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HYDROGEOLOGIC INVESTIGATION

DEVIL'S GATE WATER COLLECTION TUNNEL
Pasadena, California

PREPARED FOR

City of Pasadena Water and Power department
200 South Los Robles Avenue - Suite 150
Pasadena, California 91101

CCW Project No. 95-31-114-01

August 29, 1995

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Ms. Rebecca Fisher
City of Pasadena
Water & Power Department
200 South Los Robles Avenue - Suite 150
Pasadena, CA 91101

Subject: **HYDROGEOLOGIC INVESTIGATION**
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Dear Ms. Fisher:

We are pleased to present this report of our hydrogeologic investigation at the Devil's gate Water Collection Tunnel. The purpose of this investigation was to evaluate geologic and hydrogeologic information in the tunnel area and determine the amount of groundwater that can percolate into the tunnel considering various hydrogeologic scenarios.

Results of this investigation show monthly water production from the Devil's Gate Tunnel is dependant on the height of the groundwater table above tunnel invert. As groundwater levels fall, tunnel water production decreases until the groundwater elevation is below tunnel invert, when water production stops.

Comparison of well hydrographs and rainfall records shows a correlation between high groundwater levels and high rainfall indicating when a lake is not allowed to develop behind the dam, monthly water production from the tunnel is generally proportional to rainfall. During periods when a lake is present behind the dam, monthly water production from the tunnel is greatly increased and is also spread more evenly through out the year. This suggests that groundwater levels in the arroyo and below the Altadena Fan decline at a much lower rate and remain at a relatively high elevation for the entire year when a lake is present.

A hydrogeologic model developed for this investigation was analyzed under five different scenarios. The scenarios cover a wide range of surface and subsurface conditions including high, medium, and low groundwater levels when no lake is

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A hydrogeologic model developed for this investigation was analyzed under five different scenarios. The scenarios cover a wide range of surface and subsurface conditions including high, medium, and low groundwater levels when no lake is present, and high groundwater levels associated with a lake at current spillway elevation. The scenarios cover time intervals from 1927, which followed a roughly 14 year period when high tunnel water production was common, to 1995 which followed a roughly 25 year period when low tunnel water production was common. The model accurately predicted tunnel water production for all of the scenarios for which actual tunnel water production measurements are available. The fact that the model accurately predicts tunnel water production for all of the scenarios indicates the low production during the last 25 years is probably not the result of deteriorating conditions within the tunnel.

The most likely reason for the great difference in tunnel water production from the period between 1913 to 1927 to the period between 1970 to 1995 is the presence and absence respectively of an intermittent lake behind Devil's Gate Dam. Results of the hydrogeologic model indicate if an intermittent lake were allowed to develop on a yearly basis today, within a few years tunnel water production would likely show a similar pattern and reach a similar order of magnitude as that achieved between 1913 to 1927. Other factors such as groundwater withdrawal from pumping and groundwater recharge from the spreading grounds were not considered in this evaluation.

The current condition of the tunnel is poorly known and even though this investigation suggests the current condition of the tunnel should have a minimal effect on water production, we recommend a full inspection of the tunnel be performed. Based on this inspection, additional recommendations could be developed to repair collapsed areas, remove secondary mineral deposits and iron bacteria that may clog weep holes or drainage devices, provide for easy access through existing shafts, and provide for maintenance of the tunnel and water collection piping.

We appreciate this opportunity to be of service. If you have any questions, or would like to discuss report findings, please call the undersigned.

Respectfully submitted,

CONVERSE CONSULTANTS WEST

Douglas S. Santo, CEG 1866
Project Engineering Geologist

John R. Stellar, CHG 165
Principal Hydrogeologist

DSS/JRS/wpd
Dist: 3/Addressee

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Devil's Gate Water Collection Tunnel
CCW Project No. 95-31-114-01

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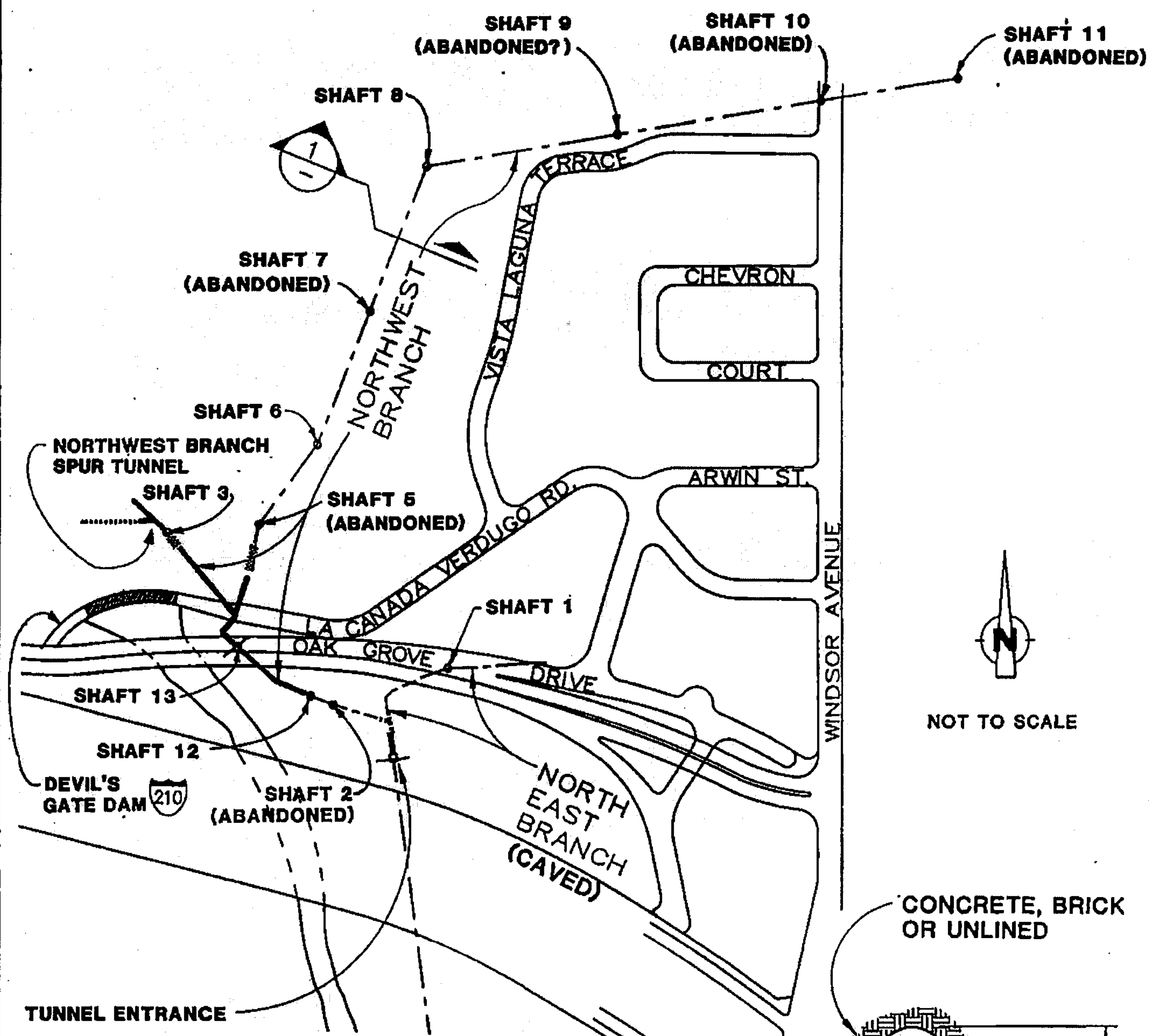
1.0 INTRODUCTION AND PURPOSE

This presents results of our hydrogeologic investigation at Devil's Gate Water Collection Tunnel in Pasadena. The purpose of this investigation was to evaluate existing geologic and hydrogeologic information in the area and determine the amount of groundwater that can percolate into the tunnel during different scenarios. The scenarios include seasonal variations in groundwater levels behind Devil's Gate Dam and the effects of an intermittent lake behind the dam. This work was performed in accordance with our proposal Dated January 26, 1995 and your Purchase Order No. 078281 dated June 2, 1995.

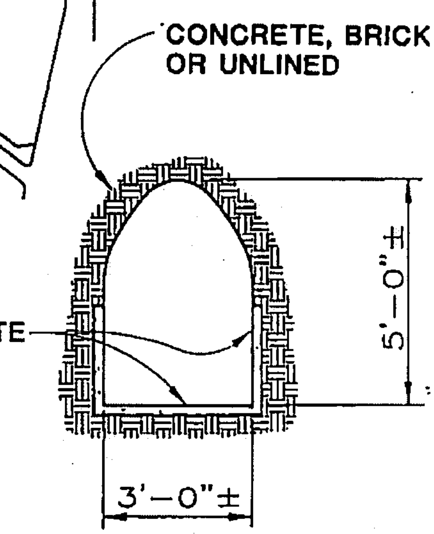
2.0 BACKGROUND AND SITE CONDITIONS

The Devil's Gate Water Collection Tunnel is located near the east bank of the Arroyo Seco adjacent to Devil's Gate Dam (Figure 1.1). The tunnel was constructed sometime prior to 1902 and is approximately 4,370 feet long including two short spur tunnels. Ground cover varies from about 50 feet below the arroyo to 170 feet below Windsor Drive. Construction was apparently by hand excavation in alluvium and drill & blast techniques in bedrock. The entrance or south portal of the tunnel is located along the toe of the east bank of the arroyo, south of the dam, between Oak Grove Drive and the 210 Freeway. The north end of the tunnel is located approximately 300 feet east of the intersection of Windsor Avenue and Vista Laguna Terrace. The north portal was accessed by a vertical drop shaft abandoned sometime in the late 1940's. The tunnel has a southerly gradient of 0.2% which equals a drop of 2 feet per 1,000 feet. The tunnel has a modified horseshoe shape in cross section, with a nominal vertical height of 5 feet and a nominal width of 3 feet (Figure 1.1). According to information provided by Pasadena Water and Power Department (PWPD) personnel, sections of tunnel located south of the dam have full concrete lining. North of the dam, the invert is lined with concrete and the crown and shoulders may be lined with brick or may be unlined, though this seems unlikely. The type, extent and condition of the tunnel lining is not fully known. The tunnel has a total of 13 drop shafts apparently large enough for a man to be lowered down. The shafts are numbered consecutively generally from south to north. Six of the shafts are abandoned and no longer accessible. PWPD personnel have inspected the southern portion of the tunnel up to a bulkhead located adjacent to Shaft 8. Sections of tunnel north of the dam have not been inspected in recent memory of PWPD personnel. The last complete inspection was apparently in 1937. A roughly 400 foot long spur named the "Northeast Tunnel" has apparently collapsed. It is not known if other sections of the tunnel have collapsed. No as-built geology or construction reports for the tunnel have been identified.



TUNNEL GEOLOGY (AFTER CITY OF PASADENA)

- ROCK
- DECOMPOSED ROCK
- INVERT IN ROCK, CROWN IN ALLUVIUM
- ALLUVIUM



TYPICAL TUNNEL SECTION 1

REFERENCE:

City of Pasadena Water and Power Department, 11/1/94, Brookside Golf Course Water Resources Tunnel Location Plan: File No. E-1362.

City of Pasadena, 2/16/93, Portion of Tract Map No. 210-B, Showing Soil Strata Surrounding Tunnel.

TUNNEL LOCATION MAP

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Project No.	Figure No.
95-31-114-01	1.1

3.0 SCOPE OF WORK

The scope of work for this investigation included:

- Review of information and records provided by PWPD.
- Research and review of geologic and hydrogeologic reports and documents from the United States Geological Survey, California Division of Mines and Geology, California Department of Water Resources, Los Angeles County Flood Control District, Foothill Municipal Water District, California Institute of Technology, and the CCW Technical Library.
- Site reconnaissance at Devil's Gate Dam and the Arroyo Seco with PWPD personnel.
- Tunnel discharge measurements from a tunnel discharge pipe draining to the arroyo near Manhole 2.
- Hydrogeologic analyses of the collected data and preparation of this report and accompanying illustrations.

4.0 DATA COLLECTION

4.1 Well Records

A search of data bases at the Los Angeles County Flood Control District (LACFCD) and the California Department of Water Resources (DWR) combined with information from PWPD revealed 8 wells within close proximity of the tunnel. The well locations are shown on Drawing 1. Well characteristics are summarized in Table 4.1. Hydrographs for 6 of the wells are shown on Figures 4.1 and 4.2. Transmissivity and hydraulic conductivity estimates based on specific capacity test data were made by CH2M HILL for 6 of the wells (CH2M HILL, 1990). These estimates are also reported in Table 4.1 and discussed in following sections.

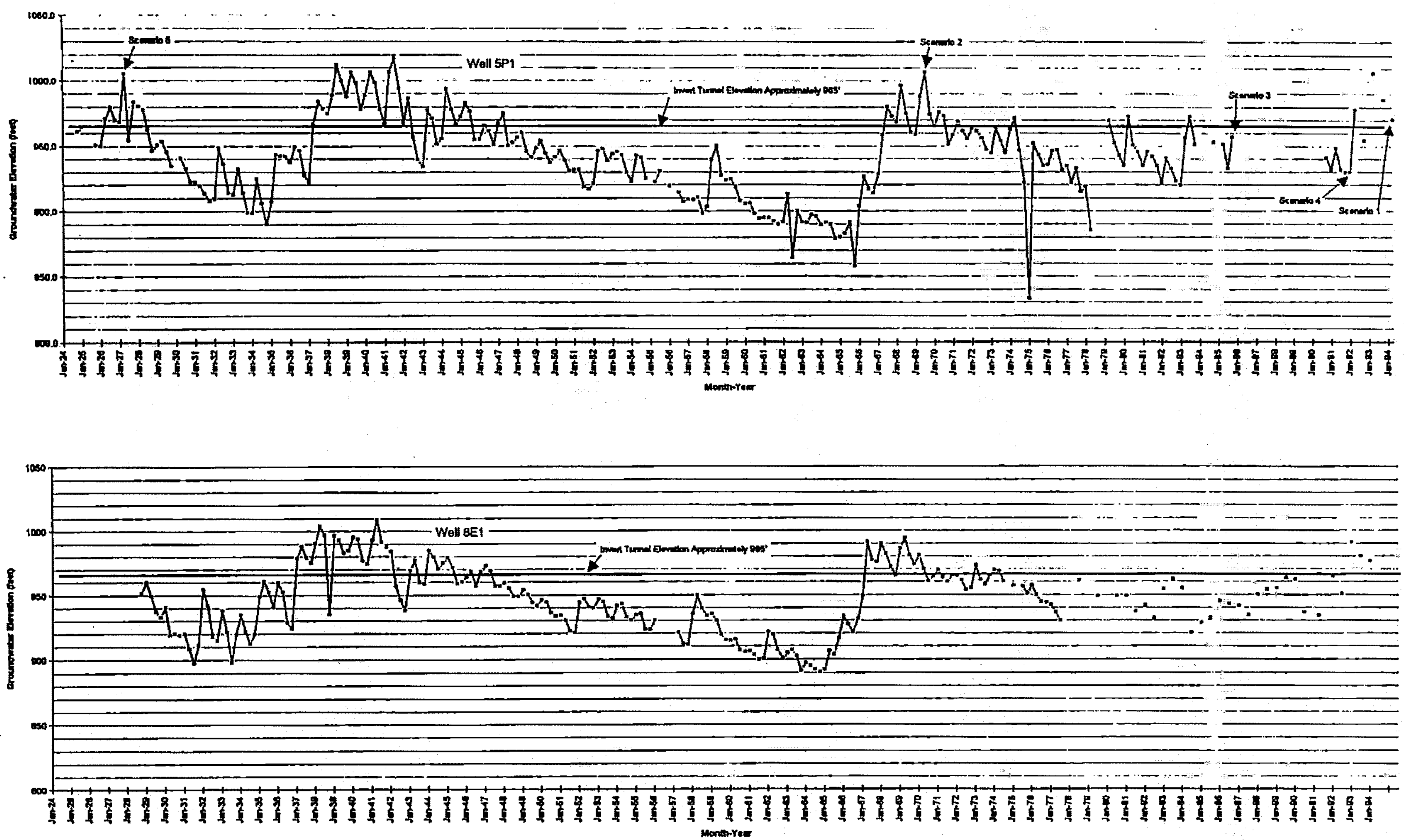
The state well numbering system will be used in this report. The number consists of 6 parts including township, range, section number, a letter identifying the ¼ section, a sequence number, and a letter identifying the base and meridian. All of the wells in this investigation are located in township 1N, range 12W, San Bernardino base and meridian. The state number will be modified to include only the section number, ¼ section letter, and sequence number.

All of the wells were drilled during or prior to 1930 with the total depths between 367 to 701 feet. Wells 7H1, 8E2, and 8E3 were drilled through Devil's Gate Tunnel Shafts 9, 11, and 10 respectively.

Table 4.1. Summary of well characteristics.

*State Well	LACFCD Well	City of Pas Well	Date Drilled (mo-yr)	Total Depth (ft)	Perforated Interval (depth, ft)	Specific Capacity (gpm/ft)		Transmissivity (gpd/ft)		†Hydraulic Conductivity (gpd/ft^2)	Comments
						Range	Latest	Range	Latest		
5M1	4030D(?)	Arroyo	Aug-30	668	127-624	28-61	59 (Jul-37)	7928-17272	16706 (Jul-37)	2580	Qal_1/Qal_3 to -200' Qal_4 -200' to -660' Bedrock at 660'
5N1	4030B	Ventura	April-24	489	102-468	14-140	58 (Oct-38)	3964-39642	16423 (Oct-38)	3467	Qal_1/Qal_3 to -150' Qal_4 -150' to -489'
5P1	4030	No. 3	July-24	507	185-494	12-26	25 (Feb-38)	3398-7362	7079 (Feb-38)	2097	—
7H1	4021B	No. 9 Shaft 9	1905	466	—	—	—	—	—	—	Qal_1/Qal_3 to -272' Qal_4 -272' to -466'
8D1	4030C	Windsor	—	573	316-561	16-30	18 (Nov-38)	4530-8495	5097 (Nov-38)	968	Qal_1/Qal_3 to -210' Qal_4 -210' to -573'
8E1	4031	No. 13	June-09	566	160-446	19-91	23 (Sep-36)	5380-25767	6513 (Sep-36)	1935	Qal_1/Qal_3 to -220' Qal_4 -220' to -542' Bedrock at 542'
8E2	4031B	No. 11 Shaft 11	Dec-29	701	200-677	16-26	16 (Sep-33)	4530-7362	4530 (Sep-33)	806	Qal_1/Qal_3 to -310' Qal_4 -310' to -686' Bedrock at 686'
8E3	4031C	No. 10 Shaft 10	Pre-1902	367	—	—	—	—	—	—	Qal_1/Qal_3 to -307' Qal_4 -307' to -367'

*T1N/R12W, Pasadena Quadrangle, San Bernardino base and meridian.
†Hydraulic conductivity estimate based on latest specific capacity test.



Approved for publication ______ by ______

State well numbering system, Pasadena Quadrangle
T1N, R12W, San Bernardino base and meridian

HYDROGRAPHS FOR WELLS 5P1 AND 8E1

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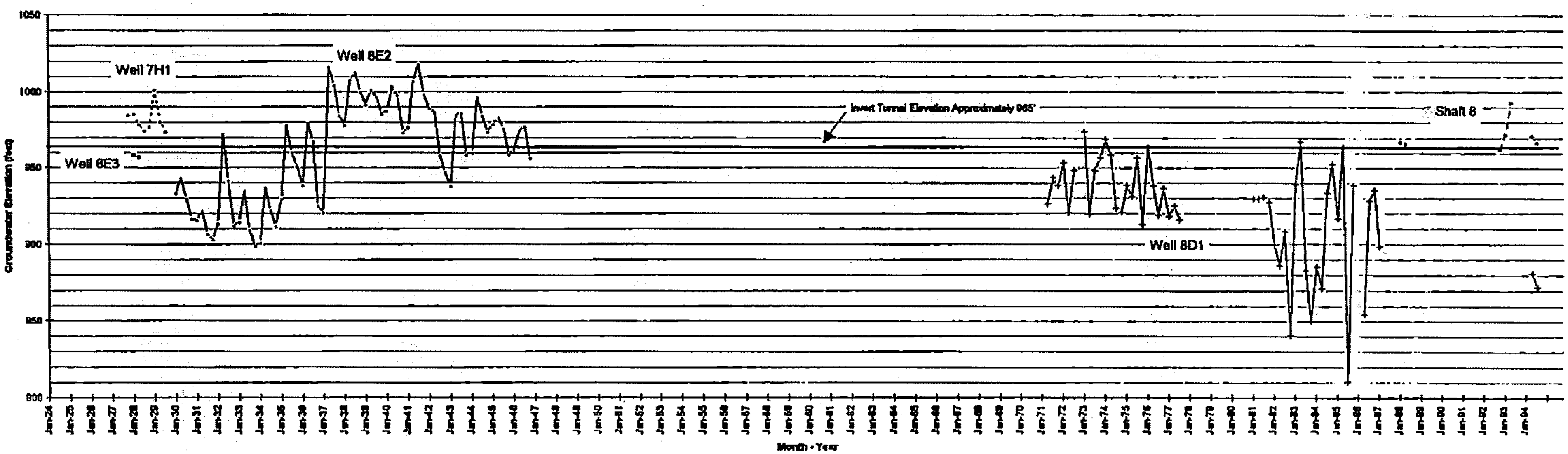
Figure No. 4.1



Approved for publication ____________ by ____________

State well numbering system, Pasadena Quadrangle
T1N, R12W, San Bernardino base and meridian

HYDROGRAPHS FOR WELLS 7H1, 8D1, 8E2, 8E3, AND SHAFT 8

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Figure No. 4.2

4.2 Rainfall Data

Rainfall records at LACFCD Rainfall Station Nos. 453D and 612B were collected for the rainfall years 1911-12 through 1994-95. Station 453D is located on Devil's Gate Dam, and station 612B is located at the Pasadena Chlorine Plant. The rainfall year is from October to September. A histogram showing seasonal rainfall at Devil's Gate Dam is on Figure 4.3. Average yearly rainfall for this 83 year period is 20.4 inches.

4.3 Water Production at Devil's Gate Tunnel

A record of monthly water production at Devil's Gate Tunnel was provided by PWPD. The record covers the years from 1913-14 through 1994-95. There is a 34 year gap between 1937-38 through 1970-71 where no data is available. Data prior to the year 1971-72 is for production when an intermittent lake occurred behind the dam. After 1971-72 no lake occurred. Maximum yearly production since 1971-72 is 160 ac-ft, the average yearly production is 59 ac-ft. This data is shown in Figure 4.4.

5.0 SITE GEOLOGY

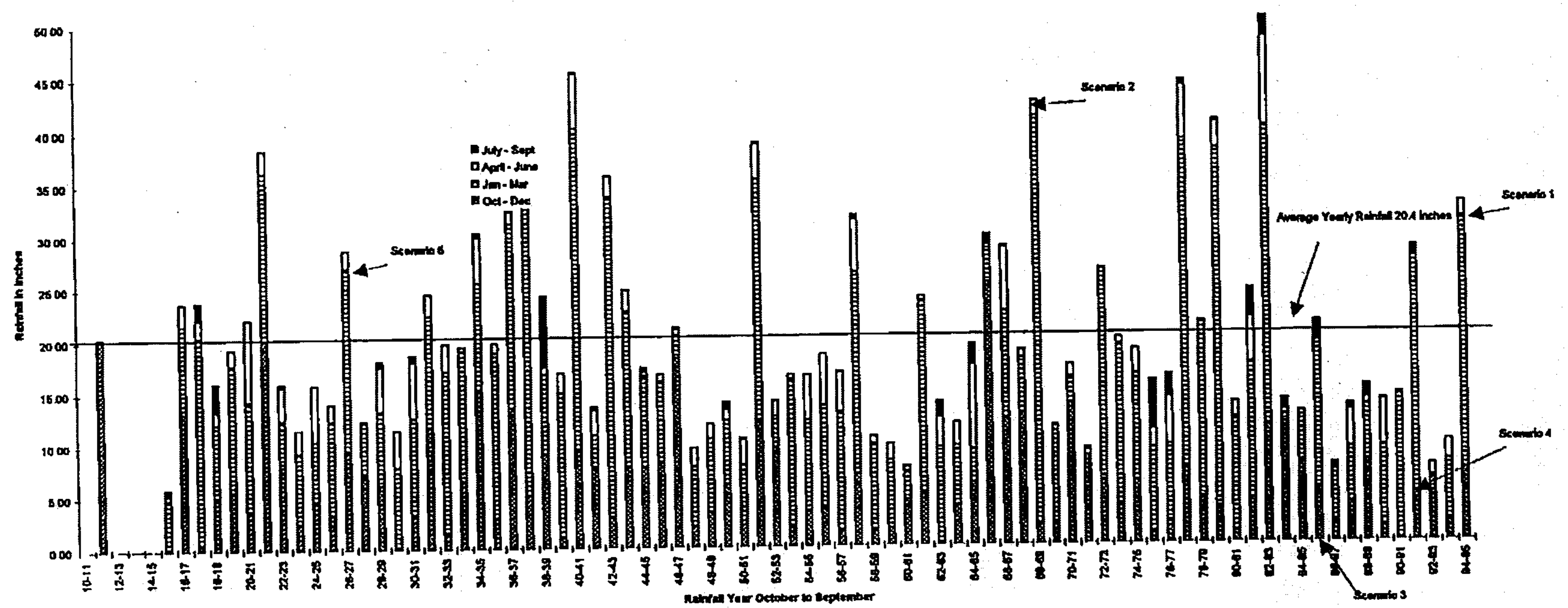
The tunnel is located in the Arroyo Seco generally between the San Rafael Hills on the south and the San Gabriel Mountains on the north. The San Rafael Hills and the San Gabriel Mountains consist of crystalline bedrock assigned variously to the Wilson Diorite, Rubio Diorite and unnamed units of quartz monzonite and gneiss. The bedrock is Cretaceous and Pre-Cretaceous age. For the purposes of this report all of these rocks will be collectively referred to as bedrock.

The headwaters of the Arroyo Seco are in the San Gabriel Mountains north of Gould Mesa. The arroyo is underlain by younger and older alluvium and stream channel deposits. The arroyo lies between the La Canada Alluvial Fan on the west and the Altadena Alluvial Fan on the east. The fans are underlain by older alluvium. The alluvium is Pleistocene to Holocene in age.

The closest known fault is the Sierra Madre Fault Zone (SMFZ) located approximately 1 mile north of Devil's Gate Dam. A prominent salient of this fault zone, named the Bridge Fault, has been identified below Gould Mesa in the Jet Propulsion Laboratory. The Bridge Fault and this segment of the SMFZ are not currently classified as a State of California Earthquake Study Zone. The most recent surface rupture due to earthquakes on these faults is thought to have occurred in Pre-Holocene time (greater than 11,000 years ago). However, the 1991 M5.8 Sierra Madre earthquake, epicentered roughly 10 miles northeast of Devil's Gate Dam, is attributed to the SMFZ.

5.1 Stratigraphy

Alluvial soils at the foot of the San Gabriel Mountains have been differentiated based on geomorphology, soil development, and contact relations into four time-stratigraphic units.



Record from L.A. County Rainfall Station No.'s 453 D and 612 B located at Devil's Gate Dam and Pasadena Chlorine Plant

SEASONAL RAINFALL AT DEVIL'S GATE DAM

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Figure No. 4.3

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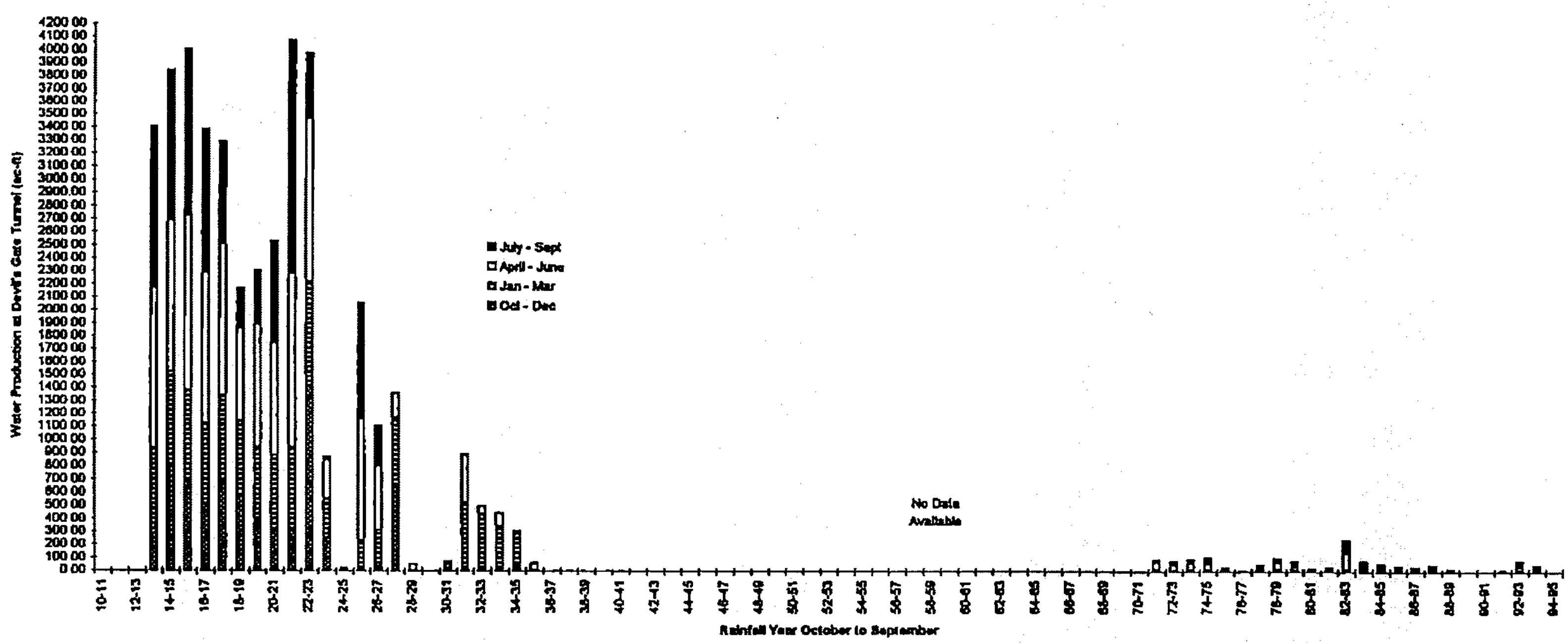

Record provided by Pasadena Water and Power Department

WATER PRODUCTION AT DEVIL'S GATE TUNNEL

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Project No.	Figure No.
95-31-114-01	4.4

Approved for publication ______ by ______

The units are numbered from youngest to oldest Qal_1 - Qal_4 (Crook, et.al., 1987). The alluvium unconformably overlies crystalline bedrock. Isolated areas of colluvium and artificial fill are encountered locally. The areal distribution of earth materials adjacent to the tunnel is shown on Drawing 1. Geologic sections along the tunnel alignment showing interpreted subsurface conditions are on Drawing 2. Following is a brief description of the earth materials adjacent to the tunnel with emphasis on the physical properties that may effect their hydrogeologic characteristics.

5.1.1 Alluvium: Qal_4 is the oldest alluvial unit in the study area and rests directly on bedrock. It underlies the Arroyo Seco, and the La Canada and Altadena Alluvial Fans. Unit 4 is generally not exposed at the ground surface except in the area of Gould Mesa where it has been exposed by faulting. The unit consists of poorly consolidated to well consolidated fine to coarse sand, silty sand, gravel, and minor amounts of coarse debris-flow and mud-flow deposits. Pedogenic processes have resulted in highly weathered clasts and a high clay content due to relict and buried paleosols. The unit is locally strongly cemented with alkaline earth carbonates and iron oxide. Fractures and joints are common, but may be healed with secondary carbonate. The color is generally red to reddish brown. The unit is up to 400 feet thick in the study area.

Qal_3 is the most abundant of the exposed alluvial units in the study area and rests directly on Qal_4. Unit 3 deposits underlie the Arroyo Seco and form the surfaces of the La Canada and Altadena Fans. Exposures along the flanks of the arroyo show crudely bedded moderately consolidated to unconsolidated sand and gravel with abundant boulders to 2 feet in diameter. Some of the finer sand layers contain minor amounts of clay. The unit is generally not cemented and fractures and joints are not common. The color is generally yellowish brown to brown. Unit 3 is up to 300 feet thick.

Qal_2 is exposed along the west side of the Arroyo Seco, but is not found in the area of the Devil's Gate Tunnel. Qal_2 rests directly on unit 3 and consists of unconsolidated fluvial and alluvial deposits of fine to coarse sand, gravel and boulders. The color is generally gray to pale brown.

Qal_1 is exposed along the east side of the Arroyo Seco. Qal_1 rests directly on unit 3 where Qal_2 is absent or has been removed by erosion. Unit 1 consists of unconsolidated coarse sand, gravel and boulders. The unit is not cemented. The color is generally white to gray. Unit 1 is estimated to be up to 70 feet thick in some portions of the arroyo. The upper few feet of Unit 1 deposits within the arroyo may have a higher silt and clay content than Unit 1 material at greater depth.

5.1.2 Bedrock: As previously described, bedrock consists of plutonic igneous rock of diorite, quartz monzonite, and gneissic composition. The jointing characteristics of the various rock types are not known.

5.1.3 Groundwater Levels: Groundwater elevations below the Altadena Fan and adjacent to the tunnel are shown on well hydrographs on Figures 4.1 and 4.2. The hydrographs show groundwater levels fluctuate on both a long term and seasonal basis. Comparison of the well hydrographs with the seasonal rainfall histogram on Figure 4.3 reveals a correlation between heavy rainfall years and high groundwater levels.

Assuming an elevation of approximately 965 feet for the invert of the section of tunnel below the Altadena Fan, the well hydrographs show long term groundwater levels are generally below the invert elevation of the tunnel. This is true except for a roughly 2 year period between 1926 and 1928, a roughly 10 year period between 1937 and 1947, and a roughly 3 year period between 1967 and 1970. Since 1970 groundwater levels have risen above invert elevation between 3 and 5 times. Each of these times has been for a period of roughly 3 months generally corresponding with above normal rainfall between January and March. January, 1993 shows an anomalously high groundwater level in wells 5P1 and 8E1 that does not appear to correlate with rainfall records.

Comparison of groundwater elevations between wells 8E1, 8D1, and 5P1 shows the hydraulic gradient below the Altadena Fan is to the north, with short term exceptions generally during periods of heavy rain.

Groundwater levels within the Arroyo Seco and adjacent to the tunnel are reflected by an incomplete 8 year record of measurements made in Shaft 8. The measurements show that the shaft is typically dry during summer months and may have 1 to 2 feet of water during wet winter months. Groundwater levels within the arroyo and adjacent to the tunnel appear to be similar to those below the Altadena Fan based on records from shaft 8. Shaft 8 shows a similar high groundwater anomaly in 1993 to wells 5P1 and 8E1. Analyses presented in later sections of this report indicate groundwater levels within the arroyo may be between 5 to 15 feet higher than groundwater levels below the Altadena Fan.

6.0 HYDRAULIC CONDUCTIVITY OF ALLUVIUM AND EQUIVALENT PERMEABILITY OF BEDROCK

The hydraulic conductivity (*K*) of alluvial materials was estimated from specific capacity tests performed in 6 of the wells used for this investigation (CH2M HILL, 1990). Full penetration of the aquifer was assumed for the estimates, though this is not the actual case. The estimates represent a vertically averaged value. Hydraulic conductivities ranged from 806 to 3,467 gpd/ft^2. Data are presented in Table 4.1.

The perforated interval for each of the 6 wells primarily penetrates Unit 4 alluvium. The hydraulic conductivity estimates may be considered representative of this material type. Unit 4 is the oldest alluvial unit and has the highest clay content and the greatest level of consolidation and secondary cementation. These characteristics indicate this unit should have a lower hydraulic conductivity than younger alluvial units such as Unit 3 and Unit 1. Unit 3 and Unit 1 are generally coarser grained than Unit 4, have a lower clay content, and are poorly consolidated to unconsolidated with no cementation.

Hydraulic conductivity estimates made from data on the Arroyo Seco Spreading Grounds and from shallow percolation test pits yield *K* values orders of magnitude lower than the estimates made from well data. The values are generally lower than 40 gpd/ft^2. The spreading ground estimates were made in Unit 1 type material. As just described, Unit 1 should have a higher hydraulic conductivity than Unit 4. The reasons for the low spreading ground estimates may be siltation in the spreading ponds combined with artificial compaction of surficial soils due to equipment, etc. The spreading ground estimates were not considered in our analyses.

North of Devil's Gate Dam the tunnel primarily penetrates Unit 3 and Unit 1 alluvium. For the purposes of this investigation, we have assigned a hydraulic conductivity of 3,467 gpd/ft^2 for each of these units. This is the highest value obtained for Unit 4 alluvium from well estimates. This value compares well with published data for unconsolidated material consisting of fine to coarse gravel to fine to coarse sand (Driscoll, 1986).

6.1 Equivalent Permeability of Bedrock

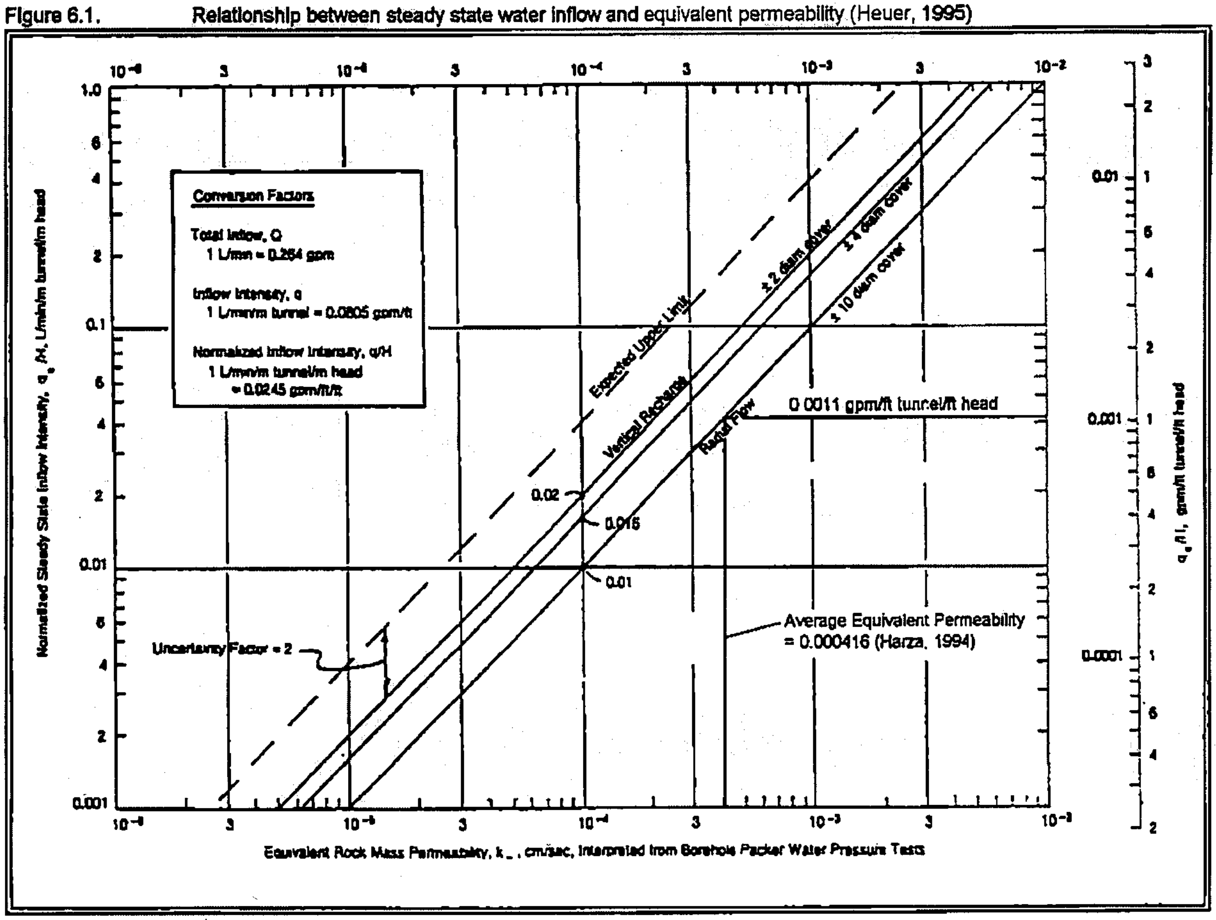
The primary permeability of crystalline bedrock is very low and groundwater traveling within this material follows open joints and fractures. Because the jointing characteristics of the rock mass below ground surface are difficult to estimate, even with exploratory borings, predicting the quantity of water that may be contributed by sections of tunnel passing through bedrock is also difficult. One way to estimate this quantity is by using borehole packer test data. This type of data was collected adjacent to Devil's Gate Dam as part of a design criteria report prepared for rehabilitation of the dam in 1994 (Harza, 1994). Packer test data was collected in 5 diamond core borings excavated for that investigation.

The disadvantage of the packer test is that it does not yield a "true" permeability that can be used in standard hydrology equations. Permeability calculated from a packer test in rock is an "equivalent" permeability (Heuer, 1995). It is a number which describes the permeability of an equivalent sand mass which would accept the same volume of water at the same pressure as in the test. The method for calculating the equivalent permeability assumes a homogeneous, isotropic porous medium with pore spaces and flow paths that are well interconnected, small, and closely spaced relative to the size of the well or boring. Actual conditions in a fractured or jointed rock mass are different. Water flow away from a packer test or into a tunnel, occurs along individual planar joints that are not well interconnected, whose open width is variable, and whose spacing is large compared to the boring diameter, packer spacing, or tunnel diameter. To account for these discrepancies, a method was developed to estimate tunnel water inflow using packer test data correlated with measurements of actual water inflow from tunnel case histories (Heuer, 1995). Packer test data are plotted on a graph giving a relationship between normalized steady state water inflow and equivalent permeability for various groundwater levels above tunnel crown. Results are given as the quantity of inflow in gallons per minute per foot of tunnel per foot of head.

Artesian conditions developed in one of the Harza diamond core borings during drilling.

The artesian conditions indicate that there may be considerable groundwater within joints or fractures in the bedrock. Based on this, we assumed the groundwater elevation is at least 50 feet above the crown of the tunnel in reaches where the tunnel penetrates bedrock for the purpose of calculating steady state water inflow. This should also account for potential effects generated by the proposed grout curtain to be located north of, and below the dam. The grout curtain would be part of a proposed dam rehabilitation scheme. The average equivalent permeability for crystalline bedrock based on Harza packer test data is 0.000416 cm/sec. Combining these two conditions into the graph shown on Figure 6.1 yields a tunnel water inflow rate of 0.0011 gpm/ft tunnel/ft head for reaches penetrating crystalline bedrock.

Figure 6.1. Relationship between steady state water inflow and equivalent permeability (Heuer, 1995)



7.0 ESTIMATION OF WATER INFLOW TO THE TUNNEL

To estimate the quantity of water entering the tunnel it is necessary to develop a hydrogeologic model of the local conditions including the length of tunnel through which water is expected to enter, differing geologic conditions surrounding the tunnel that could effect water inflow, and the hydrogeologic characteristics of alluvium and bedrock. Different scenarios are then applied to the model to determine the effects of seasonal variations of groundwater levels behind the dam with and without an intermittent lake.

7.1 Hydrogeologic Model

Sections of tunnel south of Devil's Gate Dam have been identified as having a full concrete lining. Also, geologic materials south of the dam should potentially contribute only a small quantity of groundwater since most subsurface groundwater flow is blocked by the dam. For these reasons, only sections of tunnel north of the dam will be considered in the model. Sections of tunnel north of the dam are divided into four reaches according to geologic conditions. All four reaches are assumed to have a concrete box invert and a brick lined crown. Characteristics of each reach are summarized in Table 7.1. Reach 1 is the section of the Northwest Branch Tunnel between the north side of the dam and Shaft 5 and also includes sections of the Northwest Branch Spur north of the dam. These sections include approximately 550 linear feet of tunnel located in bedrock, and 220 feet located in Unit 1 alluvium or with crown in Unit 1 alluvium. This entire reach underlies the Arroyo Seco. Reach 2 is the section of the Northwest Branch Tunnel between Shaft 5 and Shaft 8. This reach includes approximately 370 linear feet of tunnel in Unit 1 alluvium and approximately 760 linear feet in Unit 3 alluvium. Reach 2 underlies the arroyo. Reach 3 is the section of the Northwest Branch Tunnel between Shaft 8 and Shaft 11. This reach includes approximately 1,500 linear feet of tunnel in Unit 3 alluvium. Reach 3 underlies the Altadena Fan. Reach 4 is the Northeast Branch Tunnel beginning at its intersection with the Northwest Branch and running north. This reach includes approximately 550 feet of tunnel in Unit 3 alluvium. Reach 4 underlies the Altadena Fan. This reach is located roughly due east of the dam and is included in the model even though it is reported to have collapsed.

7.2 Water Inflow Scenarios

Five inflow scenarios were chosen to represent various groundwater level conditions in the arroyo and below the Altadena Fan. One scenario was chosen to represent an intermittent lake behind the dam. The groundwater levels chosen for the various scenarios are based on records for well 5P1. Groundwater levels from this well are considered representative of groundwater levels below the Altadena Fan. Groundwater levels in the arroyo are less accurately known, but were estimated through a series of iterations using the model and known monthly production values for the tunnel. Based on this, it is apparent groundwater levels within the east side of the arroyo are generally about 15 feet in elevation above groundwater levels below the fan. This is true except during periods of above average rainfall or when an intermittent lake is behind the dam. During these times, groundwater levels in the arroyo are roughly 5 feet in elevation above levels below the fan.

Scenarios 1, 3, 4, and 5 were selected so well records could be correlated with rainfall records and monthly production statistics for the tunnel. No monthly production statistics are available for Scenario 2. Following is a brief discussion of the conditions assumed for each scenario.

<u>Scenario 1</u>: This scenario represents roughly current conditions, with groundwater elevations approximately 5 feet above tunnel invert below the Altadena Fan and

Table 7.1. Results of hydrogeologic model for five inflow scenarios.

Scenario	Reach	Geologic Condition	Total Footage	Inflow in gpm/ft tunnel/ft head in Reaches Penetrating Bedrock	Hydraulic Conductivity of Alluvium (gpd/ft2)	Height of Groundwater Above Invert (feet)	Water Inflow (gpd)	Monthly Production Predicted (ac ft)	Monthly Production Actual (ac ft)
1	1	Bedrock	550	0.0011		20	17424		
		Unit 1	220		3,467	20	105936		
	2	Unit 3	760		3,467	20	365961		
		Unit 1	370		3,467	20	178165		
	3	Unit 3	1500		3,467	5	45143		
	4	Unit 3	550		3,467	5	16553		
						Total Daily Production	729182	6.7	6.75
2	1	Bedrock	550	0.0011		50	43560		
		Unit 1	220		3,467	50	662101		
	2	Unit 3	760		3,467	50	2287257		
		Unit 1	370		3,467	50	1113533		
	3	Unit 3	1500		3,467	45	3656602		
	4	Unit 3	550		3,467	45	1340754		
						Total Daily Production	9103806	83.8	No measurement
3	1	Bedrock	550	0.0011		15	13068		
		Unit 1	220		3,467	15	59589		
	2	Unit 3	760		3,467	15	205853		
		Unit 1	370		3,467	15	100218		
	3	Unit 3	1500		3,467	0	0		
	4	Unit 3	550		3,467	0	0		
						Total Daily Production	378728	3.5	3.42
4	1	Bedrock	550	0.0011		5	4356		
		Unit 1	220		3,467	5	6621		
	2	Unit 3	760		3,467	0	0		
		Unit 1	370		3,467	0	0		
	3	Unit 3	1500		3,467	0	0		
	4	Unit 3	550		3,467	0	0		
						Total Daily Production	10977	0.1	0.11
5	1	Bedrock	550	0.0011		90	78408		
		Unit 1	220		3,467	90	2145206		
	2	Unit 3	760		3,467	90	7410713		
		Unit 1	370		3,467	90	3607847		
	3	Unit 3	1500		3,467	52.5	4977041		
	4	Unit 3	550		3,467	45	1340754		
						Total Daily Production	19559969	180.1	186.04

approximately 20 feet above tunnel invert below the arroyo. Discharge measurements at the tunnel made in June yielded a total production of 678,857 gpd. The groundwater levels and discharge measurements are correlated with rainfall records through March of this year. This rainfall year experienced 31 inches of rain between October 1994 and March 1995 following two years of below average rainfall.

Scenario 2: This scenario is based on conditions during July 1969 and represents maximum groundwater elevations without a lake present behind the dam. Groundwater elevations are assumed to be approximately 45 feet above tunnel invert below the Altadena Fan and approximately 50 feet above tunnel invert below the arroyo. The rainfall year 1968-69 experienced roughly 39 inches of rain between January and March, 1969. This followed three previous years of rainfall at or significantly above seasonal average.

Scenario 3: This scenario is based on conditions during October 1985, with groundwater elevations below tunnel invert in the Altadena Fan and approximately 15 feet above tunnel invert in the arroyo. The rainfall year 1985-86 experienced a normal seasonal rainfall, but this scenario represents conditions present following 2 years of below average rainfall before a normal year.

Scenario 4: This scenario is based on conditions during January 1992, with low groundwater elevations below Altadena Fan and the arroyo. Groundwater is 5 feet above tunnel invert in Reach 1 immediately adjacent to Devil's Gate Dam, but is below tunnel invert for all other Reaches. This scenario represents conditions present following 5 consecutive years of below average rainfall.

Scenario 5: This scenario is based on conditions during April 1927, with a lake present behind the dam and maximum groundwater elevations below the Altadena Fan. The lake level is assumed to be at elevation 1154, which is the current spillway elevation and results in approximately 90 feet of surface water and groundwater above tunnel invert in the arroyo. Groundwater is assumed to be between approximately 52.5 to 45 feet above tunnel invert below the Altadena Fan.

7.3 Equations Describing Flow Rate Into Tunnel

The tunnel is similar to an infiltration gallery located on-land adjacent to a water body. The equation describing flow rate into an infiltration gallery in unconsolidated sediments is given in Driscoll, 1989 and assumes the gallery is pumped. The equation is as follows:

$$Q = \frac{KL(D^2 - d^2)}{2880 r_0} \qquad \text{Equation 7.1}$$

where
K = hydraulic conductivity of the geologic formation in gpd/ft^2

D = depth of tunnel invert below static water level in feet
d = depth of tunnel invert below static water level while being pumped in feet
r_0 = distance to point of no drawdown while being pumped in feet

Since the tunnel drains by gravity flow and no pumping is applied, the d^2 and r_0 terms drop out and the equation is simplified. Equation 7.1 is applied for reaches of tunnel penetrating alluvial soils.

For reaches of tunnel penetrating bedrock, the results of the equivalent permeability analysis are used to estimate inflow. The results are given in gallons per minute of water inflow, per foot length of tunnel, per foot height of water head. To estimate water inflow, the result of the equivalent permeability analysis is multiplied by the length of tunnel penetrating bedrock, the product of which is then multiplied by the height of water above the tunnel.

7.4 Comparison of Predicted Versus Actual Tunnel Water Production

Results of the hydrogeologic model along with actual production measured during the time interval of each scenario are shown in Table 7.1. The hydrogeologic model accurately predicts tunnel water production for each scenario. The greatest discrepancy is for Scenario 5, where the hydrogeologic model under-predicts monthly production by 3.2%.

8.0 CONCLUSIONS AND RECOMMENDATIONS

Monthly water production from the Devil's Gate Tunnel is dependant on the height of the groundwater table above tunnel invert. Analyses of well hydrographs and tunnel production statistics combined with results of the hydrogeologic model indicate as groundwater levels fall, tunnel water production decreases until the groundwater elevation is below tunnel invert, when tunnel water production stops.

Comparison of well hydrographs and rainfall records shows a correlation between high groundwater levels and high rainfall indicating, when a lake is not allowed to develop behind the dam, monthly water production is generally proportional to rainfall. If a lake is allowed to accumulate behind the dam, lake water greatly increases the total height of water above tunnel invert in the arroyo and also has a relatively long term effect on groundwater elevations below the Altadena Fan. Prior to the rainfall year 1927-28 when intermittent lakes were allowed to develop on a yearly basis, the monthly water production from the tunnel was greatly increased from current levels and also spread more evenly through the seasons. This is interpreted to suggest that groundwater levels in the arroyo and below the Altadena Fan declined at a much lower rate and remained at a relatively high elevation for the entire year. Groundwater measurements do not extend far enough back in time to support or refute this interpretation, though rainfall records generally do support it. We do not currently have enough information to evaluate lake conditions and their effects on subsurface hydrogeologic conditions during the years between 1930 to 1970. After 1971, lakes were no longer allowed to develop.

Results of the hydrogeologic model developed for this investigation accurately predict tunnel water production for all four of the scenarios for which actual measurements are available. This indicates the model parameters such as hydraulic conductivity and equivalent permeability are reasonable representations of actual in-situ conditions. The five scenarios analyzed cover a wide range of surface and subsurface conditions including high, medium, and low groundwater levels when no lake is present, and high groundwater levels associated with a lake at current spillway elevation. The scenarios cover time intervals from 1927, when high tunnel water production was common, to 1995 which followed a roughly 25 year period when low tunnel water production was common. The fact that the model accurately predicts tunnel water production for all of the scenarios indicates that the low production during the last 25 years is probably not the result of deteriorating conditions within the tunnel. If deteriorating tunnel conditions were the cause of the low water production between 1970 and 1995, the model should either significantly under-predict water production for Scenario 5, or significantly over-predict water production for Scenarios 1, 3, and 4. In actuality the model under-predicted production for Scenario 5 by 3.2%, which is considered well within the accuracy of the model.

The most likely reason for the great difference in tunnel water production from the period between 1913 to 1927 to the period between 1970 to 1995 is the presence and absence respectively of an intermittent lake behind Devil's Gate Dam. Results of the hydrogeologic model indicate if an intermittent lake were allowed to develop on a yearly basis today, within a few years tunnel water production would likely show a similar pattern and reach a similar order of magnitude as that achieved between 1913 to 1927. Other factors such as groundwater withdrawal from pumping and groundwater recharge from the spreading grounds were not considered in this evaluation.

The current condition of the tunnel is poorly known and even though this analysis suggests the current condition of the tunnel should have a minimal effect on water production, we recommend that a full inspection of the tunnel be performed. The inspection should include at a minimum the following:

- Type, extent, and condition of tunnel lining in crown and invert, including collapsed reaches and areas of invert instability.
- Type, extent, and condition of weep holes or drainage devices, including secondary mineral deposits and iron bacteria.
- Type, location, and condition of bulkheads and water collection piping installed subsequent to construction.
- Location and inspection of access shafts not previously abandoned.
- Geologic mapping of the tunnel to the extent possible, including rock type, hardness, jointing, grain size, weathering, etc, also location of seepage zones and estimates of seepage rates if applicable.

- Representative liner and geologic conditions should be documented with photographs, and all of the collected data presented on a base map at a suitable scale.

Based on this inspection, additional recommendations could be developed to repair collapsed areas, remove secondary mineral deposits and iron bacteria that may clog weep holes or drainage devices, provide for easy access through existing shafts, and provide for maintenance of the tunnel and water collection piping.

9.0 CLOSURE

The conclusions and recommendations of this report were prepared in accordance with generally accepted professional engineering geology and hydrogeology principles and practice in Southern California at this time. We make no other warranty, either express or implied. The conclusions and recommendations are based on review of existing records and documents, no field exploration or laboratory testing was performed.

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August 8, 1995

Ms. Rebecca Fisher
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Subject: **ADDENDUM - HYDROGEOLOGIC INVESTIGATION**
Devil's Gate Water Collection Tunnel
Pasadena, California
CCW Project No. 95-31-114-01

Dear Ms. Fisher:

This is an addendum to our July 21, 1995 "Draft Report - Hydrogeologic Investigation Devil's Gate Water Collection Tunnel". The purpose of this addendum is to extend the hydrogeologic model in an effort to predict tunnel water production on a yearly basis. This work was performed in accordance with your verbal request on July 31, 1995.

DISCUSSION

The model developed to estimate tunnel water inflow relates water production to the height of the groundwater table above tunnel invert. Scenarios were chosen for specific intervals in time for which actual groundwater elevation and tunnel water production measurements are available. The measurements were used in an iterative process to calibrate the model. This technique worked and the model accurately predicted monthly water production for five scenarios.

However, an underlying assumption to the model is that groundwater elevations along the tunnel are at a steady state and do not vary over a 1 month period and are accurately represented during this period by a single measurement from Well 5P1. The measurement from Well 5P1 may have been taken up to 3 months before or after the month for which the prediction is being made. Another assumption is that groundwater elevations below the Arroyo Seco and groundwater elevations below the Altadena Fan are interrelated and rise and fall together such that the difference in elevation between the two is always between 5 to 15 feet. These assumptions are necessary because actual groundwater level measurements are only available on roughly 4 month intervals and only for wells located in the Altadena Fan. Wells located within the arroyo are too far from the tunnel to be representative, so no control on groundwater elevation within the arroyo is available.

The assumptions appear to be valid for short periods of time, say up to 1 month. For longer periods of time the assumptions break down and are no longer valid. For instance, some years show evidence indicating groundwater levels within the arroyo vary significantly from groundwater levels within the Altadena Fan, especially for months when an intermittent lake is present behind the dam. Similarly, well hydrographs indicate groundwater levels in the area are not static, but often change significantly over relatively short periods of time. Also, other factors may have a significant role in tunnel water production including the surface elevation and duration of lakes present behind the dam, groundwater withdrawal from pumping, and more recently, groundwater recharge from the spreading grounds. Incorporating these factors into the model would be complicated and is beyond the scope of this study.

Keeping these shortcomings in mind, an effort was made to extend the model to a yearly basis following Scenario 4 from the previous report. Results are shown in Table 1.

Table 1. Predicted versus actual yearly tunnel water production for Scenario 4.

Scenario 4 Rainfall Year 1991-92	Groundwater level Above Invert In Altadena Fan (feet)	Predicted Water Production (ac-ft)		Actual Average production (ac-ft)	
		Per Month	3 Months	Per Month	3 Months
October November December	-35	0.04	0.12	1.4	4.16
January February March	-35	0.04	0.12	0.04	0.11
April May June	-10	0.4	1.2	0.06	0.19
July August September	-10	0.4	1.2	1.01	3.03
		Yearly Predicted Total	2.64	Actual Total	7.49

The model under predicted water production by a factor of 2.8. The reason for this is evident from observations of the hydrograph for Well 5P1 (Figure 4.1 from previous report). In January 1992 the groundwater elevation was 35 feet below tunnel invert. In April the groundwater elevation was 15 feet above tunnel invert. No measurement was made in July, but in October, the groundwater elevation is 10 feet below tunnel invert. These three groundwater elevation measurements were taken over a 10 month period and include at least one 50 foot rise in groundwater elevation and one 25 foot drop in groundwater elevation. The lack of a measurement in July results in a 6 month gap in groundwater elevation data. There is no information to indicate how long the groundwater took to reach it's high and low points or how long it remained at these points.

The results shown in Table 1 assume that from April to September the groundwater was 10 feet below tunnel invert, based on the measurement made in October. This ignores the April measurement which represents the highest groundwater elevation measured for this period. This is probably the reason the model under predicts water production. If it was assumed the April measurement was representative of groundwater elevation from April to June, the model would over predict water production by a factor of 2.7. Either assumption is speculation and is at the discretion of the modeler.

The problems just described are worse for the other scenarios, especially Scenario 5 which represents conditions when a lake was present behind the dam. There is simply not enough information available and the current model is not detailed enough to make meaningful predictions of water production on a yearly basis.

It should also be noted that the tunnel water production statictics used to calibrate the model may be representative of only a portion of the total production from the tunnel, especially for measurements made in recent years. Therefore, the results of this study should not be used in quantitative analyses; rather, they should be used in a qualitative approach to gauge which factors may have the greatest or least effect on tunnel water production.

Respectfully submitted,

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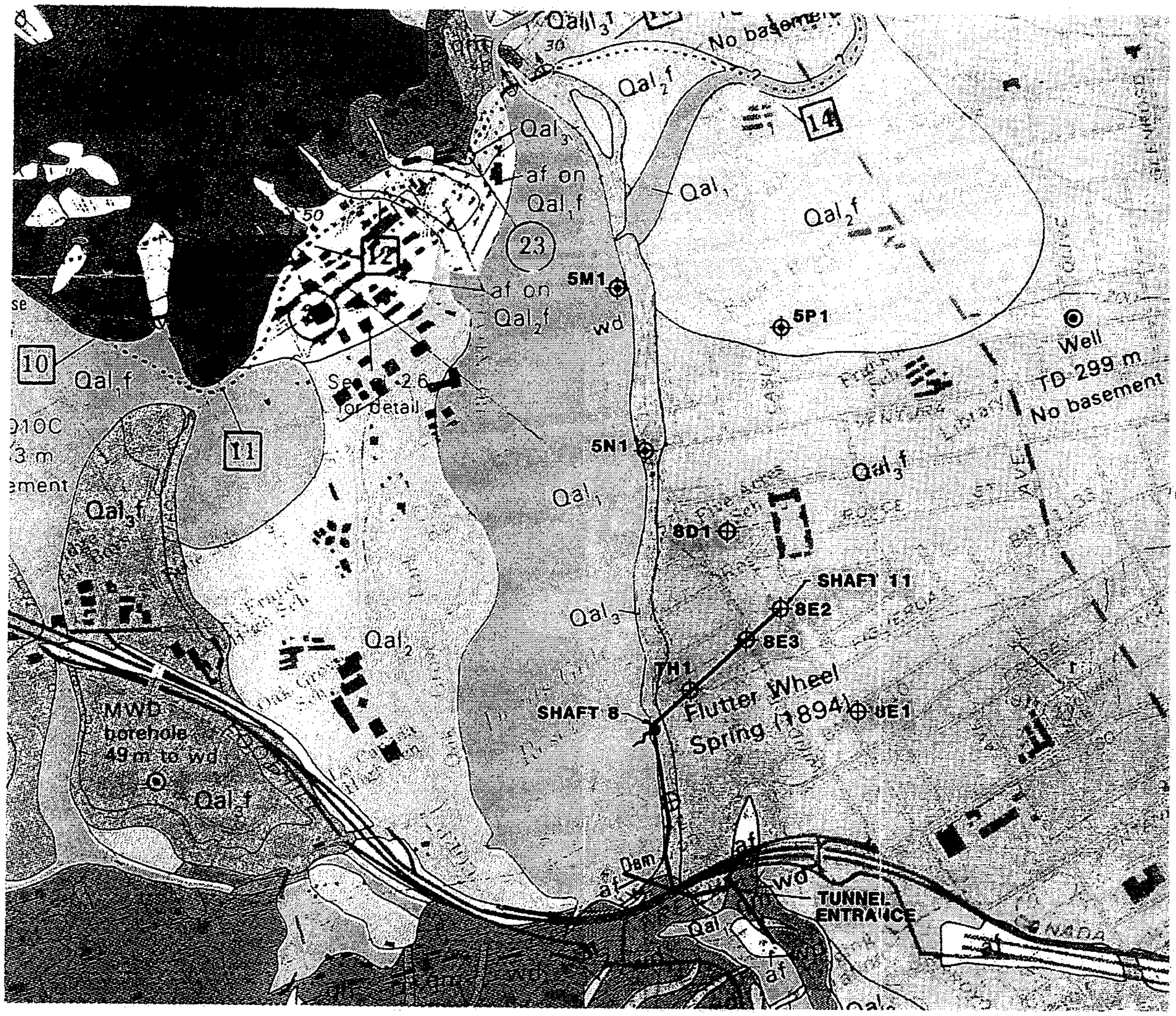

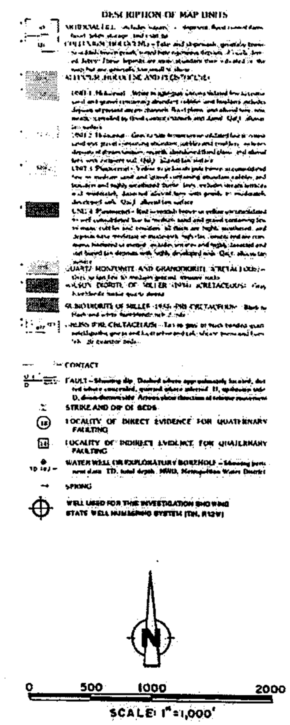

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GEOLOGIC MAP

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Project No.	Drawing No.
95-31-114-01	1