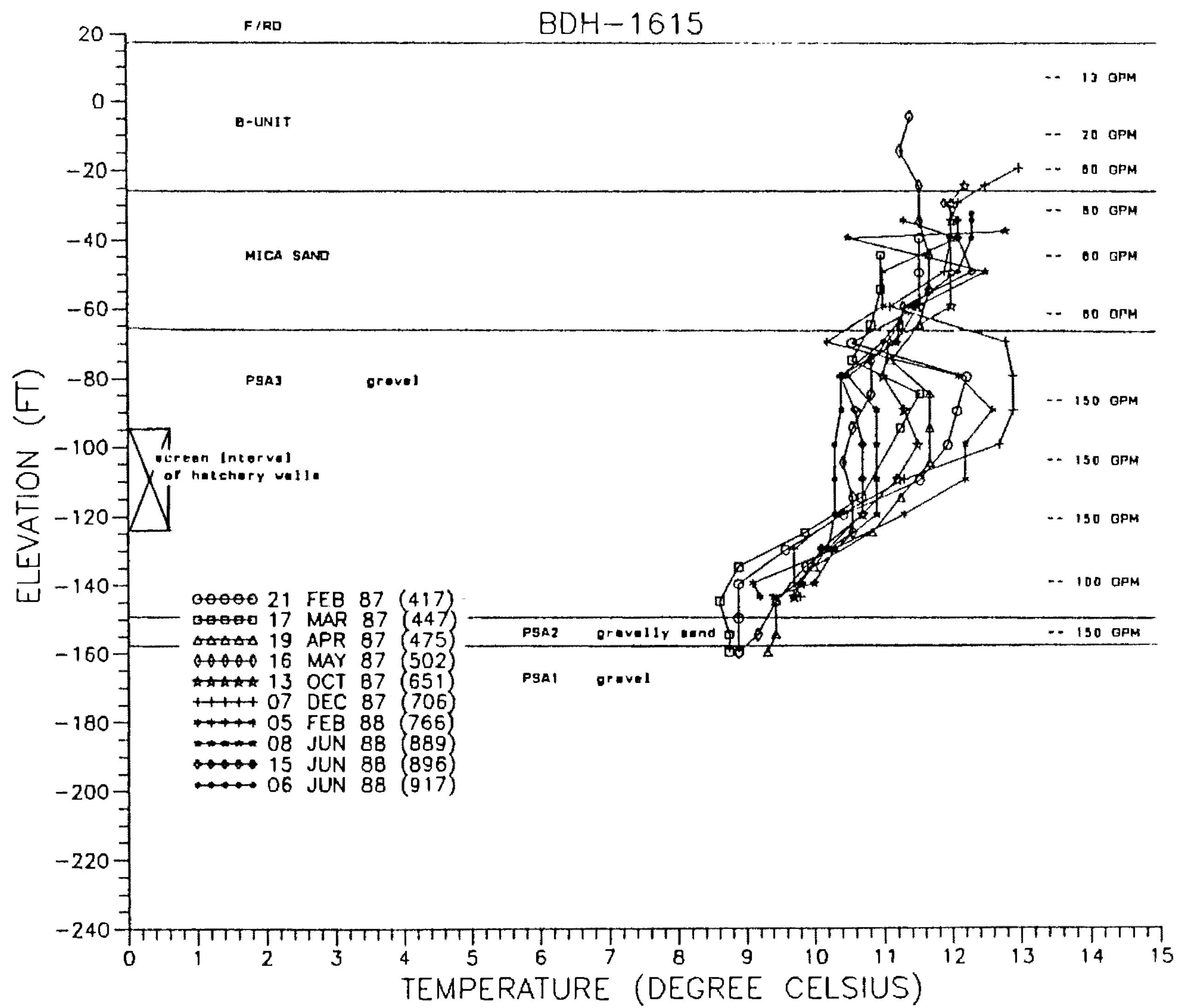
The thermal profile of BDH-1614 indicates a unique thermal behavior due to the thick section of Mica Sand that it penetrates. The profile indicates that there is less groundwater movement in the Mica Sand than in either the overlying B unit or the underlying $PSA_3$. The $PSA_3$ at BDH-1614 is relatively thin with the temperature profile indicating that a large amount of groundwater movement occurs in the upper section of the sub-unit. The greater thickness and lower permeability of the Mica Sand in this region of the terrace illustrates the effectiveness of the Mica Sand as a thermal moderator. The Mica Sand in the terrace and specifically at BDH-1614 is observed to behave as an aquitard. The lower PSA sub-units are not encountered at this piezometer. The $PSA_3$ has a defined behavior of having the coldest groundwater in June and the warmest in October. The upper B unit has a similar behavior as the $PSA_3$ but with a wider temperature range. This suggests that more thermally variable water is coming from a direction other than the north.

BDH-1615

The thermal profile of BDH-1615 indicates moderate thermal variation throughout the year and a narrow temperature range in the $PSA_1$. Strong influence on thermal behavior from hatchery well pumping is indicated in the profile. Greater groundwater movement in the form of a temperature difference in the thermal profile is created by pumping of the hatchery wells. This behavior

BDH-1614


ELEVATION (FT)
80
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
TEMPERATURE (DEGREE CELSIUS)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
F/RD
B-UNIT
mostly gravel
MICA SAND
PSA3
WEIGLE FM.
-- 88 GPM
-- 80 GPM
-- 80 GPM
-- 75 GPM
-- 85 GPM
-- 100 GPM
14 OCT 87 (652)
02 NOV 87 (671)
07 DEC 87 (706)
05 FEB 88 (766)
29 MAR 88 (818)
06 APR 88 (826)
01 JUN 88 (882)
20 JLY 88 (931)



BDH-1615
F/RD
B-UNIT
MICA SAND
PSA3
gravel
PSA2
gravelly sand
PSA1
gravel
screen interval of hatchery wells
-- 13 GPM
-- 20 GPM
-- 80 GPM
-- 80 GPM
-- 80 GPM
-- 80 GPM
-- 150 GPM
-- 150 GPM
-- 150 GPM
-- 100 GPM
-- 150 GPM
21 FEB 87 (417)
17 MAR 87 (447)
19 APR 87 (475)
16 MAY 87 (502)
13 OCT 87 (651)
07 DEC 87 (706)
05 FEB 88 (766)
08 JUN 88 (889)
15 JUN 88 (896)
06 JUN 88 (917)
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

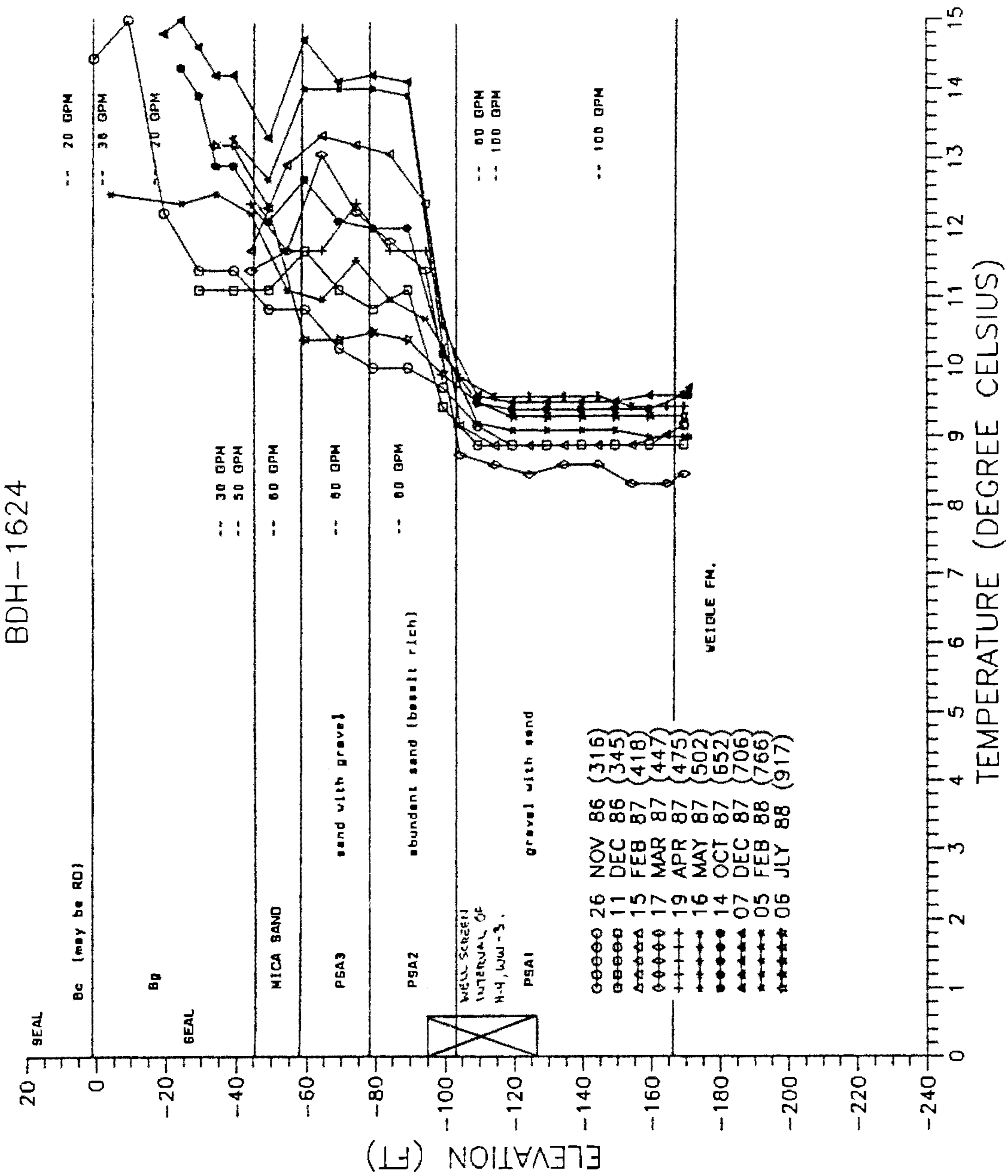
is observed as a two degree Celsius warming gradient within the $PSA_3$. This gradient occurs in the area associated with the hatchery well screen intervals.

The closest hatchery well (H-5) is 250 feet east of BDH-1615 (see Figure 3). The narrower temperature range observed at BDH-1615 is considered to be a function of groundwater recharge dominantly from the eastern end of the terrace. All of the hatchery wells are west of BDH-1615. The longer travel time for groundwater in the terrace alluvium produces greater thermal moderation. This tends to be the general thermal behavior of piezometers located east of the hatchery well field.

BDH-1624

The thermal profile of BDH-1624 indicates a thermal gradient between the upper and lower PSA-aquifer. The lithology at this piezometer is distinct because the $PSA_3$ is a relatively thin layer, the $PSA_2$ is a relatively thick layer of higher permeable material, and the Mica Sand is a thin layer. It has been observed that even with the $PSA_2$ consisting of a more permeable material (pump test analysis), the thermal profile indicates that the $PSA_1$ is not influenced by hatchery well activity.

The closest hatchery well (H-5) is located 650 feet away (see Figure 3). Hatchery well pumping activity is dominantly confined to moving water in the thinner $PSA_3$ layer with this activity carrying into the $PSA_2$ but not over to the $PSA_1$. The wider temperature range observed in the upper section of BDH-1624 as compared to BDH-1615 is interpreted as reflecting a closer recharge source from

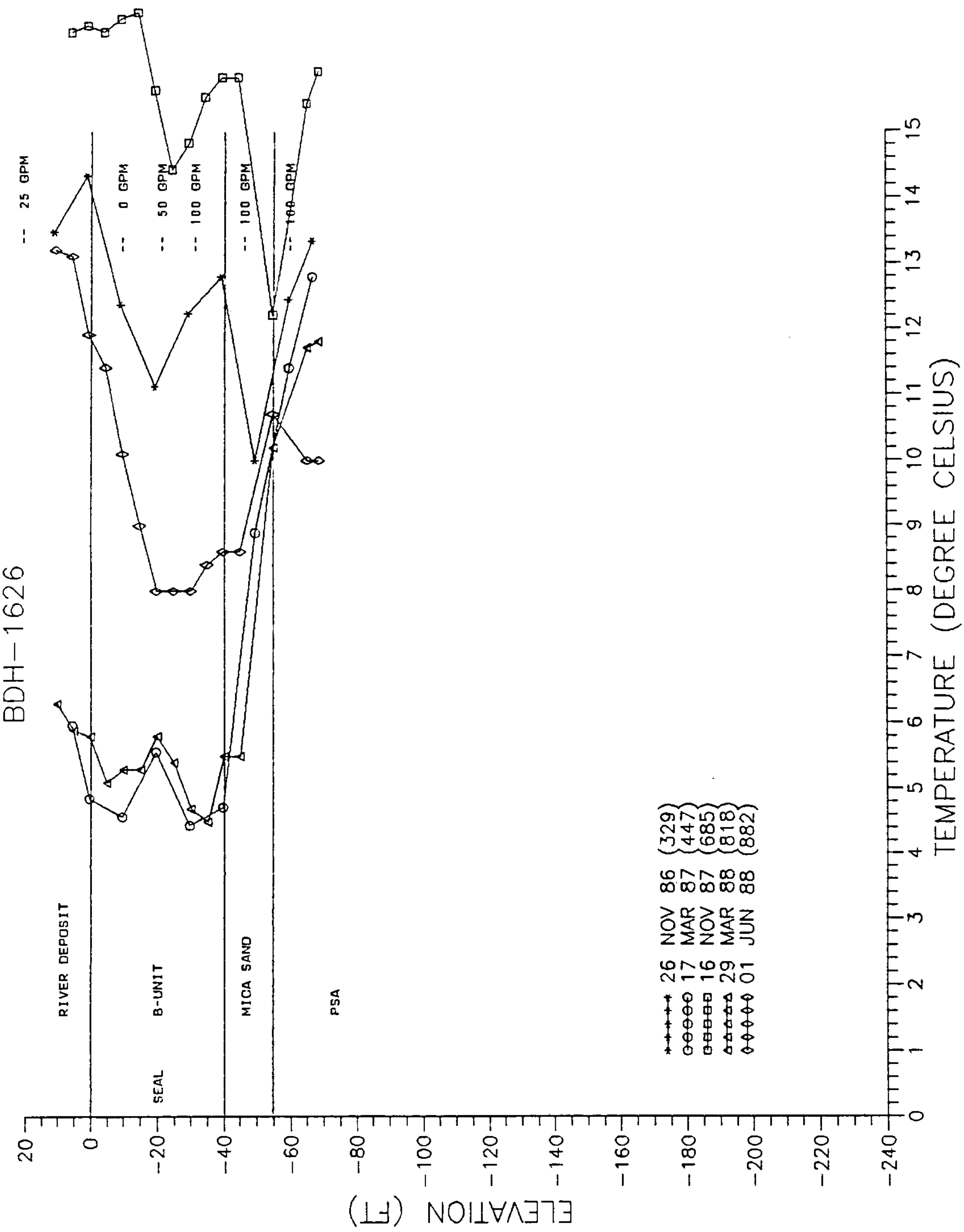

BDH-1624
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)
SEAL
Bc (may be RD)
Bg
SEAL
MICA SAND
PSA3
PSA2
WELL SCREEN INTERVAL OF H-4, WW-3.
PSA1
sand with gravel
abundant sand (basalt rich)
gravel with sand
WEIDLE FM.
-- 20 GPM
-- 30 GPM
-- 20 GPM
-- 30 GPM
-- 50 GPM
-- 60 GPM
-- 60 GPM
-- 60 GPM
-- 60 GPM
-- 100 GPM
-- 100 GPM
26 NOV 86 (316)
11 DEC 86 (345)
15 FEB 87 (418)
17 MAR 87 (447)
19 APR 87 (475)
16 MAY 87 (502)
14 OCT 87 (652)
07 DEC 87 (706)
05 FEB 88 (766)
06 JLY 88 (917)

the Columbia River. The $PSA_3$ is observed to have the coldest groundwater in the summer with the warmest in the winter. The thermal behavior of the Mica Sand at BDH-1624 illustrates its thermal buffering behavior supporting the aquitard classification of the Mica Sand.

BDH-1626

The thermal profile of the groundwater temperature at this piezometer illustrates the greatest observed thermal range in the terrace. The piezometer is shallow, located close to the Columbia River and impacted by groundwater with small temperature variation. It is of interest that the warmest groundwater temperatures are observed in the winter months and the coldest groundwater temperatures are in the spring months.

BDH-1626 is a shallow piezometer located close to the Columbia River in the area considered to be the main eastern recharge route of the terrace. The wide temperature range observed at this location is considered to be due to a strong thermal influence from the Columbia River rather than hatchery well impacted behavior. Considering the wide range of this piezometer's temperature, its shallow depth, and close proximity to the river, it was not expected that this amount of lag time would exist between the Columbia River temperatures and the upper hydrogeologic unit groundwater temperatures.



BDH-1626
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)
RIVER DEPOSIT
SEAL
B-UNIT
MICA SAND
PSA
-- 25 GPM
-- 0 GPM
-- 50 GPM
-- 100 GPM
-- 100 GPM
-- 100 GPM
26 NOV 86 (329)
17 MAR 87 (447)
16 NOV 87 (685)
29 MAR 88 (818)
01 JUN 88 (882)
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

BDH-1629

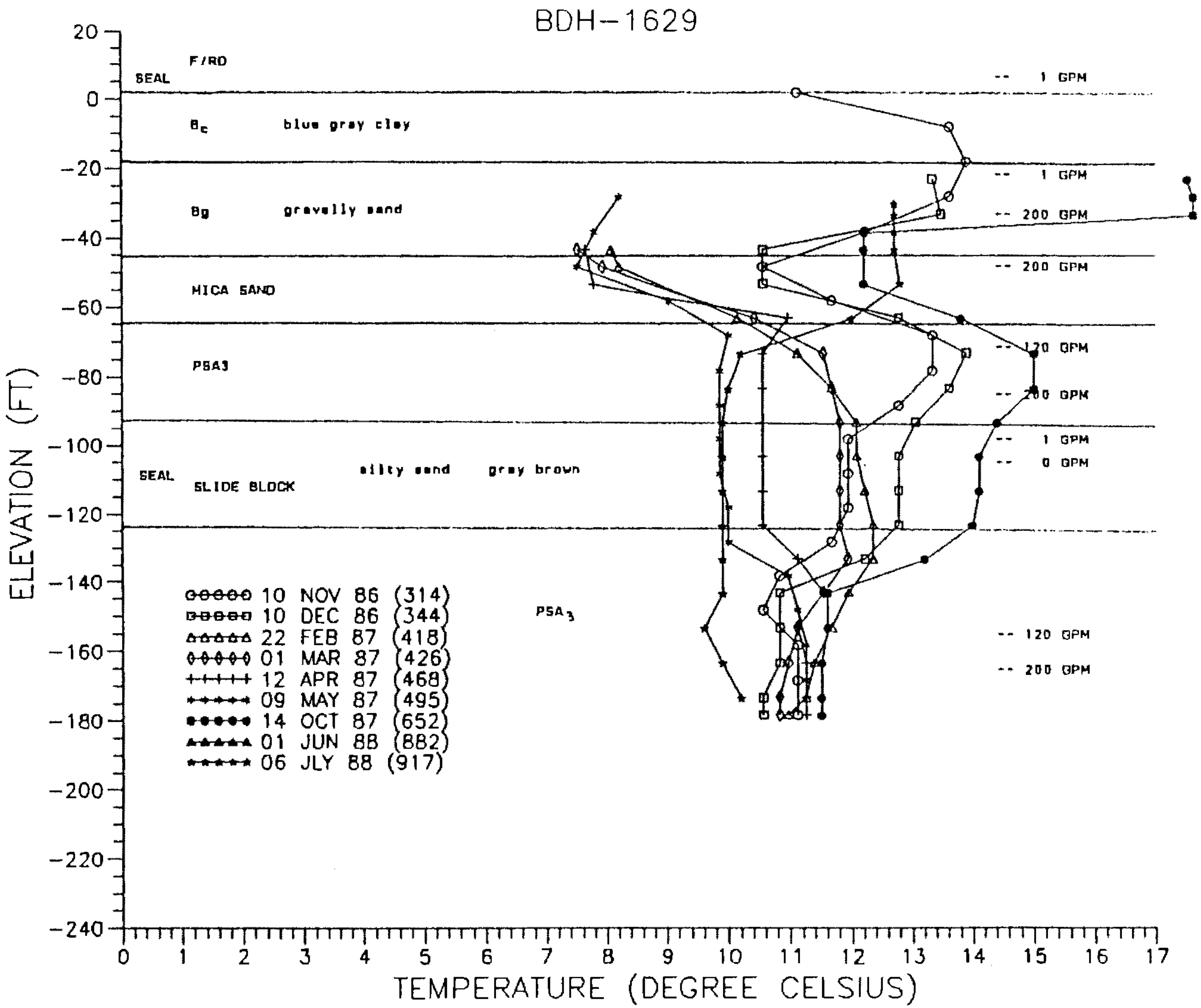
The thermal profile indicates that the stratigraphy in this section of the terrace is complicated by the introduction of slide block material in the $PSA_3$. The PSA-SB, which the drilling log for the piezometer indicates as lacking water, is observed to generally maintain a similar thermal behavior as the $PSA_3$ material above and below it.

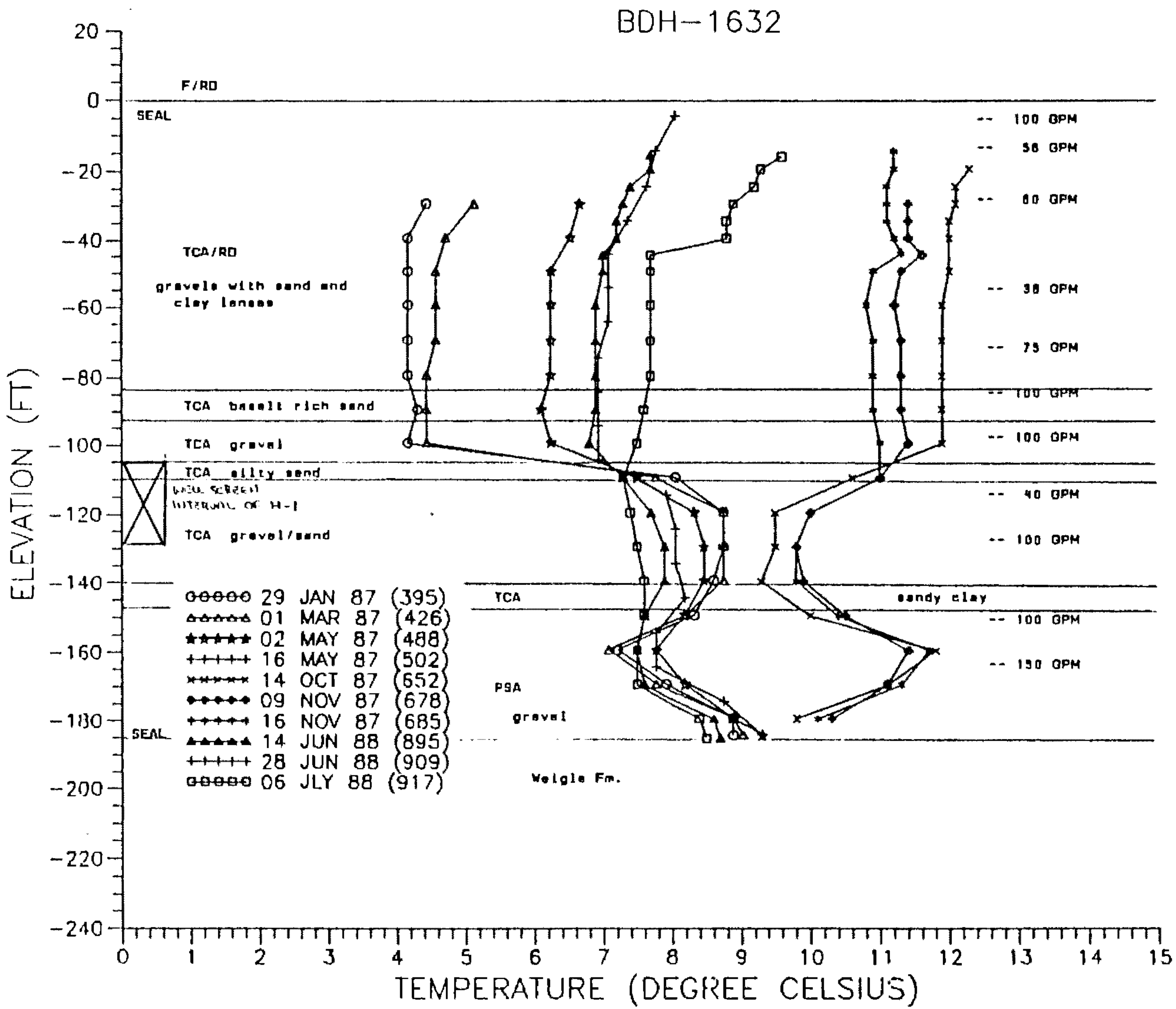
This type of thermal behavior is not expected since the slide block material is of low permeability and should not transport heat as efficiently as the $PSA_3$ material that surrounds it. The temperature behavior of this piezometer suggests that the region between BDH-1626 and the Bonney Rock intrusion is the primary eastern groundwater recharge route for the terrace. Thermal activity in the temperature profile indicates minimal influence from fish hatchery pumping in this area of the terrace. The temperature profile also indicates that the Mica Sand separates the thermal behavior of the PSA-aquifer from that of the upper B unit.

BDH-1632

The thermal profile of BDH-1632 indicates that both the lithology and stratigraphy is distinct in this area of the terrace due to the introduction of Tanner Creek alluvium.

Pump test analysis (Baron, 1990) indicates that the area around BDH-1632 is highly transmissive which is a reflection of high permeability and thickness of Tanner Creek alluvium. The wide temperature range and quick response time with


BDH-1629
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)
SEAL
F/RD
Bc blue gray clay
Bg gravelly sand
MICA SAND
PSA3
SEAL
SLIDE BLOCK
silty sand
gray brown
PSA3
-- 1 GPM
-- 1 GPM
-- 200 GPM
-- 200 GPM
-- 120 GPM
-- 200 GPM
-- 1 GPM
-- 0 GPM
-- 120 GPM
-- 200 GPM
10 NOV 86 (314)
10 DEC 86 (344)
22 FEB 87 (418)
01 MAR 87 (426)
12 APR 87 (468)
09 MAY 87 (495)
14 OCT 87 (652)
01 JUN 88 (882)
06 JLY 88 (917)


BDH-1632
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)
F/RD
SEAL
TCA/RD
gravels with sand and
clay lenses
TCA basalt rich sand
TCA gravel
TCA silty sand
TCA gravel/sand
TCA
sandy clay
PSA
gravel
SEAL
Weigle Fm.
-- 100 GPM
-- 58 GPM
-- 60 GPM
-- 38 GPM
-- 75 GPM
-- 100 GPM
-- 100 GPM
-- 40 GPM
-- 100 GPM
-- 100 GPM
-- 150 GPM
29 JAN 87 (395)
01 MAR 87 (426)
02 MAY 87 (488)
16 MAY 87 (502)
14 OCT 87 (652)
09 NOV 87 (678)
16 NOV 87 (685)
14 JUN 88 (895)
28 JUN 88 (909)
06 JLY 88 (917)
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

respect to river temperature also indicates that the upper section of Tanner Creek alluvium provides a relatively direct route of recharge from the Columbia River. Lag time in the upper section of the piezometer is less than two months. This quick response time and wide temperature range, which abruptly decreases below a silty sand layer at an elevation of -105 feet, is an expression of the large mass of low thermally moderated groundwater moving through this portion of the terrace.

Thermal behavior in the Tanner Creek alluvium gravel/sand layer (-110 to -140 feet) indicates an area of lower groundwater velocity due to greater temperature variability observed in the sections above and below this layer. These observations are of interest because the hatchery screen intervals are at the same elevation as the Tanner Creek alluvium gravel/sand layer. The observed thermal behavior from the temperature profile would support the suggestion that groundwater movement towards the hatchery wells is not taking place in this particular layer of the Tanner Creek alluvium. The wider range of groundwater temperature observed in the lower $PSA_3$ indicates that more groundwater is moving through this layer than the gravel/sand layer located above it, but from a more moderated source than the groundwater passing through the upper section of the piezometer.

DH-1946

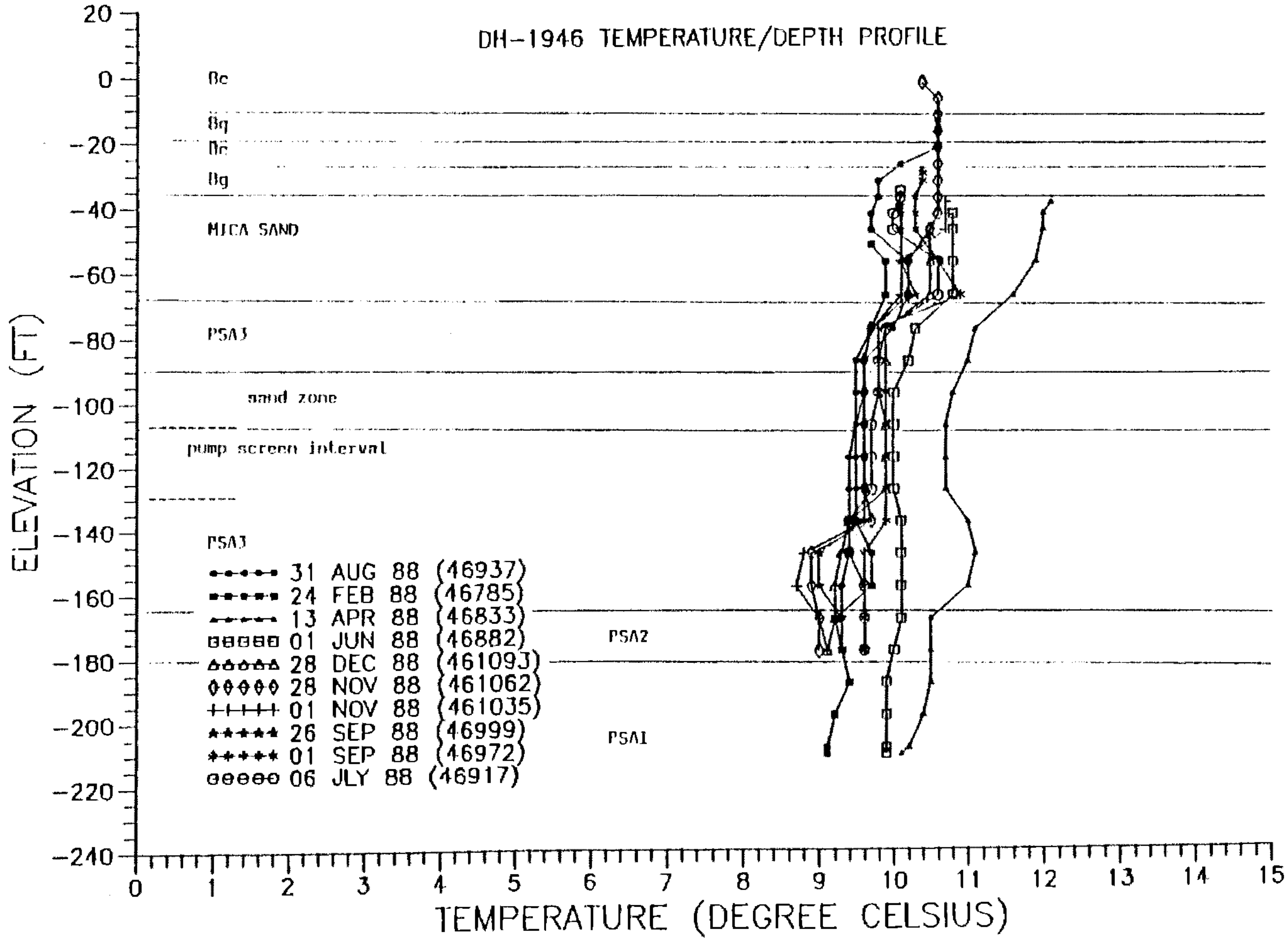
The thermal behavior of this piezometer has a very narrow annual temperature range that can be attributed to several factors, all of which are associated with depositional history and hatchery pump locations.

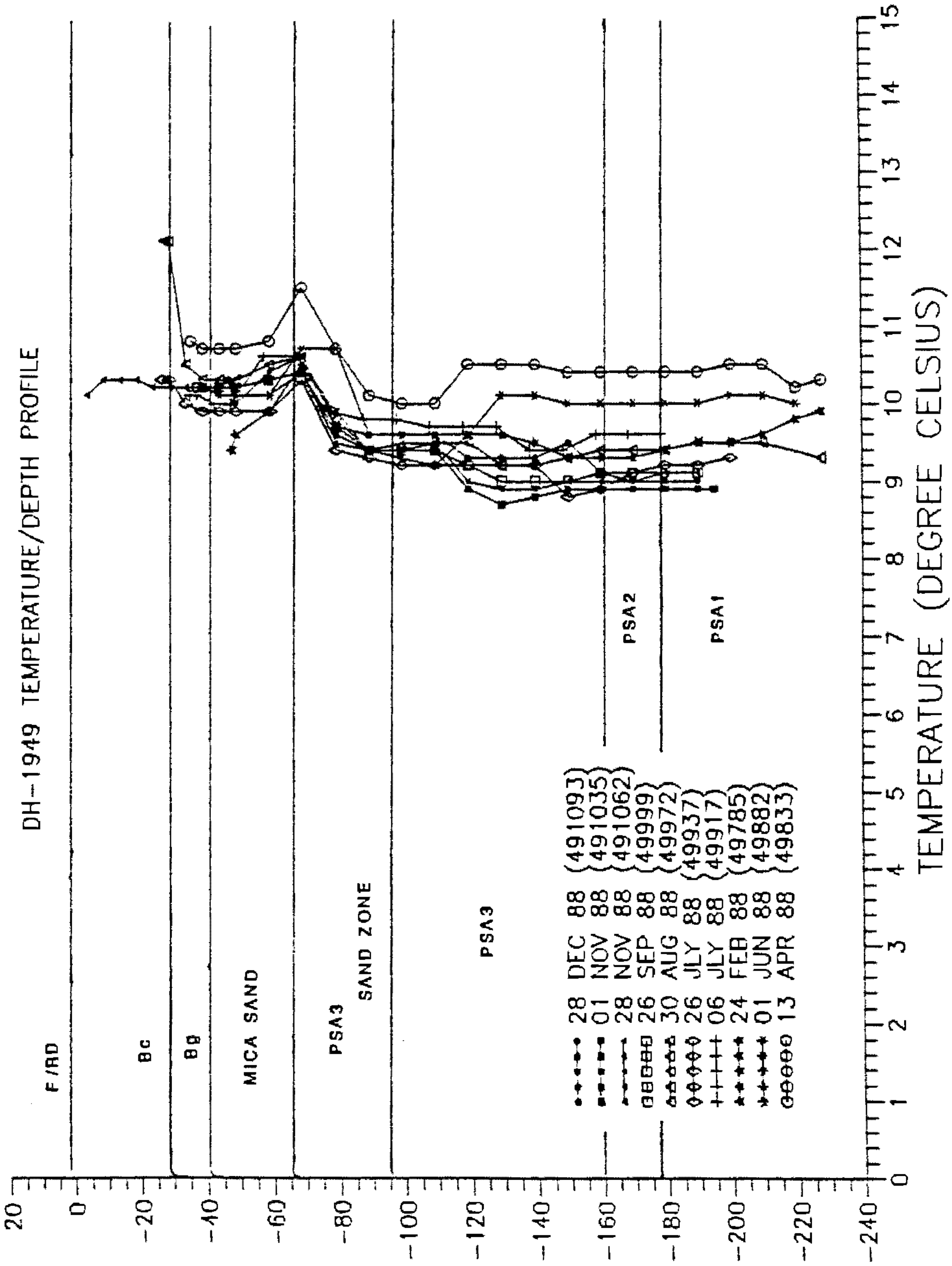
The fluvial depositional nature of the terrace has produced a strong east-west depositional orientation. Consequently, groundwater movement in the terrace is also dominantly in an east-west direction. The location of DH-1946, north of the hatchery well field and the primary east-west recharge route, creates low groundwater velocity conditions for this area of the terrace. This statement is further supported by the observation that there is no apparent hatchery well impact in the $PSA_3$ section of the piezometer at or above the elevation corresponding to the hatchery well screen interval.

A small increase in temperature range is observed in the lower section of the $PSA_3$. This thermal increase has been attributed to a gravel lens that creates a higher permeability zone allowing for an area of slightly higher groundwater velocity. A thick accumulation of clay in the B unit in the region between the Columbia River and this piezometer functions to decrease the thermal impact of the Columbia River from the north.

DH-1949

The thermal profile of DH-1949 indicates a consistent narrow annual temperature range characterizes the piezometer's thermal behavior. Lithology at

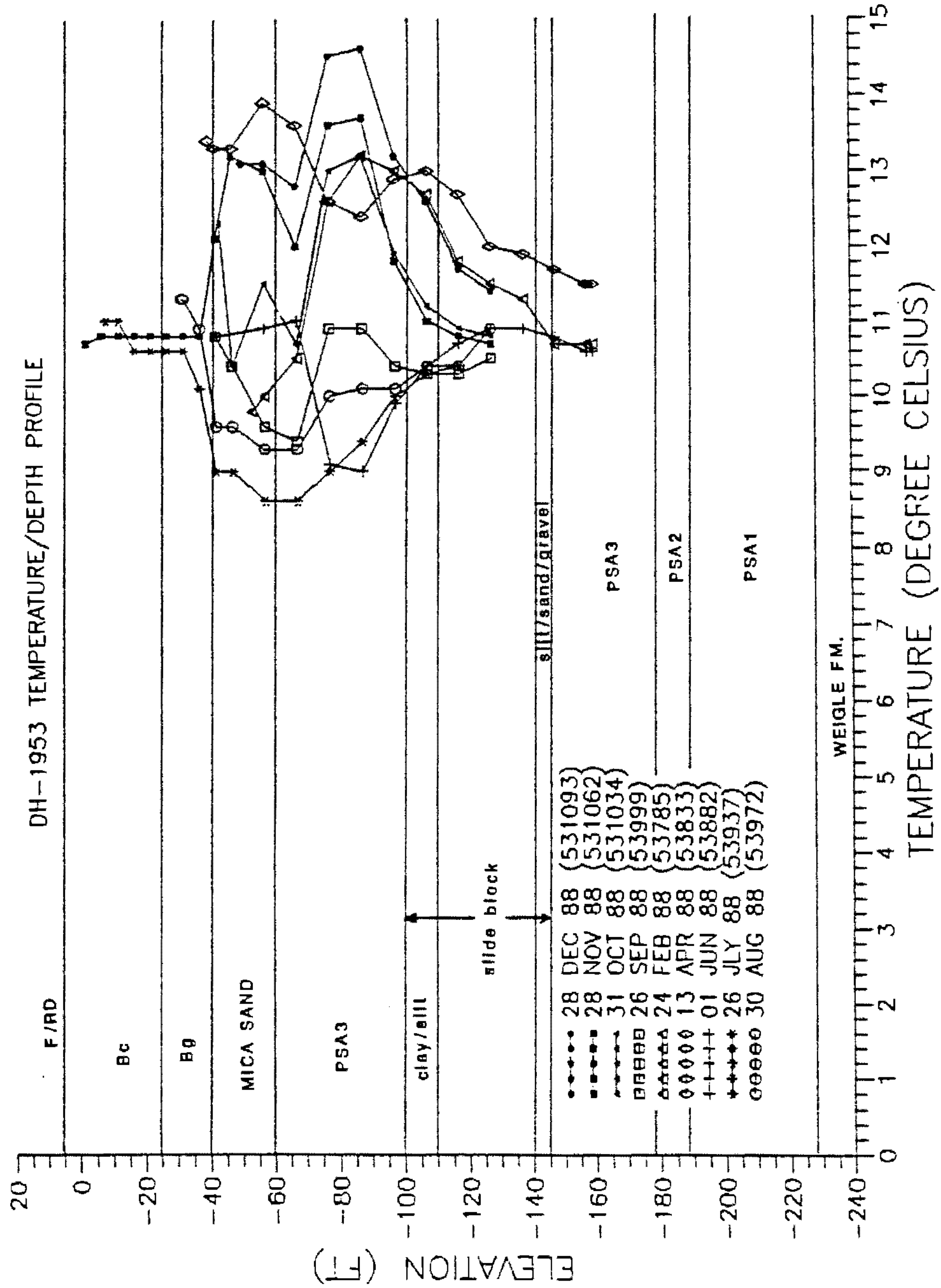

DH-1946 TEMPERATURE/DEPTH PROFILE
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)
Bc
Bq
Bc
Bg
MICA SAND
PSA3
sand zone
pump screen interval
PSA3
PSA2
PSA1
31 AUG 88 (46937)
24 FEB 88 (46785)
13 APR 88 (46833)
01 JUN 88 (46882)
28 DEC 88 (461093)
28 NOV 88 (461062)
01 NOV 88 (461035)
26 SEP 88 (46999)
01 SEP 88 (46972)
06 JLY 88 (46917)
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15


DH-1949 TEMPERATURE/DEPTH PROFILE
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)
F/RD
Bc
Bg
MICA SAND
PSA3
SAND ZONE
PSA3
PSA2
PSA1
28 DEC 88 (491093)
01 NOV 88 (491035)
28 NOV 88 (491062)
26 SEP 88 (49999)
30 AUG 88 (49972)
26 JLY 88 (49937)
06 JLY 88 (49917)
24 FEB 88 (49785)
01 JUN 88 (49882)
13 APR 88 (49833)
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

DH-1949 influences groundwater temperature behavior to a greater extent than at DH-1946 as indicated by greater thermal variation between stratigraphic units. At DH-1949 the largest temperature range occurs in the lower section of the piezometer indicating that low groundwater flow is occurring in the upper hydrogeologic units in this region of the terrace. The lack of thermal variation between the lower section of the $PSA_3$ and the $PSA_1$ suggests that the capping effect of $PSA_2$ is not thermally influential at this piezometer. This thermal behavior further supports the suggestion that the greatest amount of groundwater movement is occurring in the lower section (PSA-aquifer) of the piezometer. This thermal behavior could be associated with the gravel lens located in the lower section of the $PSA_3$ at this piezometer allowing for greater permeability. The narrow temperature range in the Mica Sand and B unit indicates that there is a large amount of isolation from direct contact with the Columbia River in this area of the terrace.

DH-1953

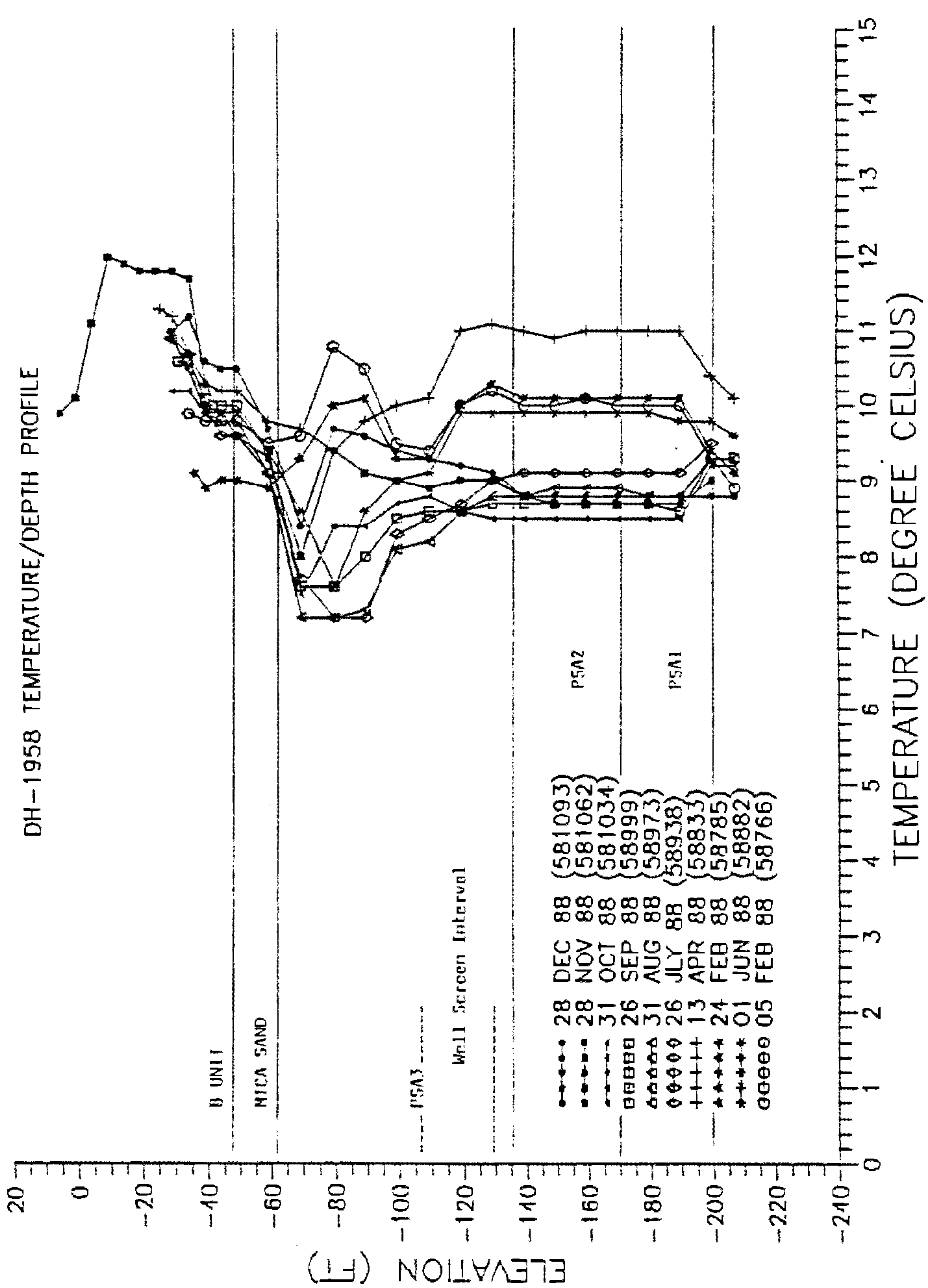
The wide temperature range observed in the thermal profile of DH-1953 does not behave in a manner as would be expected based on the argument used in the discussion of thermal behavior for DH-1949. DH-1953 and DH-1946 are 325 feet apart but their thermal behavior is distinctly different. The major lithologic/stratigraphic difference between the two locations is that the $PSA_3$ at DH-1953 consists of slide block material. The section of $PSA_3$ above the PSA-SB


DH-1953 TEMPERATURE/DEPTH PROFILE
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)
F/RD
Bc
Bg
MICA SAND
PSA3
clay/silt
slide block
silt/sand/gravel
PSA3
PSA2
PSA1
WEIGLE FM.
28 DEC 88 (531093)
28 NOV 88 (531062)
31 OCT 88 (531034)
26 SEP 88 (53999)
24 FEB 88 (53785)
13 APR 88 (53833)
01 JUN 88 (53882)
26 JLY 88 (53937)
30 AUG 88 (53972)
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
-220
-240
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

has the widest temperature range indicating that this area of the piezometer is the section of greatest groundwater velocity. This region in the upper $PSA_3$ is thought to be impacted by hatchery well pumping due to these observations. A possible reason for the wider temperature range behavior at DH-1953 is the existence of a paleochannel in this area of the terrace, allowing for a different set of conditions to dictate groundwater movement and therefore thermal behavior. The previously observed thermal behavior of highest groundwater temperature in the winter months and lowest in early summer is consistent at this location. This type of thermal behavior does not extend over to DH-1946, indicating that the two piezometers are not being influenced in the same manner. The thick clay layer in the B unit found in this region of the terrace produces a narrow temperature range similar to the behavior observed at DH-1946 and DH-1949.

## DH-1958

Thermal influence from the Columbia River and apparent impact of the hatchery wells is depicted in the thermal profile of DH-1958. The distinct thermal behavior of this piezometer is expressed in its narrow temperature range in the Mica Sand and B unit. This is consistent with the observations of thermal behavior of other piezometers in the northern section of the terrace where highly moderated temperature behavior in the upper hydrogeologic units suggest low groundwater flow and less impact from the Columbia River. This low permeability zone accentuates the east-west flow behavior in the terrace. The top section of



DH-1958 TEMPERATURE/DEPTH PROFILE
ELEVATION (FT)
TEMPERATURE (DEGREE CELSIUS)
B UNIT
MICA SAND
PSA3
Well Screen Interval
PSA2
PSA1
28 DEC 88 (581093)
28 NOV 88 (581062)
31 OCT 88 (581034)
26 SEP 88 (58999)
31 AUG 88 (58973)
26 JLY 88 (58938)
13 APR 88 (58833)
24 FEB 88 (58785)
01 JUN 88 (58882)
05 FEB 88 (58766)

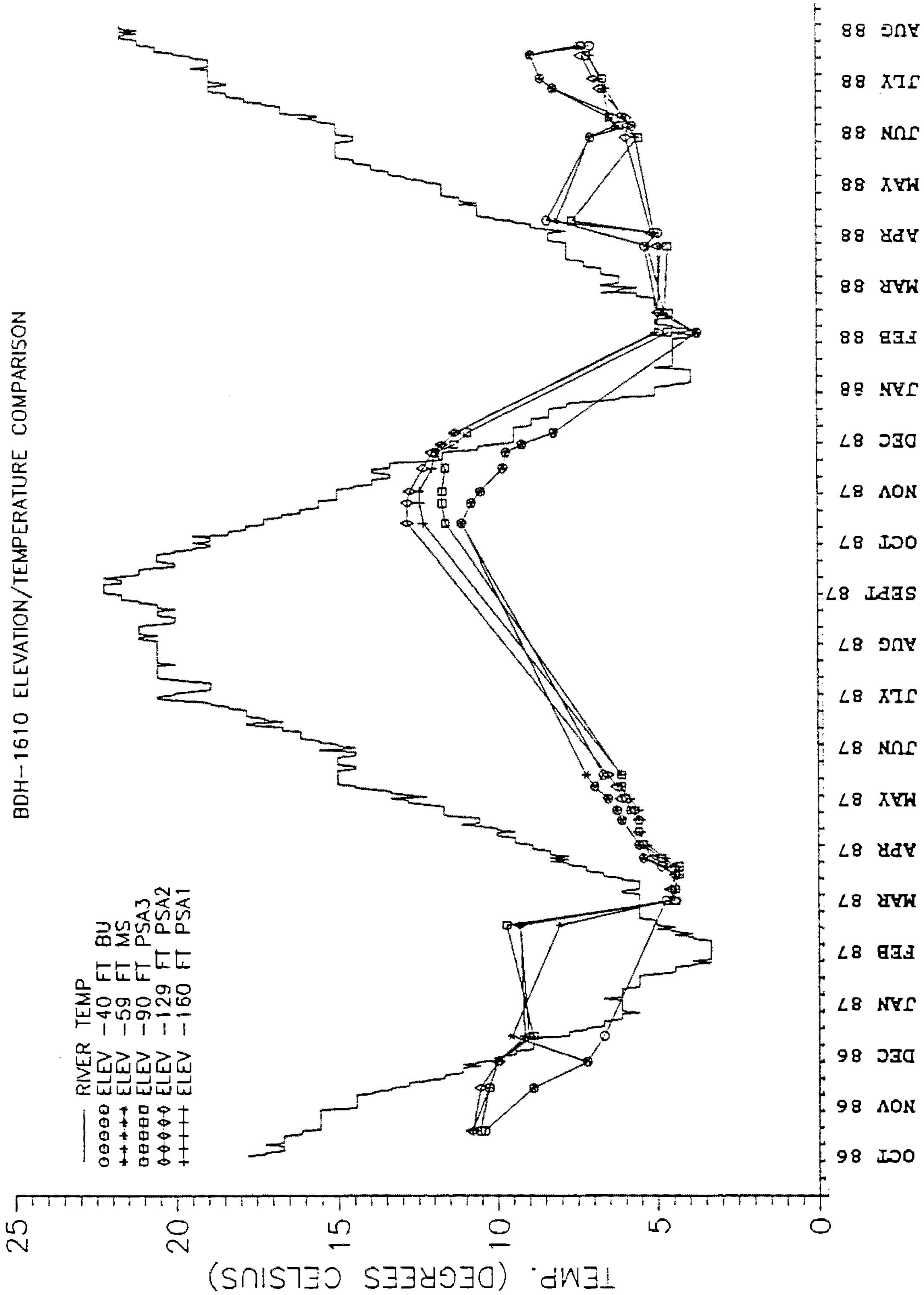
$PSA_3$ has the widest temperature range indicating that this is the section with the highest groundwater velocity. This zone of high groundwater movement could be attributed to the pumping activity of the hatchery wells. The closest well (H-3) is located 275 feet away. The temperature behavior of DH-1958 further supports the uniqueness of piezometers DH-1946 and DH-1949 just east of this piezometer.

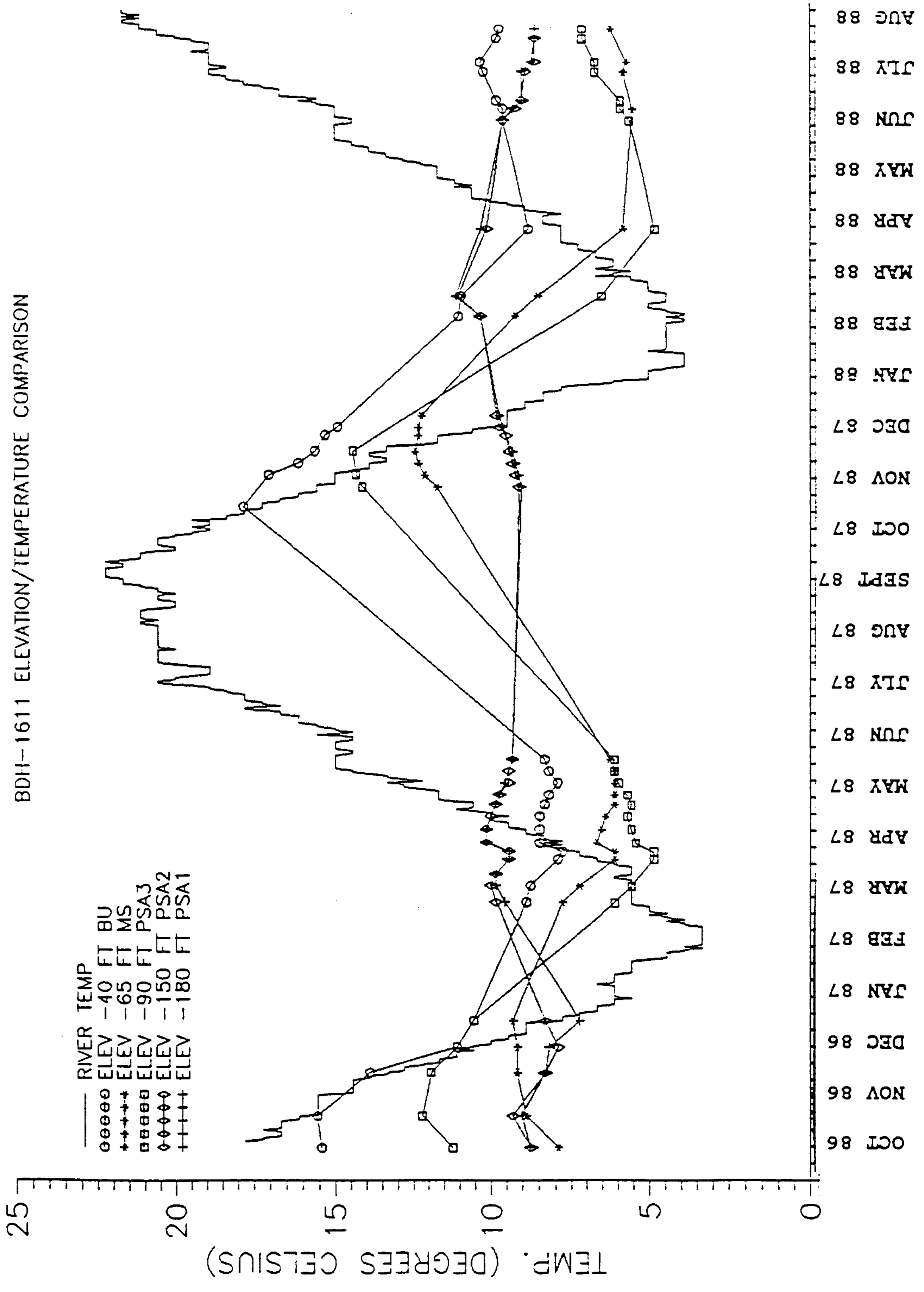
# APPENDIX B

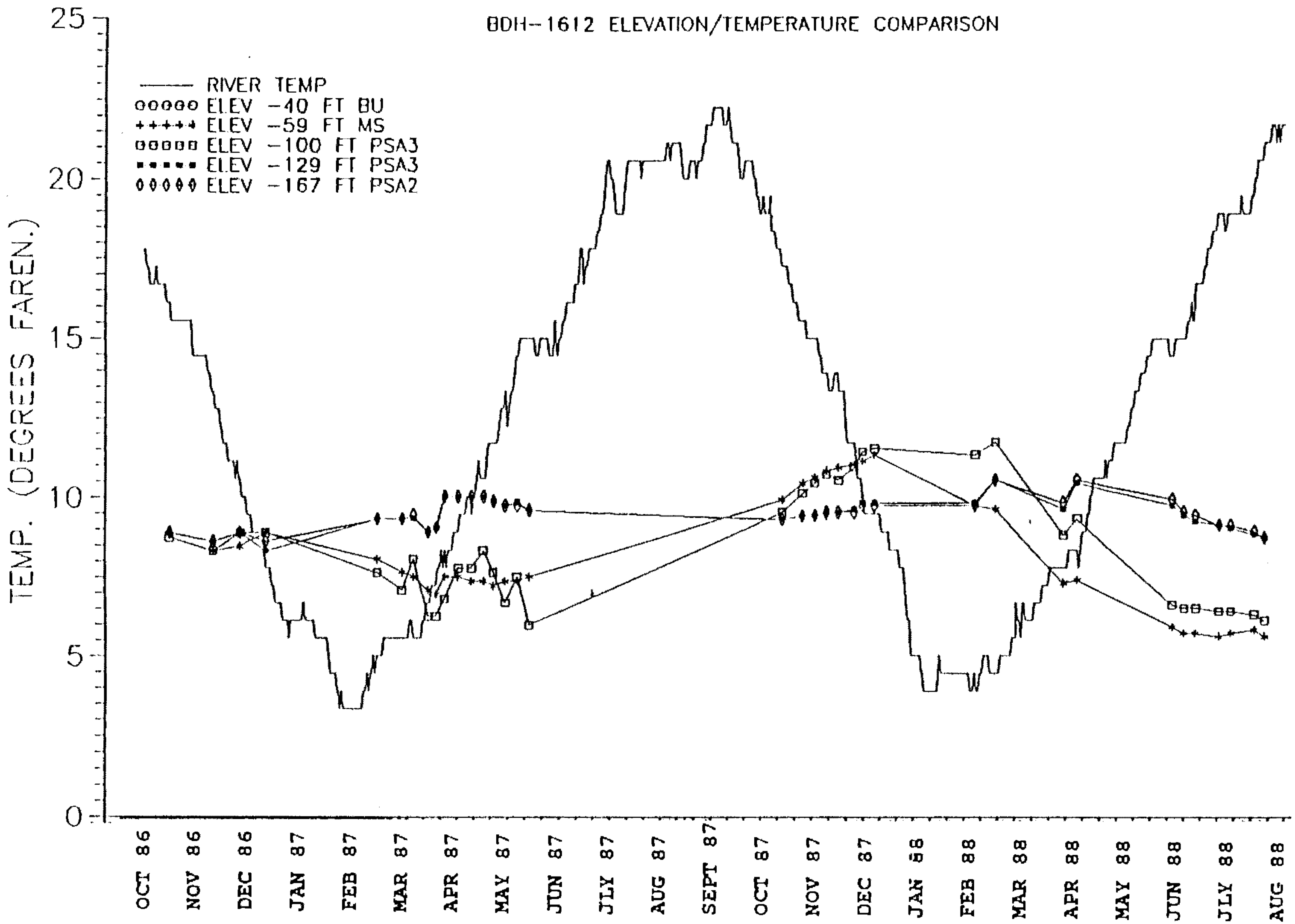
# TEMPERATURE TIME GRAPHS

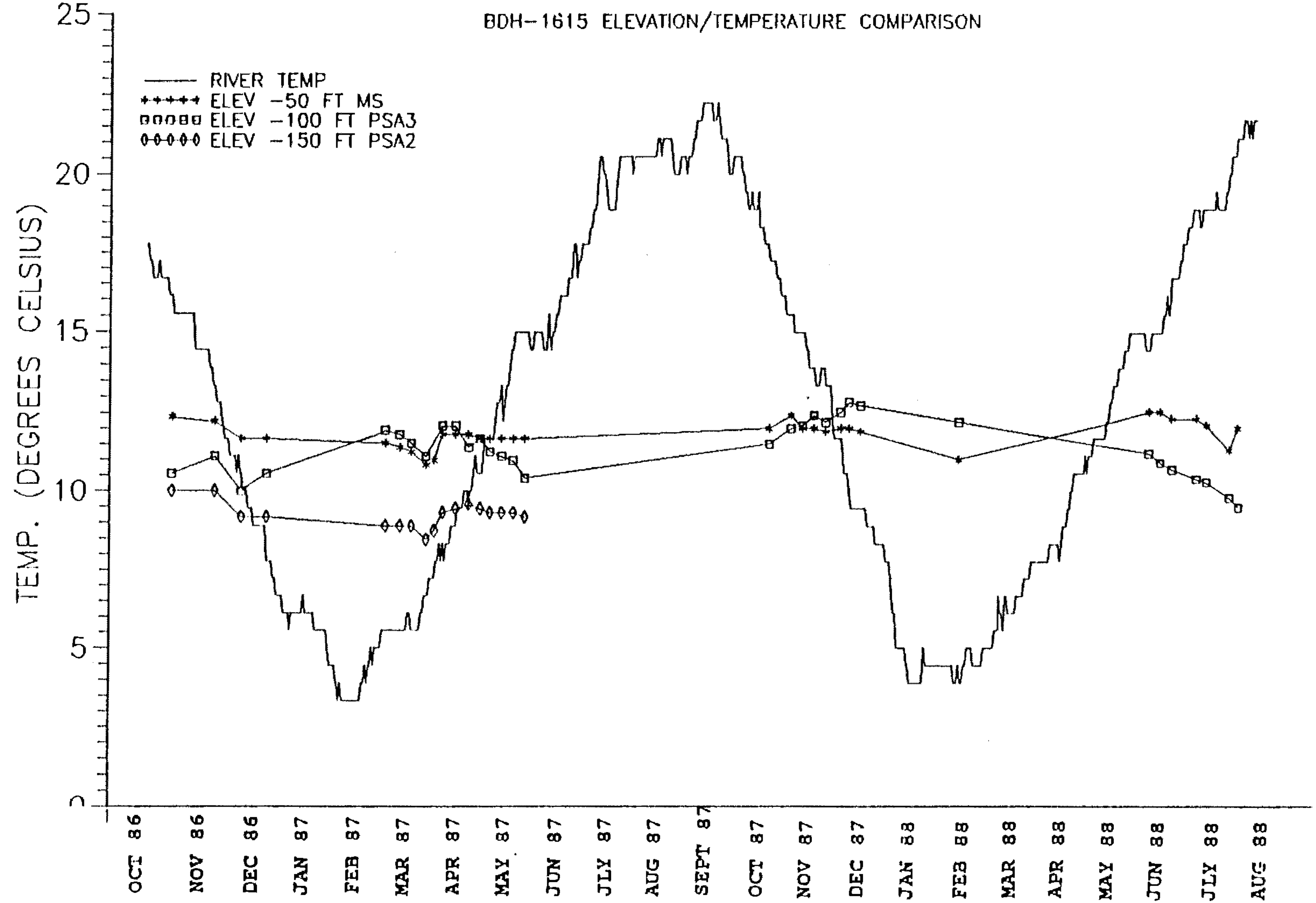
# TEMPERATURE TIME GRAPHS

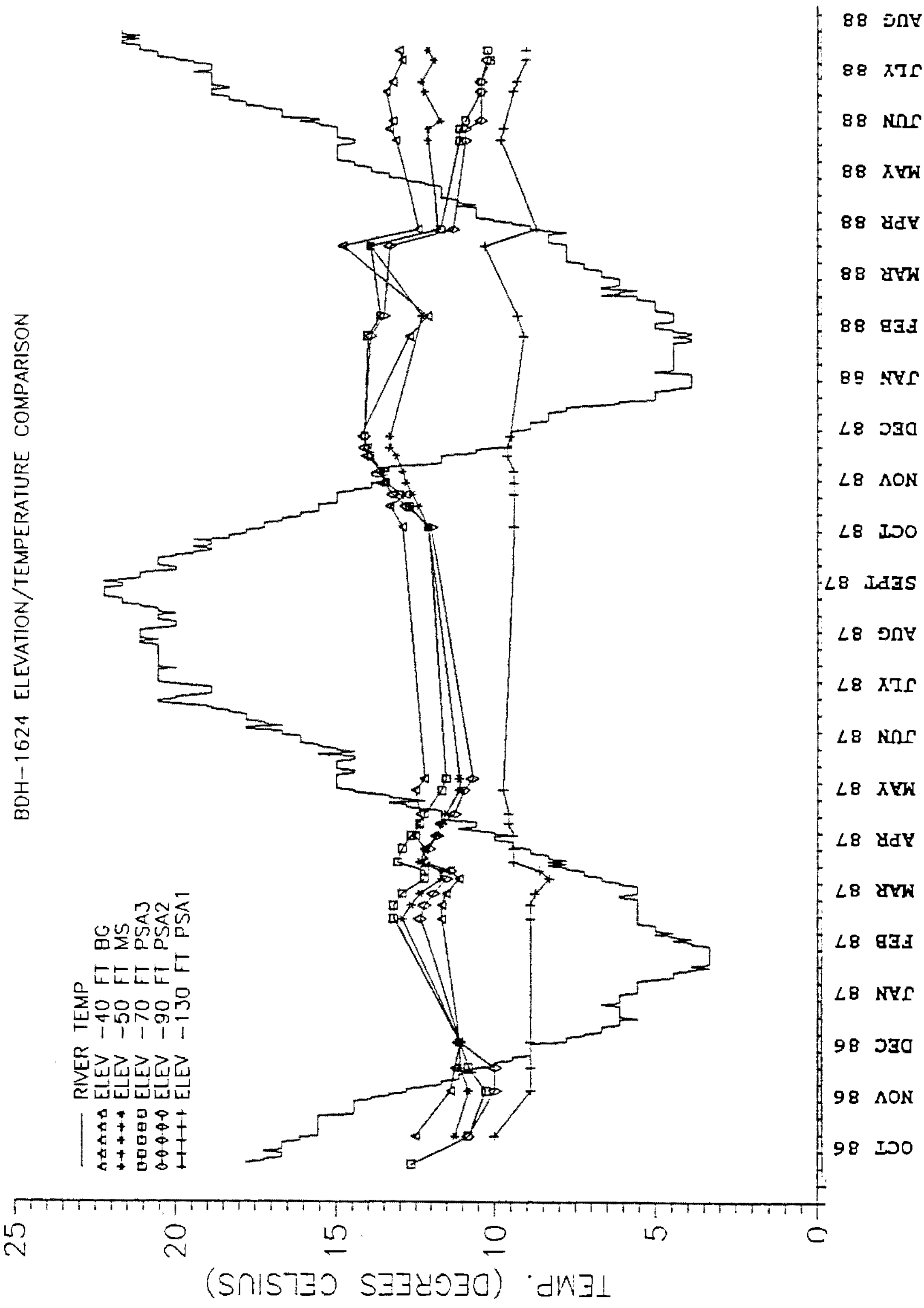
Temperature time graphs are presented in Appendix B for the following piezometers: BDH-1610, BDH-1611, BDH-1612, BDH-1615, BDH-1624, BDH-1626, BDH-1629, and BDH-1632. The temperature time graph presents temperature data of selected elevations representing each hydrogeologic unit encountered at the piezometer over a span of 23 months. The temperature of the Columbia River is also presented on the same graph and allows for a comparison of the piezometers temperature with that of the river. Temperature time graphs proved useful for estimating lag times, and maximum and minimum temperatures for each of the hydrogeologic units for each piezometer. This type of information was consolidated and presented in Table IV. Temperature time graphs were also developed that allow for an assessment the thermal behavior of a particular hydrogeologic unit for the whole terrace. These graphs are located in Chapter V and were produced by using selected temperature data of the same hydrogeologic unit for different piezometers.


BDH-1610 ELEVATION/TEMPERATURE COMPARISON
RIVER TEMP
ELEV -40 FT BU
ELEV -59 FT MS
ELEV -90 FT PSA3
ELEV -129 FT PSA2
ELEV -160 FT PSA1
TEMP. (DEGREES CELSIUS)
0
5
10
15
20
25
OCT 86
NOV 86
DEC 86
JAN 87
FEB 87
MAR 87
APR 87
MAY 87
JUN 87
JLY 87
AUG 87
SEPT 87
OCT 87
NOV 87
DEC 87
JAN 88
FEB 88
MAR 88
APR 88
MAY 88
JUN 88
JLY 88
AUG 88


BDH-1611 ELEVATION/TEMPERATURE COMPARISON
RIVER TEMP
ELEV -40 FT BU
ELEV -65 FT MS
ELEV -90 FT PSA3
ELEV -150 FT PSA2
ELEV -180 FT PSA1
TEMP. (DEGREES CELSIUS)
0
5
10
15
20
25
OCT 86
NOV 86
DEC 86
JAN 87
FEB 87
MAR 87
APR 87
MAY 87
JUN 87
JLY 87
AUG 87
SEPT 87
OCT 87
NOV 87
DEC 87
JAN 88
FEB 88
MAR 88
APR 88
MAY 88
JUN 88
JLY 88
AUG 88


BDH-1612 ELEVATION/TEMPERATURE COMPARISON
RIVER TEMP
ELEV -40 FT BU
ELEV -59 FT MS
ELEV -100 FT PSA3
ELEV -129 FT PSA3
ELEV -167 FT PSA2
TEMP. (DEGREES FAREN.)
0
5
10
15
20
25
OCT 86
NOV 86
DEC 86
JAN 87
FEB 87
MAR 87
APR 87
MAY 87
JUN 87
JLY 87
AUG 87
SEPT 87
OCT 87
NOV 87
DEC 87
JAN 88
FEB 88
MAR 88
APR 88
MAY 88
JUN 88
JLY 88
AUG 88


BDH-1615 ELEVATION/TEMPERATURE COMPARISON
RIVER TEMP
ELEV -50 FT MS
ELEV -100 FT PSA3
ELEV -150 FT PSA2
TEMP. (DEGREES CELSIUS)
0
5
10
15
20
25
OCT 86
NOV 86
DEC 86
JAN 87
FEB 87
MAR 87
APR 87
MAY 87
JUN 87
JLY 87
AUG 87
SEPT 87
OCT 87
NOV 87
DEC 87
JAN 88
FEB 88
MAR 88
APR 88
MAY 88
JUN 88
JLY 88
AUG 88


BDH-1624 ELEVATION/TEMPERATURE COMPARISON
RIVER TEMP
ELEV -40 FT BG
ELEV -50 FT MS
ELEV -70 FT PSA3
ELEV -90 FT PSA2
ELEV -130 FT PSA1
TEMP. (DEGREES CELSIUS)
0
5
10
15
20
25
OCT 86
NOV 86
DEC 86
JAN 87
FEB 87
MAR 87
APR 87
MAY 87
JUN 87
JLY 87
AUG 87
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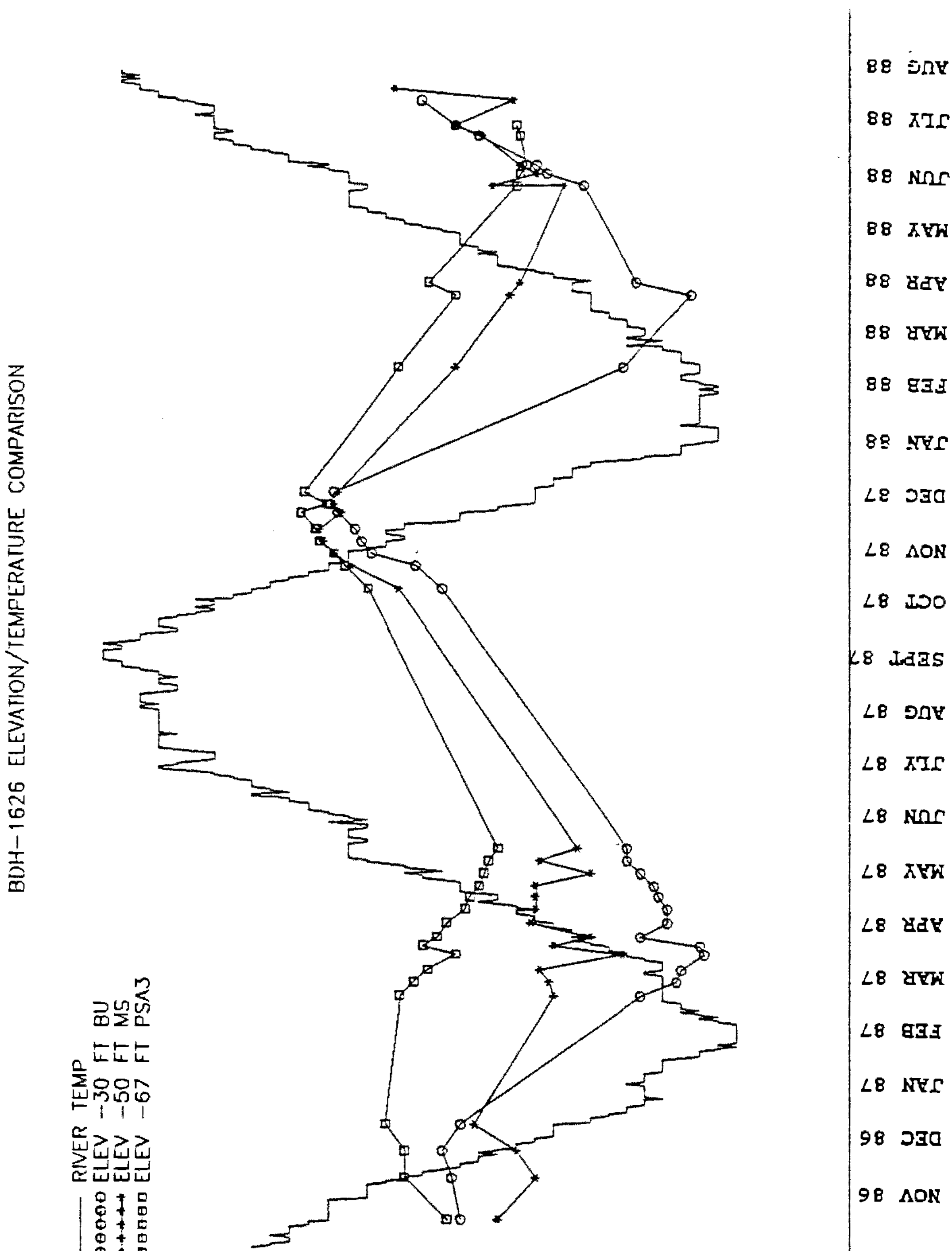
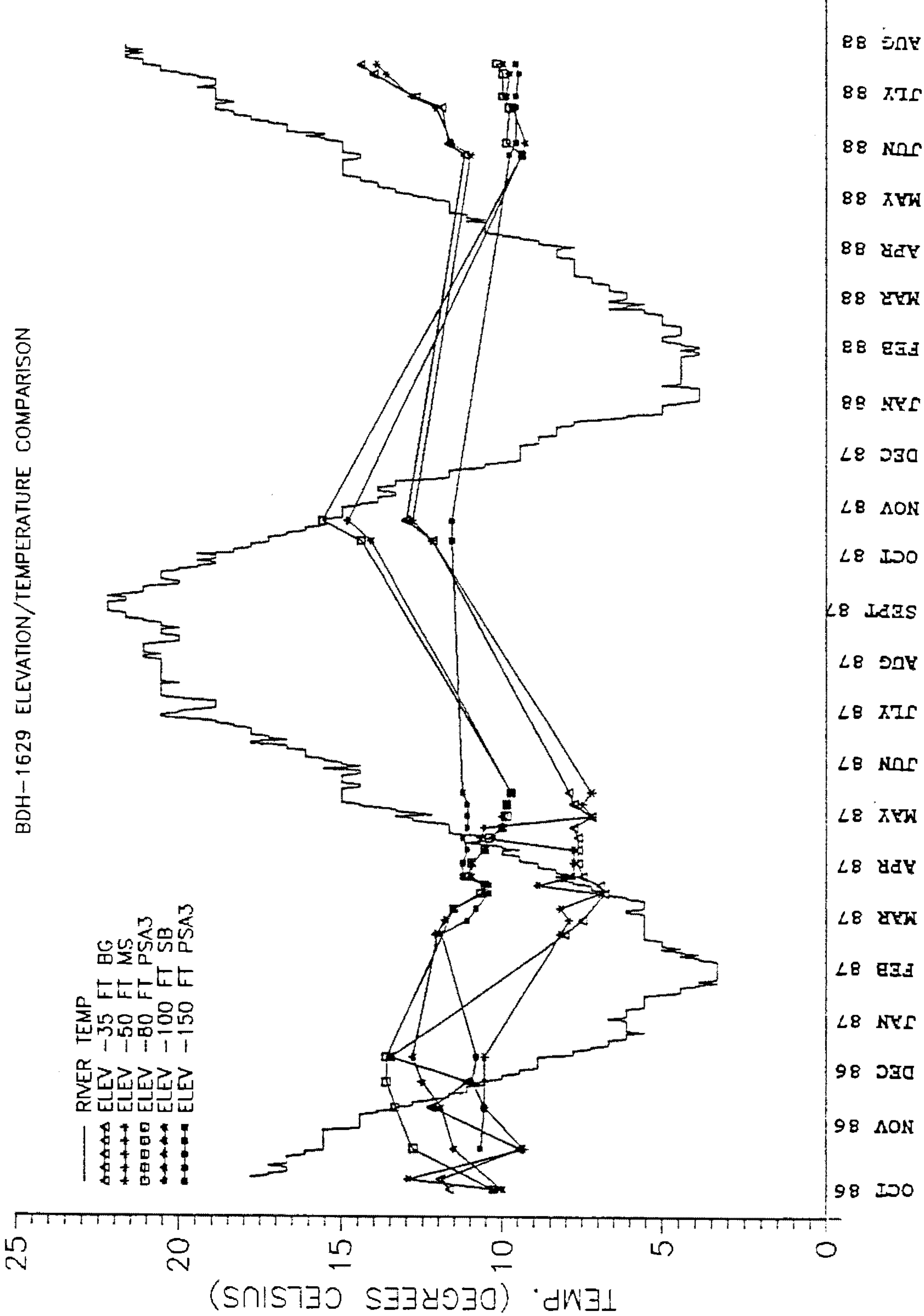
JUN 88
JLY 88
AUG 88


BDH-1626 ELEVATION/TEMPERATURE COMPARISON
RIVER TEMP
ELEV -30 FT BU
ELEV -50 FT MS
ELEV -67 FT PSA3
TEMP. (DEGREES CELSIUS)
0
5
10
15
20
25
OCT 86
NOV 86
DEC 86
JAN 87
FEB 87
MAR 87
APR 87
MAY 87
JUN 87
JLY 87
AUG 87
SEPT 87
OCT 87
NOV 87
DEC 87
JAN 88
FEB 88
MAR 88
APR 88
MAY 88
JUN 88
JLY 88
AUG 88



BDH-1629 ELEVATION/TEMPERATURE COMPARISON
RIVER TEMP
ELEV -35 FT BG
ELEV -50 FT MS
ELEV -80 FT PSA3
ELEV -100 FT SB
ELEV -150 FT PSA3
TEMP. (DEGREES CELSIUS)
0
5
10
15
20
25
OCT 86
NOV 86
DEC 86
JAN 87
FEB 87
MAR 87
APR 87
MAY 87
JUN 87
JLY 87
AUG 87
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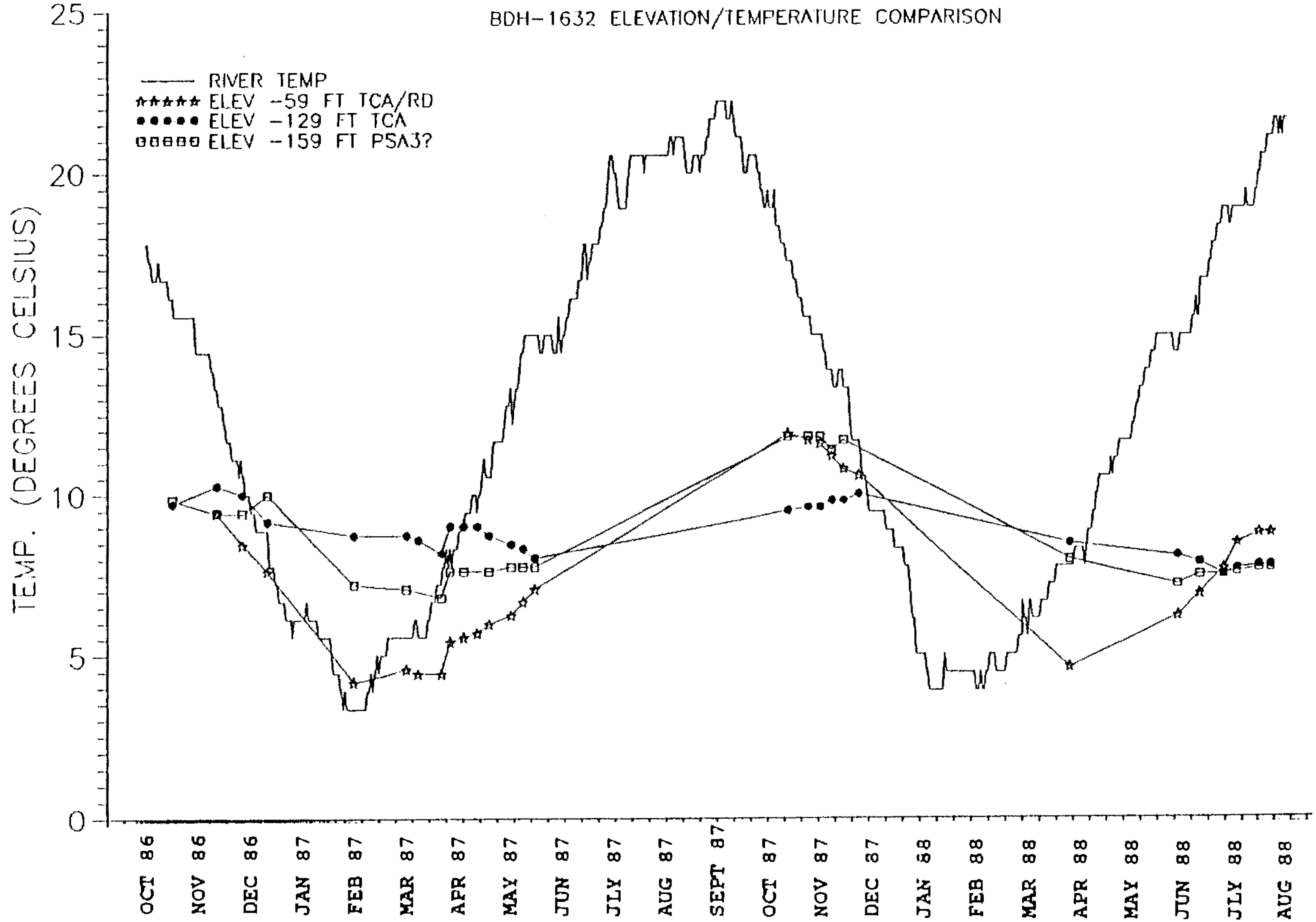
MAY 88
JUN 88
JLY 88
AUG 88


BDH-1632 ELEVATION/TEMPERATURE COMPARISON
RIVER TEMP
ELEV -59 FT TCA/RD
ELEV -129 FT TCA
ELEV -159 FT PSA3?
TEMP. (DEGREES CELSIUS)
0
5
10
15
20
25
OCT 86
NOV 86
DEC 86
JAN 87
FEB 87
MAR 87
APR 87
MAY 87
JUN 87
JLY 87
AUG 87
SEPT 87
OCT 87
NOV 87
DEC 87
JAN 88
FEB 88
MAR 88
APR 88
MAY 88
JUN 88
JLY 88
AUG 88

# APPENDIX C

# ISOTHERMAL CONTOUR MAPS

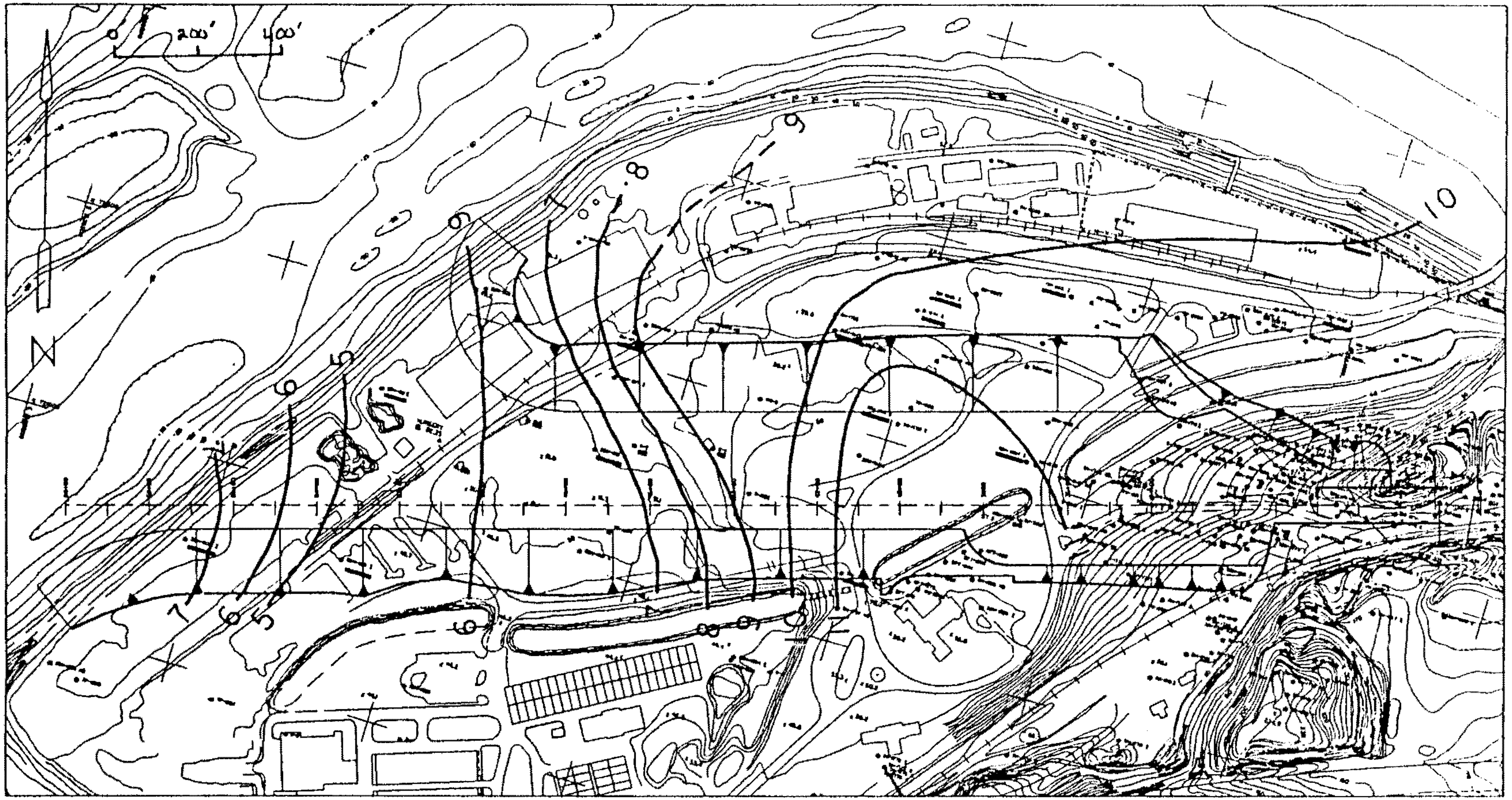
# ISOTHERMAL CONTOUR MAPS

The isothermal contour map spatially presents groundwater temperature data for the terrace area for a specific date. These maps have been developed for the $PSA_3$ hydrogeologic unit to develop to assist in analyzing how fish hatchery pumping is influencing the thermal behavior of the terrace in $PSA_3$. Isothermal contour maps were produced for the following dates in 1988: June 1, June 13, July 6, July 26, October 10, November 1, and December 15. Temperature data were selected by evaluating the temperature profile of each piezometer for a value that best represents the $PSA_3$ for the particular date of interest. These values were then placed in the appropriate location on the map and then contoured. Hatchery well pumping rates and water temperature, Columbia River and Tanner Creek temperatures are also included on the maps.

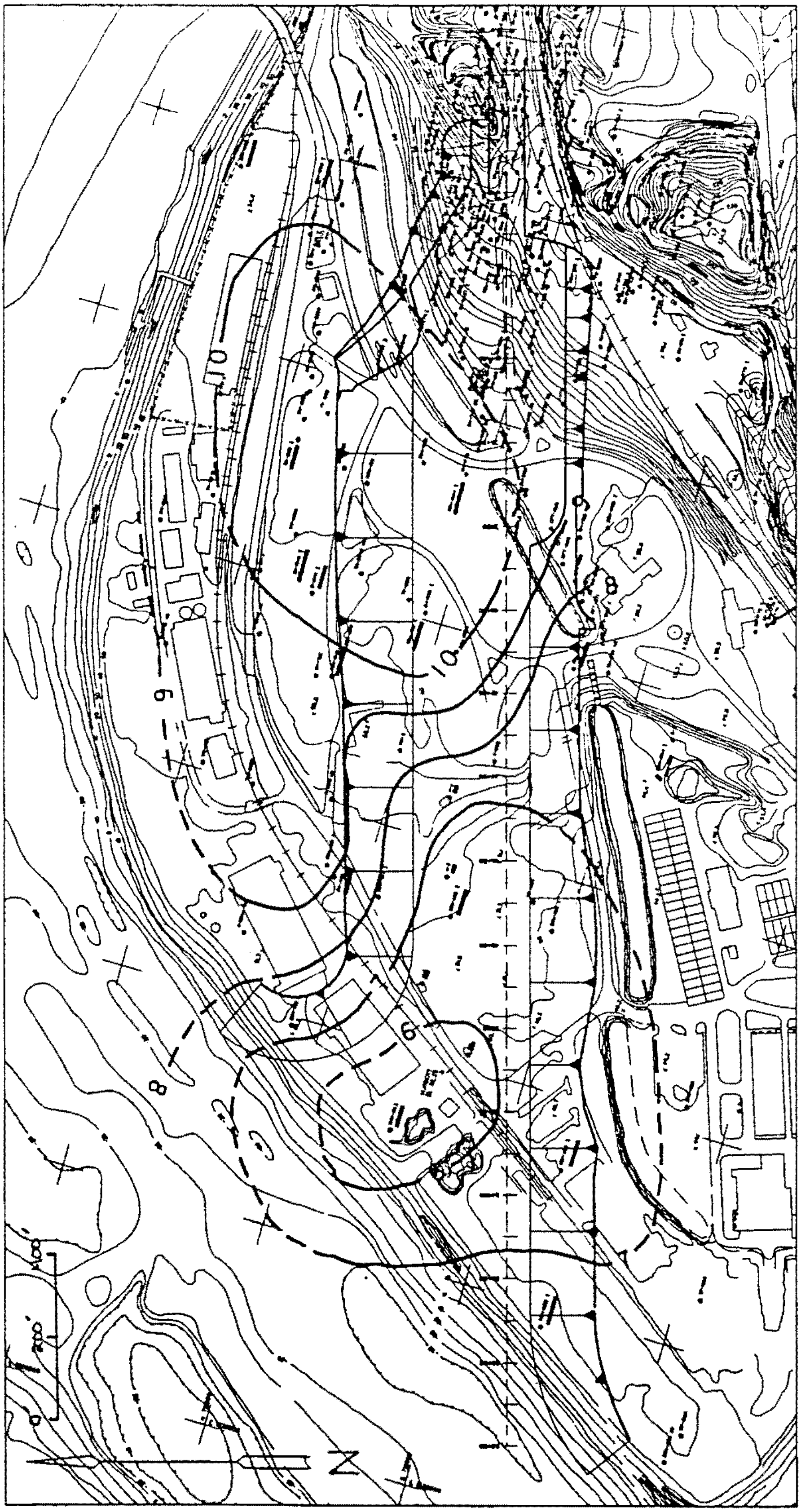
| ISOTHERMAL CONTOUR MAP DATA | | | | | | | |
|---|---|---|---|---|---|---|---|
| Date | 6/1/88 | 6/13/88 | 7/6/88 | 7/26/88 | 10/10/88 | 11/1/88 | 12/15/88 |
| Columbia River Temp. | 15.0 °C | 15.6 °C | 19.0 °C | 19.2 °C | 17.8 °C | 15.6 °C | 5.7 °C |
| Tanner Creek Temperatures | 10.3 °C | 10.3 °C | 11.0 °C | 11.0 °C | 9.4 °C | 6.0 °C | - °C |
| HATCHERY PUMPING RATES AND TEMPERATURES | | | | | | | |
| H-1 | 2975 gpm<br>- °C | 2964 gpm<br>- °C | off gpm<br>- °C | off gpm<br>- °C | 3177 gpm<br>- °C | 3083 gpm<br>- °C | off gpm<br>- °C |
| H-2 | 3860 gpm<br>9.4 °C | 3260 gpm<br>9.4 °C | 3392 gpm<br>8.9 °C | off gpm<br>- °C | off gpm<br>- °C | off gpm<br>- °C | 3129 gpm<br>- °C |
| H-3 | 3678 gpm<br>8.3 °C | 3750 gpm<br>8.3 °C | 3441 gpm<br>8.3 °C | off gpm<br>- °C | 3177 gpm<br>10.0 °C | 3197 gpm<br>11.1 °C | 3381 gpm<br>- C |
| H-4 | off gpm<br>- °C | off gpm<br>- °C | off gpm<br>- °C | off gpm<br>- °C | 3177 gpm<br>- °C | 3386 gpm<br>12.2 °C | 3500 gpm<br>- C |
| H-5 (WW-3) | 3143 gpm<br>12.2 °C | 3129 gpm<br>12.2 °C | 3354 gpm<br>11.7 °C | 3559 gpm<br>10.0 °C | 2876 gpm<br>- °C | 2955 gpm<br>11.1 °C | 2690 gpm<br>- C |

Map Explanations:

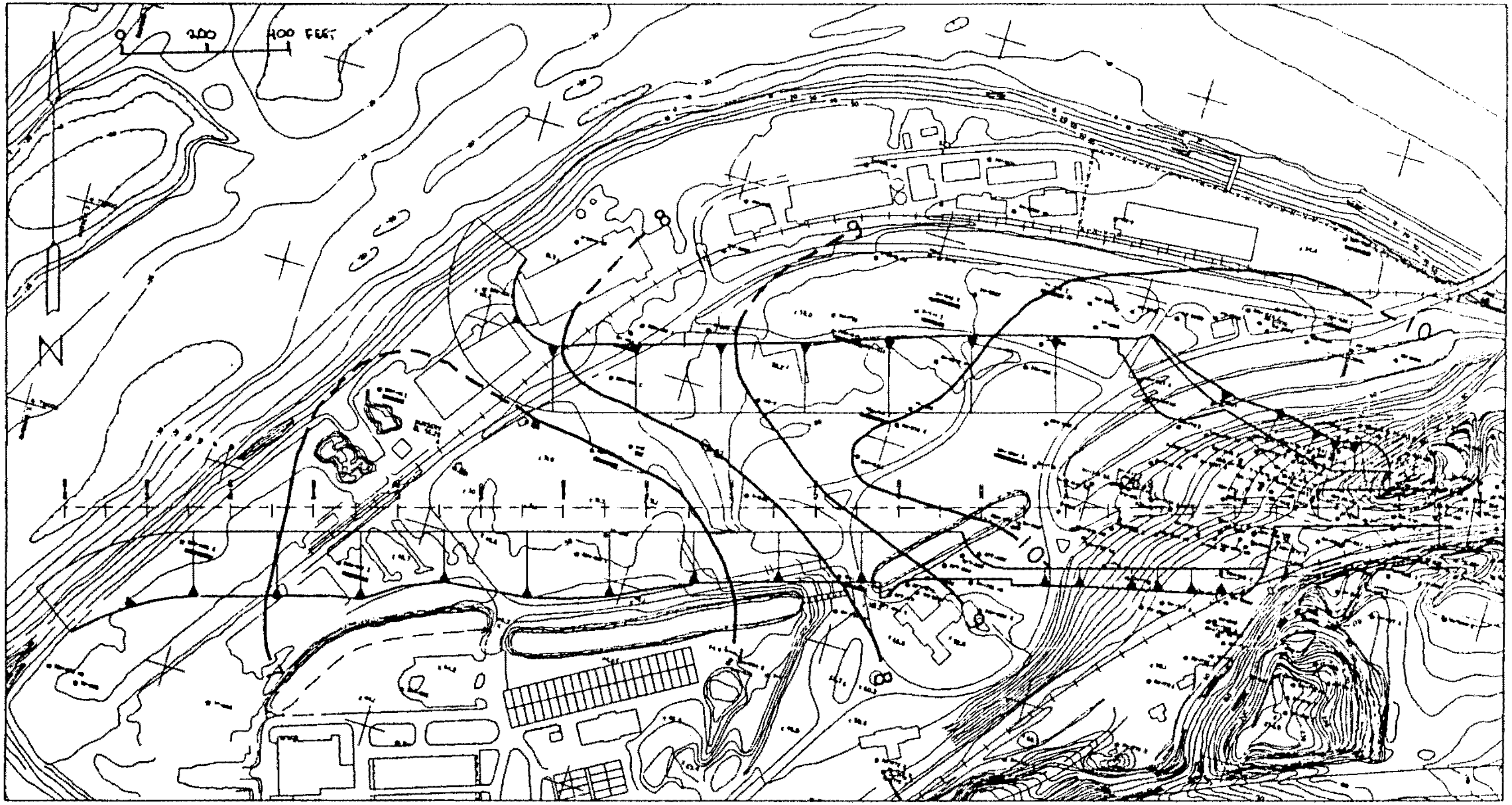
Isotherms are in degrees Celsius (°C)
Isotherm interval = 1°C
Topographic contour interval = 2 feet
Bathymetric contour interval = 5 feet
Tanner Creek temperatures are monthly averages decreasing from a high of 21.7 °C in August 1-7, 1988.



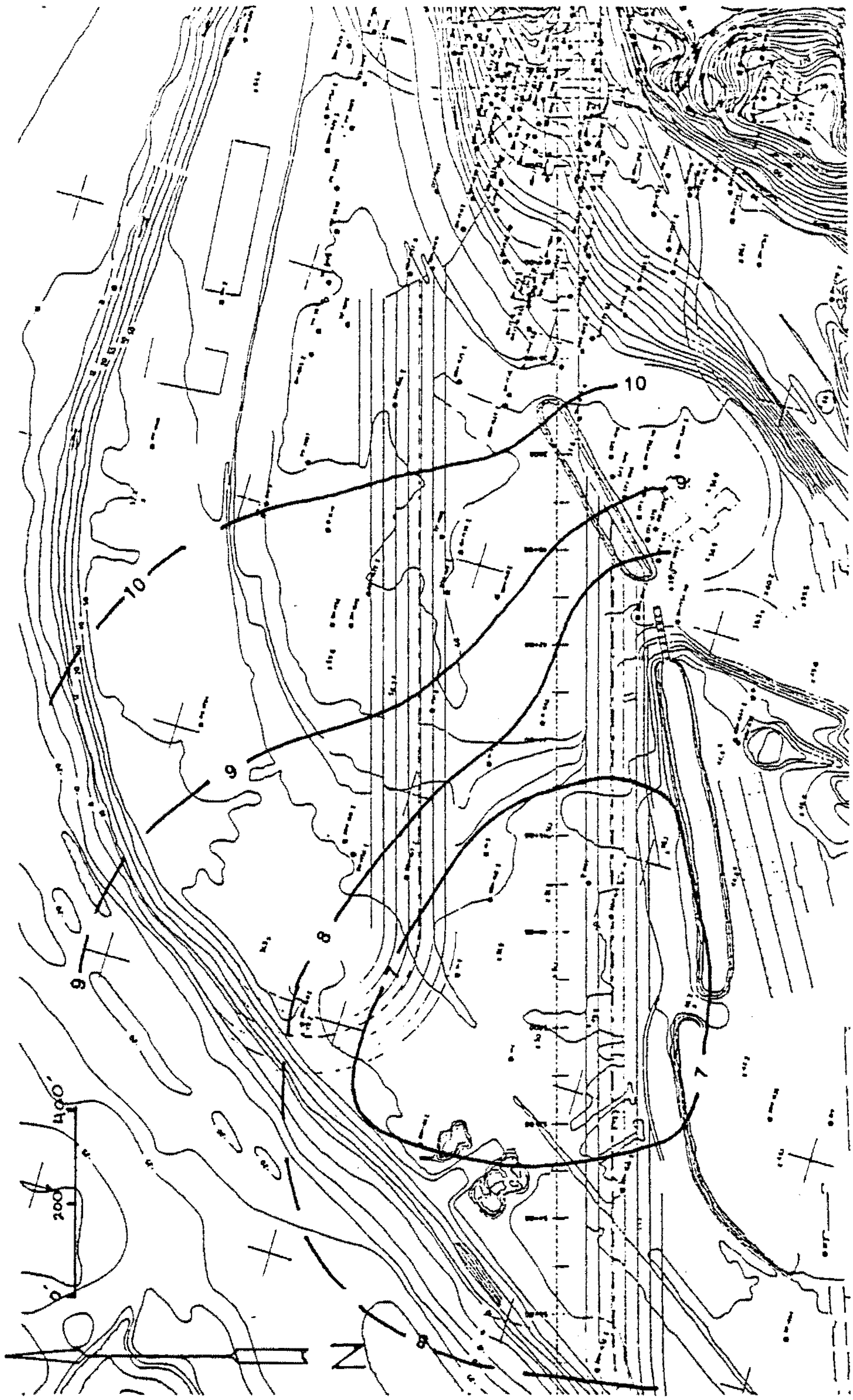

JUNE 1, 1988



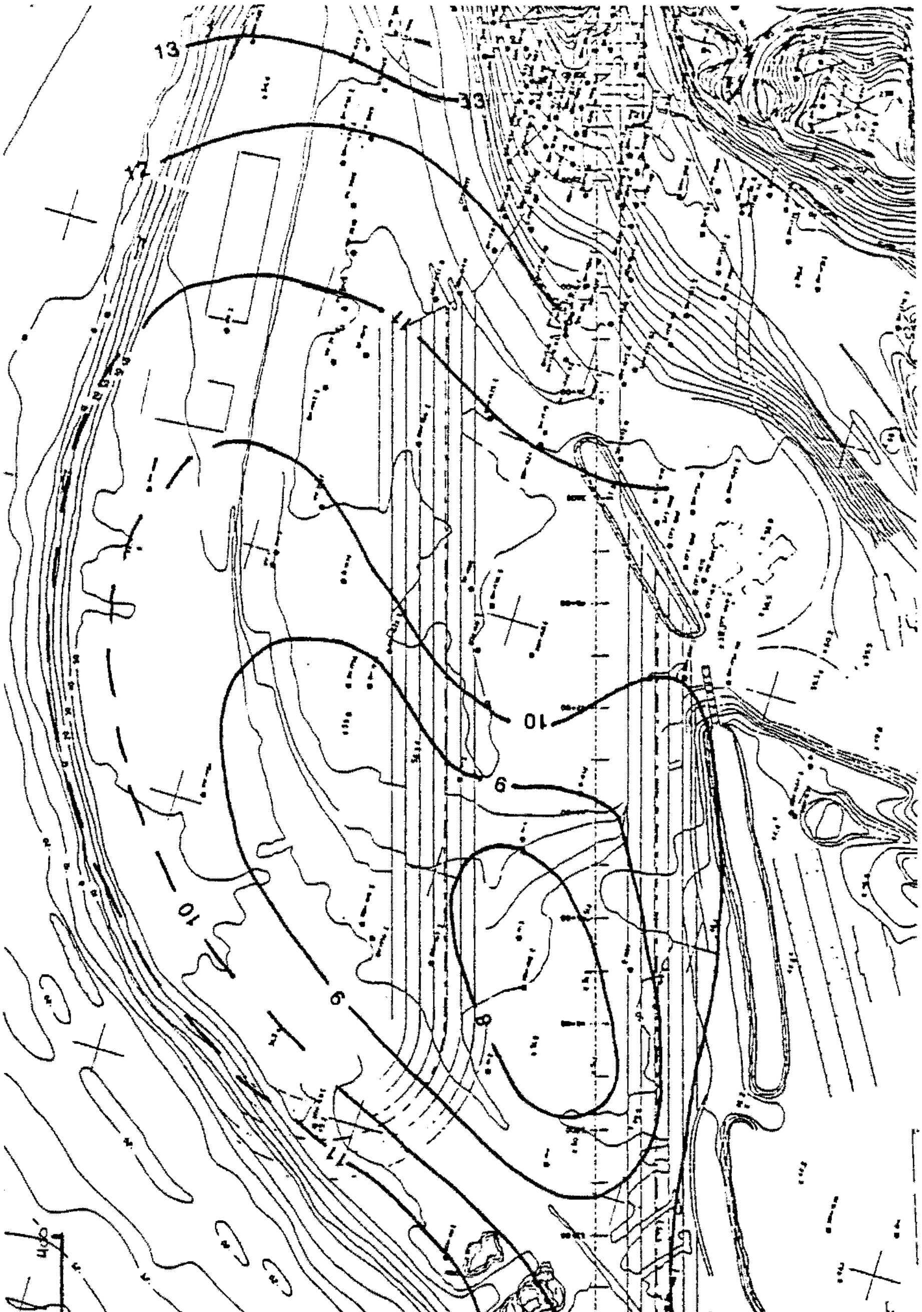

**JUNE 13, 1988**



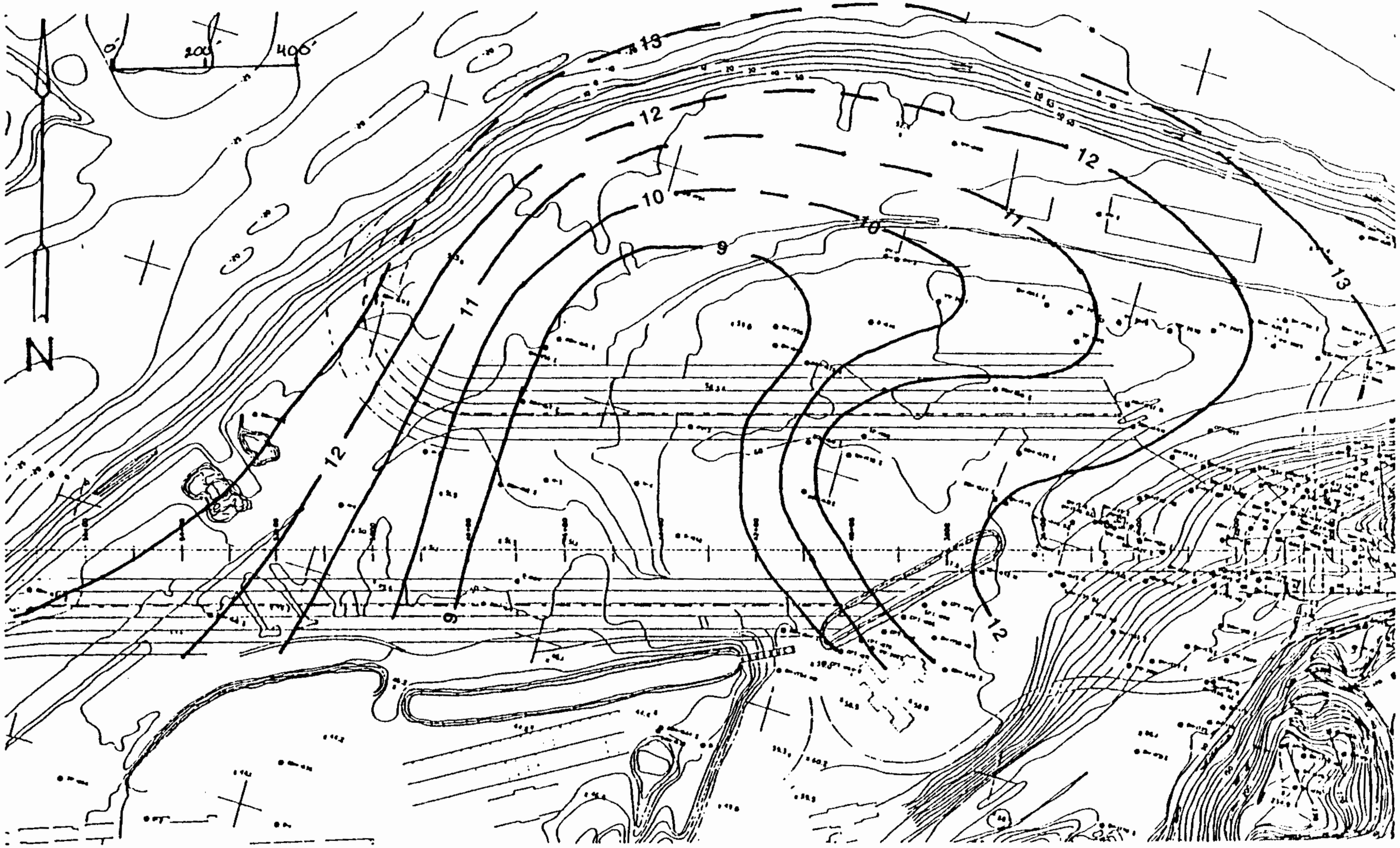

JULY 6, 1988



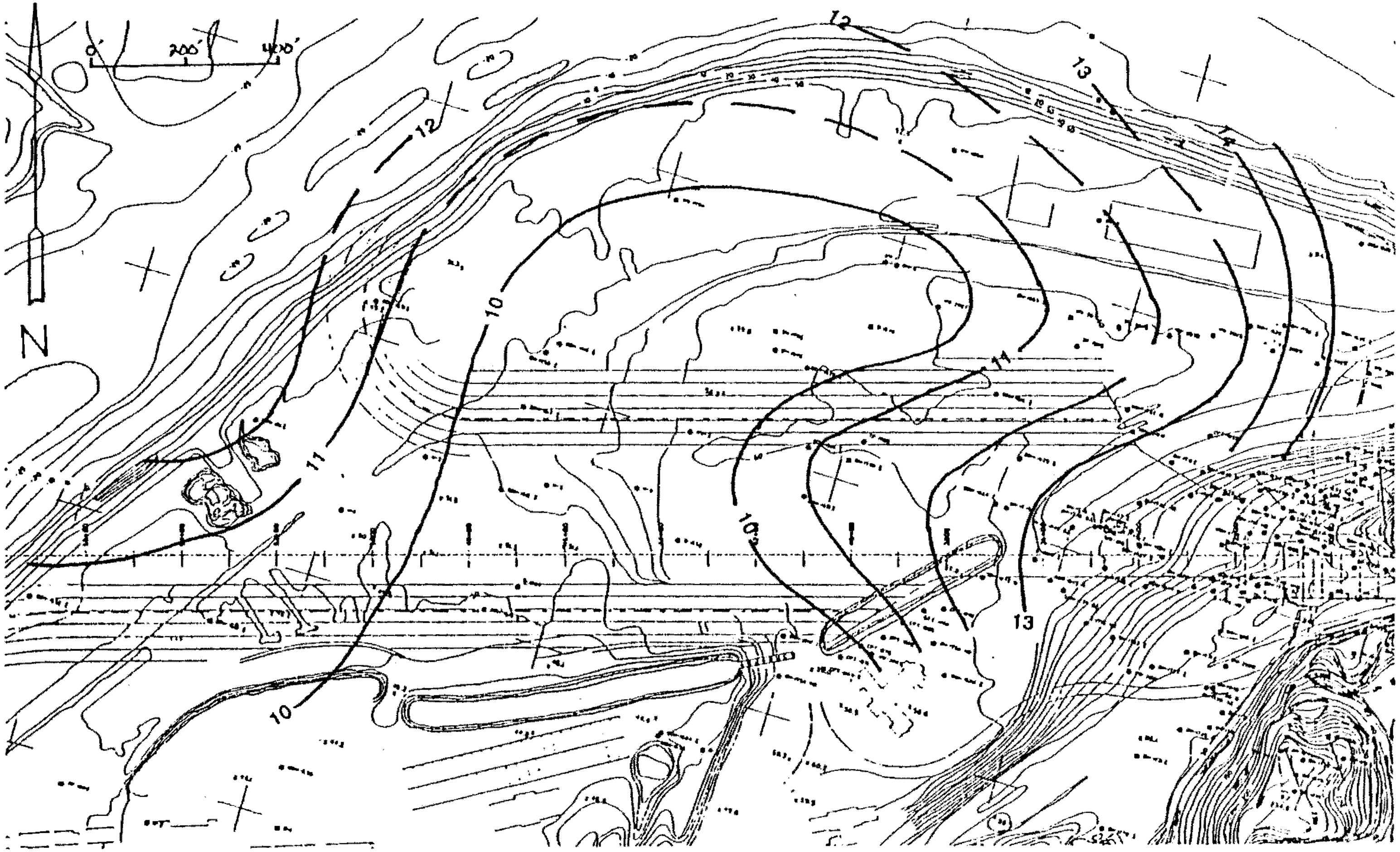

JULY 26, 1988




OCTOBER 10, 1988




NOVEMBER 1, 1988




DECEMBER 15, 1988