

HYDROGEOLOGIC CHARACTERIZATION OF CORALLINE LIMESTONE AQUIFER AT INDUSTRIAL FACILITY IN THE HAWAIIAN ISLANDS

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ABSTRACT

A hydrogeologic characterization was performed to determine horizontal and vertical flow directions, hydraulic conductivities, porosity and tidal influences. The monitoring well network is approximately two thousand feet inland from the shoreline in the uppermost unconfined aquifer. Four sets of ground-water well clusters consisting of three wells per cluster were installed as the main monitoring network. The well clusters were placed in a rectangular arrangement approximately four hundred feet apart. The well screens within each cluster were placed to divide the uppermost aquifer into three vertical intervals to evaluate vertical flow magnitude and direction. Hourly water level data was collected from the twelve wells for a two month period. In addition to the main monitoring network, three piezometers were installed near one of the well clusters to measure draw-down during three pumping tests. The pumping tests were performed in order to assess the vertical variability of hydraulic conductivity and storage coefficient within the aquifer. The interconnection of the different zones within the aquifer were apparent during the pumping tests. The aquifer is composed of varying degrees of fractured coral and limestone, and hydraulic conductivity increases with depth.

The hourly water level data was used to calculate vertical and horizontal gradients using average water levels over two different three-day averaging periods. Both the arithmetic averages and filtered, moving averages were calculated. Average horizontal gradients in the upper, middle and lower zones were 0.00018, 0.00015 and 0.00087, respectively. The average vertical gradient between the upper-middle zone and the middle-lower zone were 0.0042 and 0.0180, respectively. All average vertical gradients were in the downward direction. Time lag and attenuation between the monitoring well water levels and the hourly ocean level data was determined. Time lags and attenuation factors between the ocean stage and the aquifer were determined. The variability about the mean water levels in the monitoring wells and the ocean was assessed statistically over different time periods.

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INTRODUCTION

The purpose of this paper is to present the results of three-dimensional ground-water observation and pumping test data to characterize the ground-water flow system under an industrial facility on the Hawaiian Islands. The study of the ground-water system under the facility will be referred to as the hydrogeologic characterization of the facility. The objectives for the hydrogeologic characterization were to assess: (1) the vertical flow direction and gradient; (2) the horizontal flow direction and gradient; (3) the hydraulic conductivity, storativity, and effective porosity of the uppermost aquifer; and (4) the influence of tidal flux and injection wells on ground-water hydrogeology at the facility. The information obtained from this study is critical to determine the transport of any chemicals that may enter the ground-water system near the facility.

GROUND-WATER MONITORING AND ANALYSIS

The monitoring network under the facility consisted of twelve wells that were installed in four well clusters. The spatial distribution of the well clusters are shown in Figure 1. The well screens were placed to divide the uppermost aquifer into three vertical intervals to evaluate water quality and horizontal and vertical gradients. Well screens for each well cluster were placed at depth intervals of approximately 15 to 25 feet ("the upper zone"), 33 to 43 feet ("the middle zone"), and 50 to 60 feet below grade ("the lower zone"). The average depth to ground water under the facility is twelve feet below ground surface (bgs). The aquifer consists of coralline limestone with discontinuous lenses of siltstone, sandy silt and silty sands. Based upon the lithology and drilling conditions encountered during well installation, ground-water flow in the aquifer appears to be more representative of porous media flow as opposed to typical conduit (mature karst-type) flow.

The 12 monitoring wells in the network were monitored hourly for a period of approximately two months. A representative hydrograph of the hourly ground-water elevation data for Well CW-1A is shown in Figure 2. The associated vertical gradients for CW-1 (three wells within well cluster CW-1, i.e. CW-1A, CW-1B and CW-1C) is presented in Figure 3. Month 1 consists of data from approximately September 17 through October 14, 1992, and Month 2 consists of data from October 19 through November 17, 1992.

The ground-water elevation data throughout the monitoring period demonstrates consistency in that it compares very well to the hourly ocean stage data. The reproducibility within each cluster group is demonstrated by the vertical gradient curves, which fluctuate about a mean, with small standard deviation.

General Description of Time Dependent Vertical Gradients

The vertical gradients were consistently downward from the upper zone to the middle zone for all cluster wells, as evidenced by the vertical gradient plots. The vertical gradients varied from a minimum average of -0.00034 (from CW-2A to CW-2B) to a maximum average of -0.00865

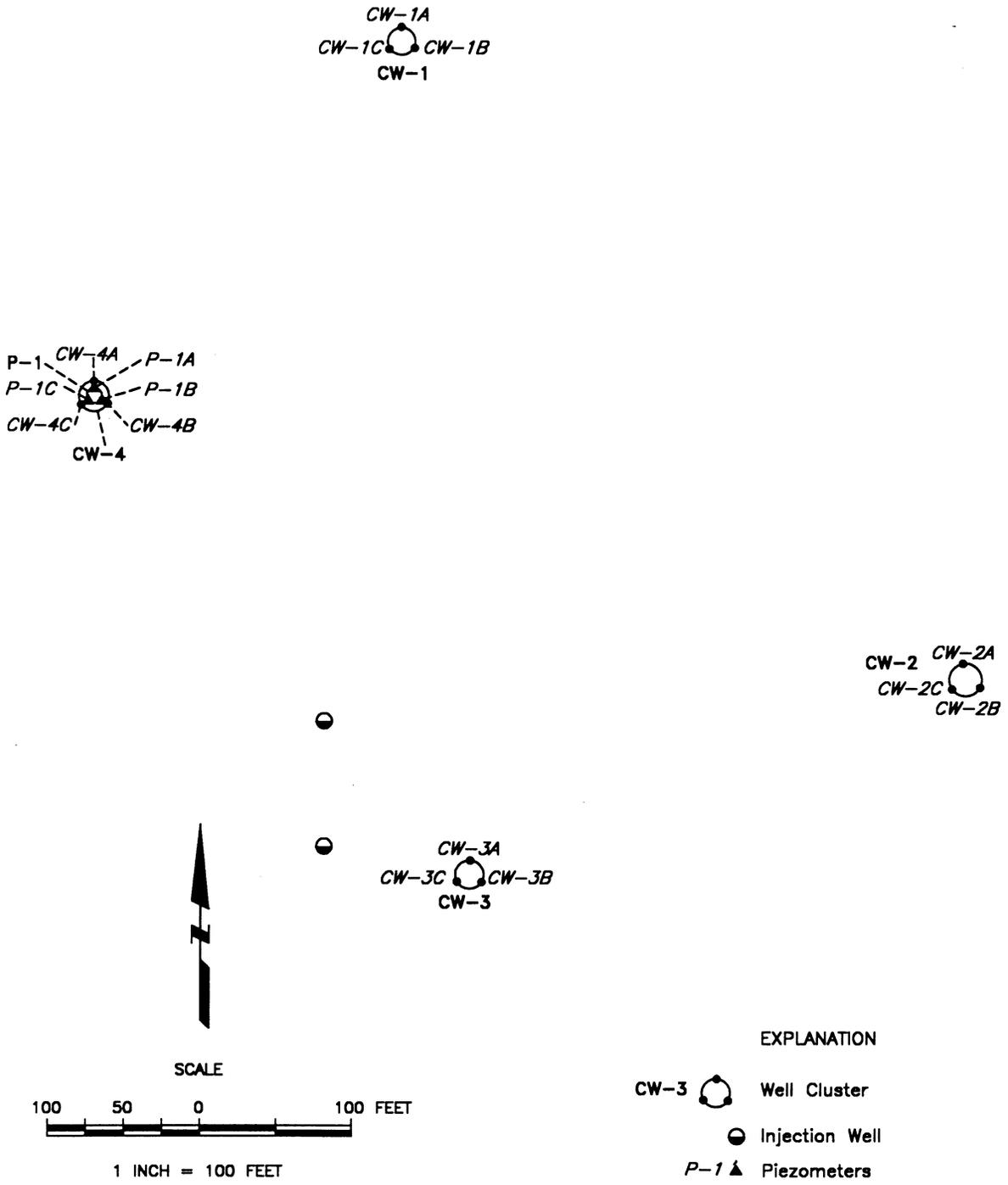


Figure 1 : Spatial Distribution of Well Clusters

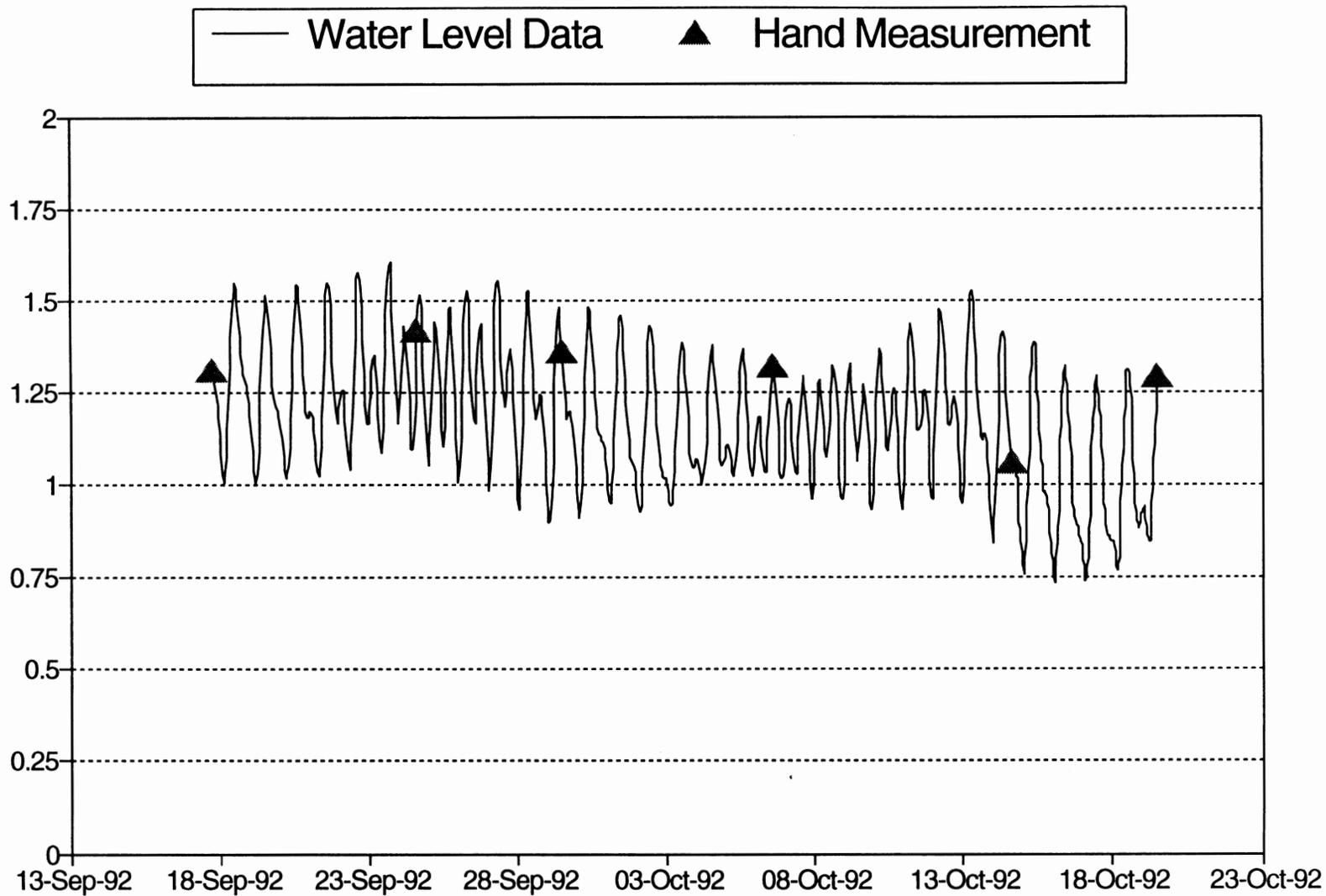


Figure 2 : Well CW-1A Hydrograph (ft.-MSL)

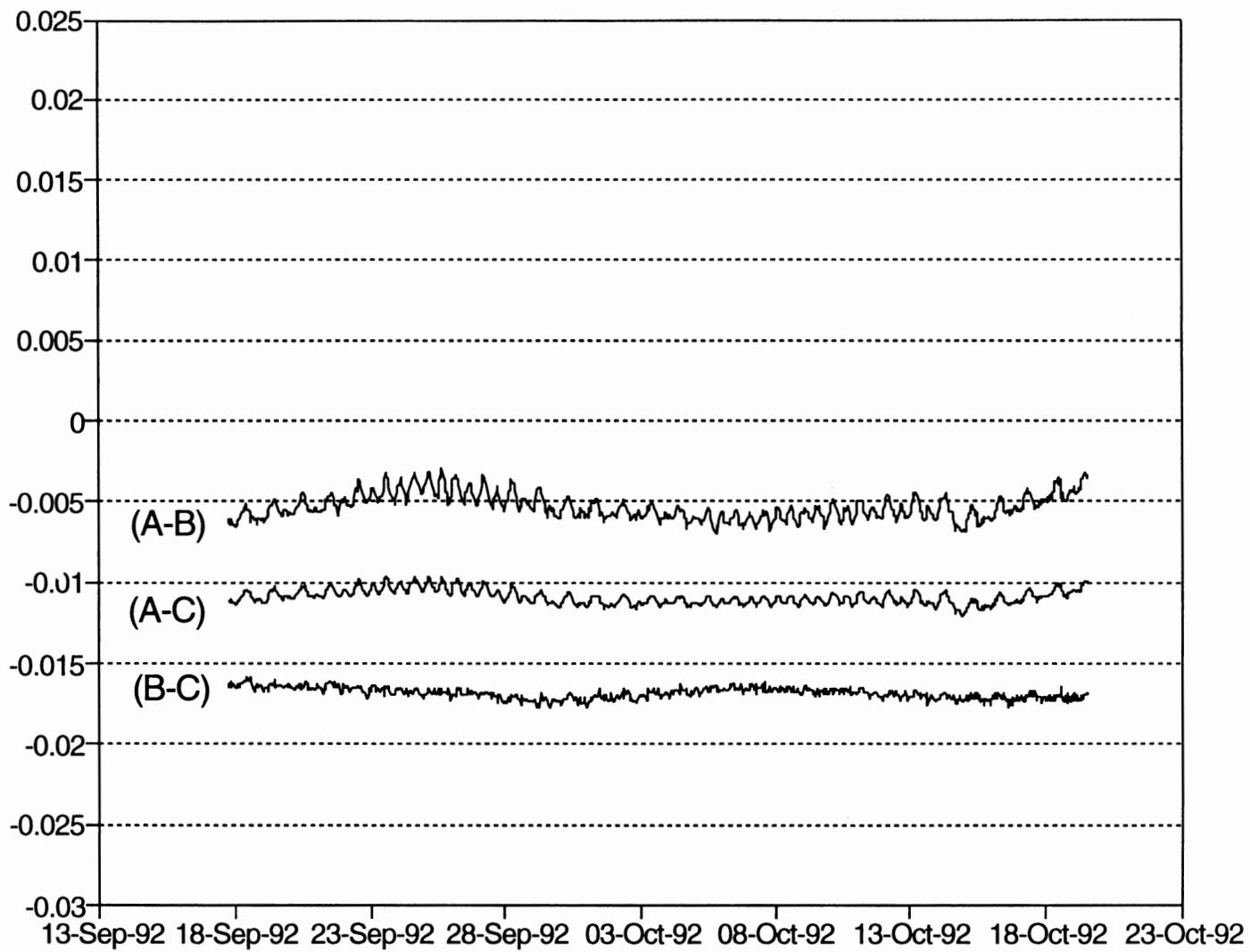


Figure 3 : Well Cluster CW-1 Vertical Gradients (-dh/dl)

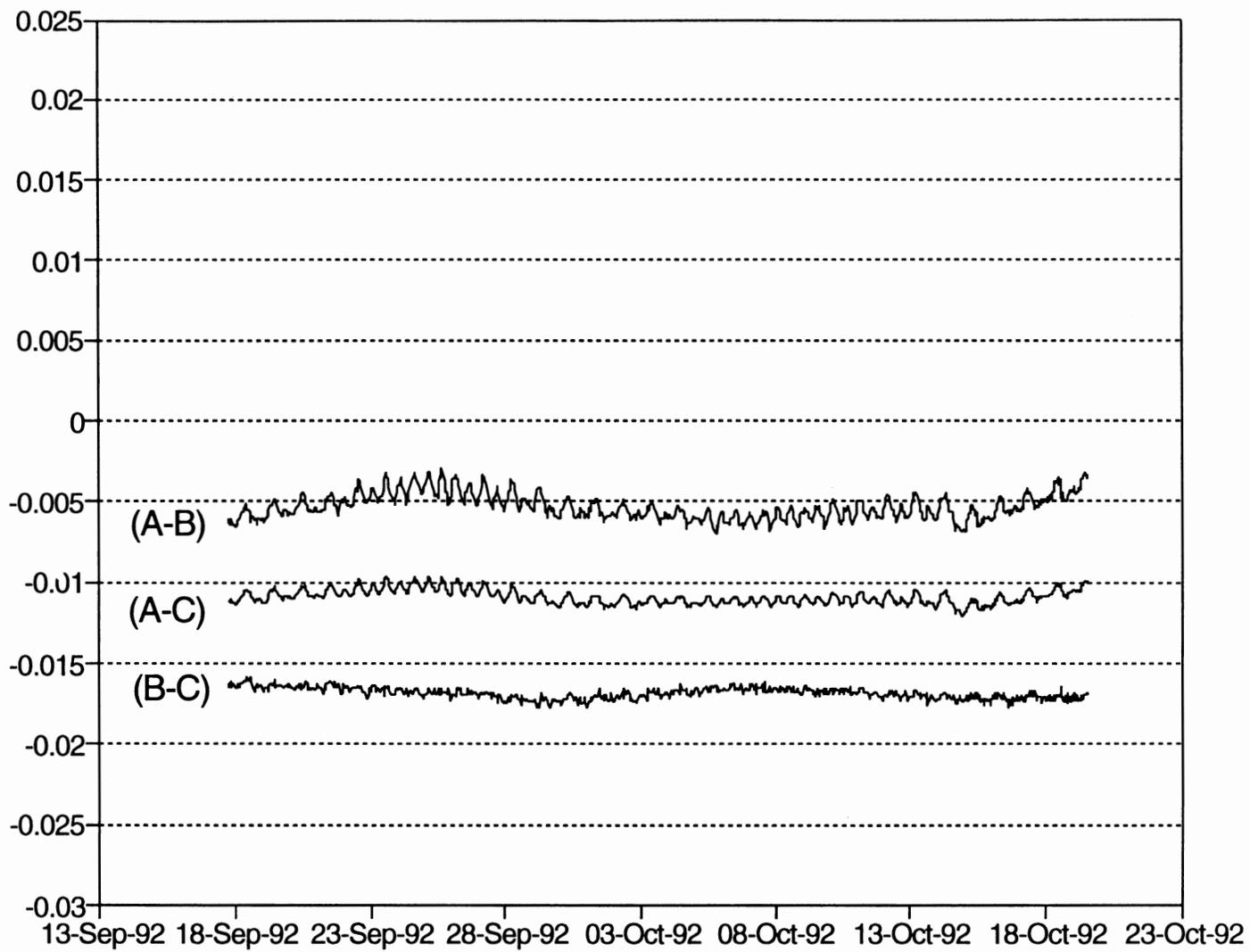


Figure 3 : Well Cluster CW-1 Vertical Gradients (-dh/dl)

(from CW-3A to CW-3B). From the middle zone to the lower zone, all the gradients were downward in CW-1, CW-2 and CW-4 and varied from -0.0154 to -0.0216. There was an upward gradient from CW-3C to CW-3B which ranged from 0.01513 to 0.0195 for Month 1 and Month 2, respectively. The vertical gradients from the upper zone to the lower zone were all downward, with the exception of CW-3A to CW-3C, which was upward.

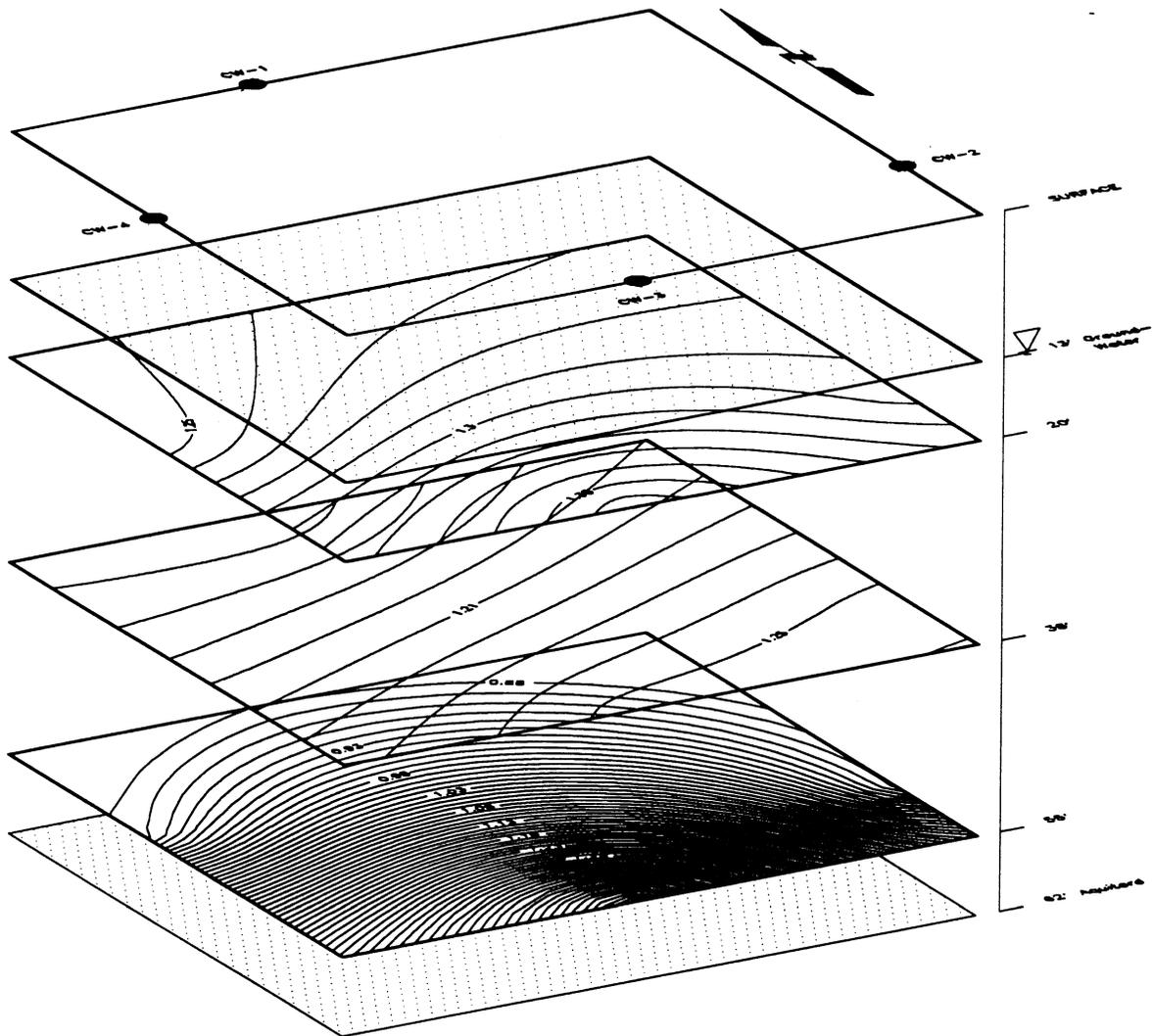
Averaged Ground-water Flow Directions

In order to determine the horizontal gradients in the upper, middle and lower portions of the uppermost aquifer, a 72-hour average of ground-water elevations at each individual well was calculated. In a paper entitled "Determining the Mean Hydraulic Gradient of Ground Water Affected by Tidal Fluctuations," Serfes (1991) suggests the use of filtered averages to accurately determine the ground-water flow regime at a tidally affected site. The filtering methodology involved the application of moving averages to remove diurnal and semidiurnal lunar and solar harmonics from the 72 consecutive hourly water level measurements.

For this characterization, the filtered average and arithmetic averages were compared on seven different 72-hour sets of monitoring data. The difference between the filtered average and arithmetic averages varied between 0.080 and 0.96 percent, assuming the filtered average is the true average. There are no obvious trends in over- or underestimation of the filtered average. The mean of the absolute value of the seven differences is 0.34 percent. Therefore, because the mean of all the ground-water elevation data is 1.2 feet, the average difference between the arithmetic and filtered average is 0.0041 foot, and the maximum deviation is 0.011 foot. Therefore, the arithmetic average was used throughout as the averaged ground-water elevation in the wells during the various 72-hour periods. The results of the arithmetic averaging are shown in Table 1.

The average ground-water flow direction for each of the three different zones was determined for four different time periods during the first month of continuous hourly ground-water monitoring. These time periods corresponded to the last quarter (September 19), new moon (September 26), first quarter (October 3) and full moon (October 11) during the monitoring period (Farmer's Almanac, 1992). The 72-hour period included the day before and the day after the aforementioned moon phase; e.g. for full moon the period began on October 10 at 12:00 A.M. and ended on October 12 at 11:00 P.M.

The averaged data for each of the four averaging periods has the same relative distribution of ground-water elevation for each level (upper, middle and lower); i.e. the flow system on the average is approximately the same for each of the four averaging periods. The only major difference among the four periods is the average ground-water elevation for each period as it relates to the phase of the lunar cycle. The contoured average potentiometric elevations are shown for each of the three levels for the last first quarter of the moon sequence in shown in Figure 4. The same contour interval (0.01 foot) was used for all contour plots to illustrate any significant changes in the flow system with depth. For the purpose of clarifying the contours in Figure 4, the averaged horizontal flow regime for each level is summarized below.



EXPLANATION

CW-2 ● Well Cluster Location

~ Potentiometric Surface Elevation Contour
Contour Interval 0.010 Feet

VERTICAL SCALE AS SHOWN
HORIZONTAL SCALE

0 70 140 280 FEET

1 INCH = 140 FEET

Figure 4 : Three-Dimensional Perspective of Average Potentiometric Surface Elevations for September 18-20, 1993

Level A - Shallow: Well Screen 15-25 feet, Plane at 20 feet below grade. Well CW-3A is approximately 0.07 foot higher than the other wells, which results in a small apparent mounding near CW-3A that is consistent from the contour plotting for all four periods. Contouring the data from only wells CW-2A, CW-3A and CW-4A, the approximate flow direction is towards the west. The flow system in the upper zone (as depicted in Figure 4 for the northern part of the domain) is towards the northwest.

Level B - Intermediate: Well Screen 33-43 feet, Plane at 38 feet below grade. The mounding observed in the upper zone near CW-3 is not consistent with the middle zone. The flow direction is approximately north-northwest in the four averaging periods.

Level C - Deep: Well Screen 50-60 feet, Plane at 55 feet below grade. Mounding effects in the vicinity of CW-3 can be clearly seen in Figure 4. The contour interval for contour plots in the three levels held constant at 0.01 foot, and the ground-water elevation at CW-3 is approximately 0.6 foot higher than the other wells in the C-plane. This mounding in the C zone is approximately an order of magnitude greater than the apparent mounding at CW-3A. The variability in ground-water elevation among the remaining wells is virtually insignificant compared to the drastic difference at CW-3C. The most likely source for this apparent mounding is the forced water injection wells located approximately 100 ft northwest of CW-3. The injection wells are screened from 62 to 92 ft bgs. The vertical gradient from CW-3C to CW-3B was consistently the strongest gradient in the system, and the only upward gradient in any well cluster.

If flow direction arrows were added to Figure 4, the flow direction would be generally toward the north-northwest for the upper and middle zones, with an outward (radial) influence for the lower zone. The reversal in flow direction is due to the limited influence of injection water from injection wells.

Comparison of the Two Month Ground-water Hourly Data to Ocean Stage (Hourly) Data

The predicted hourly ocean stage elevations for the ocean stage near the facility were obtained from the Tropical Ocean Global Atmosphere Project (TOGA) at the University of Hawaii. The predictions of hourly tidal stage data were performed by TOGA on 1991 hourly data. These data were used to compare predicted versus real measurements. In the absence of major storms, the predicted versus real residuals are within a few inches of one another.

To illustrate the damping of the ocean stage at the monitoring wells, the exaggerated ocean hydrograph has been overlaid on to ground-water data from CW-4A in Figure 5. The vertical scale is purposely exaggerated for convenient comparison to the ground-water elevation data. The approximate range for the ocean data is 2 feet, compared to the approximate range in the ground-water wells of 0.5 foot. The highest high tides and the lowest low tides are at full moon and new moon, resulting in the greatest differential between high and low tides.

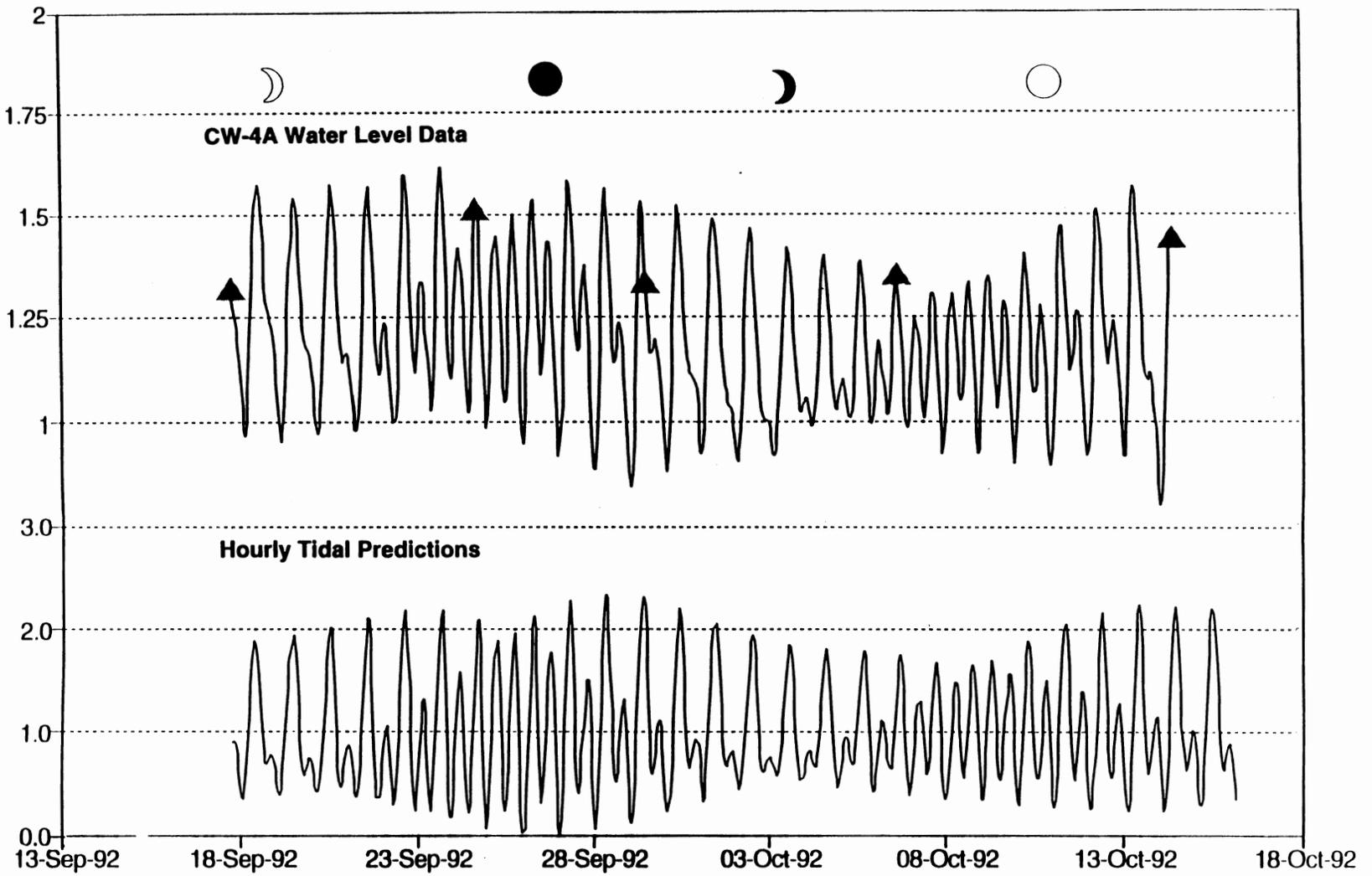


Figure 5 : Comparison of CW-4A Water Level Data vs. Hourly Tidal Predictions

In order to compare the ocean stage data to the water elevations in the 12 ground-water monitoring wells, the average and standard deviations for the ground-water elevation and ocean stage data were compiled in two tables. Table 2 is a summary of monthly ground-water elevation data and corresponding vertical gradients.

The standard deviations for the ground-water elevation data were consistently higher for the second month of data. The standard deviation for the ocean stage data was also slightly higher. The average ground-water elevation consistently decreased as a function of the distance from the Pacific Ocean, with the exception of CW-1A. In an effort to examine the amount of damping that occurs in the formation, the following analysis is offered.

Apparent Damping in Formation for the Four 72-Hour Periods

The damping factor is defined as the ratio of the standard deviation of the ocean stage divided by the standard deviation of each of the shallow monitoring wells. The standard deviation about the mean for both the ocean tides and the tidally affected ground water is a measure of the fluctuation about the mean value. In other words, the standard deviation indicates the relative influence of the tides in the form of a length above or below the mean value. Table 3 summarizes the standard deviations of the ocean stage, the four 72-hour averaging periods and the associated damping factors with the four monitoring wells in the shallow zone. The damping factors increase in an apparent linear fashion with increasing distance from the Pacific Ocean. There is a clear correlation between the amount of damping that occurs and the distance from the Pacific Ocean; i.e. the damping factor increases as the distance from the Pacific Ocean increases. The approximate distances from the Pacific Ocean are 2000 feet for CW-3, 2130 feet for CW-2, 2315 feet for CW-4 and 2550 feet for CW-1.

Time Variation of Ground-water Elevation on an Hourly Basis

The hourly ground-water hydrographs for the four shallow (upper zone) monitoring wells are plotted on the same axes for two different 72-hour time periods (Figure 6). There are changes in apparent ground-water gradient and direction on an hourly basis. For example, CW-4A consistently has the lowest ground-water elevation at low tide but has the third highest ground-water elevation at high tide. The hydrographs contain numerous crossovers, indicating an apparent reversal in flow direction at CW-1A, CW-2A and CW-4A. However, the instantaneous reversal in flow direction is not an accurate depiction of what is occurring at the facility (Serfes, 1991). The traveling wave speed from well to well in the same zone must be accounted for, i.e., implementation of an average "non-tidal" affected water level, the 72-hour average. The exception is at CW-3A, which consistently has the highest ground-water elevation regardless of the tidal influence.

Table 2 :

Summary of Monthly Ground Water Elevations, Vertical Gradients, and Variability

	Average Well Stage		Standard Deviation	
	Month 1	Month 2	Month 1	Month 2
CW-1A	1.20811	1.19340	0.15950	0.17770
CW-2A	1.26540	1.24340	0.17930	0.18750
CW-3A	1.33940	1.40580	0.19310	0.22880
CW-4A	1.19810	1.21660	0.17540	0.19830
CW-1B	1.11164	1.10970	0.16733	0.17910
CW-2B	1.23540	1.23730	0.17950	0.18820
CW-3B	1.24510	1.25010	0.18960	0.22220
CW-4B	1.15430	1.12490	0.17700	0.20360
CW-1C	0.82599	0.82550	0.16920	0.18230
CW-2C	0.86880	0.89180	0.18350	0.19600
CW-3C	1.50230	1.60480	0.19610	0.23380
CW-4C	0.83650	0.86290	0.18230	0.19810

	Average Vertical Gradient		Standard Deviation	
	Month 1	Month 2	Month 1	Month 2
CW-1 (A-B)	-0.00536	-0.00465	0.00080	0.00072
CW-1 (B-C)	-0.01680	-0.01672	0.00034	0.00047
CW-1 (A-C)	-0.01092	-0.01051	0.00043	0.00031
CW-2 (A-B)	-0.00166	-0.00034	0.00047	0.00040
CW-2 (B-C)	-0.02157	-0.02030	0.00055	0.00101
CW-2 (A-C)	-0.01133	-0.01005	0.00029	0.00045
CW-3 (A-B)	-0.00524	-0.00865	0.00140	0.00270
CW-3 (B-C)	0.01513	0.01946	0.00171	0.00278
CW-3 (A-C)	0.00465	0.00395	0.00091	0.00084
CW-4 (A-B)	-0.00243	-0.00509	0.00063	0.00080
CW-4 (B-C)	-0.01870	-0.01541	0.00071	0.00184
CW-4 (A-C)	-0.01033	-0.01011	0.00047	0.00073

Notes: Month 1 = Sept. 17, 1992 - Oct. 14, 1992

Month 2 = Oct. 19, 1992 - Nov. 17, 1992

Average Well Head and Standard Deviations in feet.

Average Vertical Gradient and Standard Deviations dimensionless.

Month 1 = 638 Hourly Values (Sept 17 6pm - Oct 14 9am) All Wells.

Month 2 = CW-1(A,B,C) 694 Hourly Values (Oct 19 1pm - Nov 17 11am)

CW-2(A,B,C) 629 Hourly Values (Oct 19 2pm - Nov 10 4pm & Nov 13 1pm - Nov 17 1pm)

CW-3(A,B) 576 Hourly Values (Oct 19 2pm - Oct 30 3pm & Nov 4 3pm - Nov 17 12pm)

CW-3(C) 310 Hourly Values (Nov 4 3pm - Nov 17 12pm)

CW-4(A,B,C) 699 Hourly Values (Oct 19 11am - Nov 17 12pm)

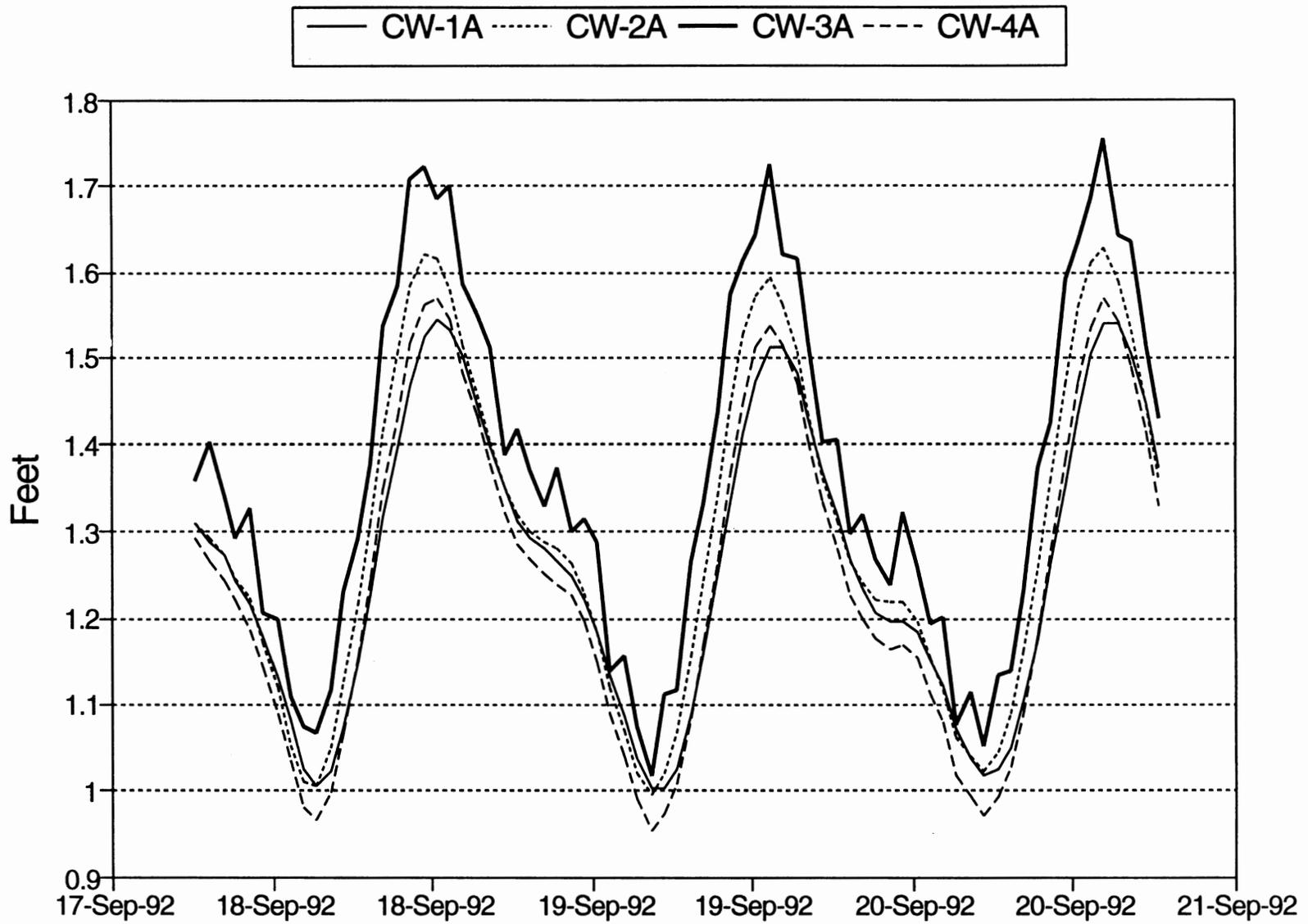


Figure 6 : Overlay of A-Hydrographs (September 18-20, 1993)

Regional Flow to Pacific Ocean

Assuming the average ocean stage for Month 1 compared to the average ground-water elevation in the shallow wells for Month 1, the approximate regional gradient from the facility to the Pacific Ocean can be estimated as follows:

$$(1.252-1.036)/2250 = 9.6 \times 10^{-5}$$

where 2250 is the average distance in feet from the Pacific Ocean for the shallow wells, and 1.252 and 1.036 are ft-MSL for the shallow wells and the ocean, respectively. A similar procedure can be performed for Month 2, yielding an apparent regional gradient of 9.8×10^{-5} . It is important to note that local features at the facility influence such calculations; however, considering the average ground-water elevations among the wells in the upper zone will in effect limit this to a minimal degree. These regional gradient values are low, but make sense since water table gradients generally "flatten out" when approaching a surface water body (Freeze and Cherry, 1979).

PUMPING TEST AND ANALYSIS

In order to estimate the horizontal hydraulic conductivity, transmissivity and storage coefficient, three pumping tests were performed at the facility. These pumping tests were conducted at the upper, middle and lower zones of the uppermost aquifer at CW-4 to estimate the vertical variability of aquifer parameters. General test procedures, analytical methods and the data obtained from the pumping tests are discussed below. The potential for vertical interconnected flow above and below the uppermost aquitard was estimated by comparing the pumping test(s) results to the vertical hydraulic conductivity of the aquitard material.

General Procedures

Three separate pumping tests were performed to characterize the aquifer with respect to its response to pumping. One pumping test was performed on each of the three monitoring wells comprising CW-4 in order to estimate aquifer parameters in each of the three arbitrary layers of the uppermost aquifer.

Each test was performed utilizing a single 4 inch diameter monitoring well (pumping well) and a single 2 inch diameter piezometer (observation well), both of which were completed with 10 foot vertically screened intervals in the appropriate zone of interest for each test. The radial distance (r) between the pumping well and the observation well was approximately 5 feet.

Each pumping test was conducted for a period of approximately 24 hours. The pumping tests were conducted using an electric submersible pump with an in-line flow meter for measuring flow rates during the duration of each test. Flow rates were 69 gpm for test CW-4A, 62 gpm for test CW-4B, and 64 gpm for test CW-4C. Drawdown versus time measurements for each test were made using an Instrumentations Northwest, Inc., multi-channel data logger outfitted

with pressure transducers having a sensitivity range of 0-5 psi. In addition to the data logger measurements, a series of hand level measurements were made during each test in order to verify the data obtained from the data logger.

Subtraction of Tidal Influence

Historical water level data from CW-4 indicate that the difference between the water levels in the upper, middle and lower zones remains constant over time (i.e. vertical gradients remain constant over time). Data obtained during the three pumping tests indicate that daily tidally influenced water levels recorded in Level C were not significantly influenced by pumping in Levels A or B due to the high transmissivity of the formation. Likewise, the daily tidally influenced water levels recorded in Level A were not significantly influenced by pumping in Level C.

A "non-pumping" curve for observation well P-1A was produced by calculating the difference in head between Levels A and C prior to pumping, and adding this difference to the Level C curve obtained during the same time period as pumping test CW-4A. This curve simulates the tidally influenced water level curve which would have been obtained from Level A during the time period of the pumping test had pumping not taken place.

The drawdown (s) versus time (t) curve utilized in analyzing the pumping test was then produced by subtracting the actual water levels versus time curve recorded in Level A during the time period of the CW-4A pumping test from the corresponding "non-pumping" curve for the same time period, resulting in an s versus t curve. Similar procedures were followed to produce s versus t curves for pumping tests CW-4B and CW-4C.

Discussion of Drawdown Versus Time Curves

The s versus t curves produced for each of the pumping tests were then plotted on log-log scales to define the early portion of the curves where most of the drawdown typically occurs during a pumping test. It is also necessary for the drawdown curves to be plotted on log-log scales in order to match them with the Neuman Type Curves, which are plotted on log-log scales.

As anticipated, the majority of the drawdown observed in each observation well during each respective pumping test occurred during the first 0.2 minutes (12 seconds) of each test. After this time period the slopes of the s versus t curves decline dramatically, as the Neuman method predicts they should. Maximum drawdowns observed during the tests were 0.20 feet for test CW-4A, 0.07 feet for test CW-4B, and 0.03 feet for test CW-4C.

The results of the calculations using the Neuman method of Transmissivity (T), Storage Coefficient (S), and Hydraulic Conductivity (K) for each of the three pumping tests are as follows:

<u>Pumping Test</u>	<u>T</u>	<u>S</u>	<u>K</u>
CW-4A	5,300 ft ² /day	0.032	530 ft./day
CW-4B	9,400 ft ² /day	0.045	940 ft./day
CW-4C	11,600 ft ² /day	0.060	1,100 ft./day

Vertical Gradients (Partial Penetration)

During the execution of each of the pumping tests, water level measurements in two piezometers not in the zone of pumping were measured with transducers and hand-level measurements. By comparing hydrographs within each of the non-pumping zones, the vertical gradients during the pumping tests were determined to be on the order of 0.02 foot between non-pumping zones. The comparison consisted of forcing each of the non-pumping zone curves to the same value at the beginning of the test and calculating the differences between the two curves during the pumping tests. The maximum difference between the two non-pumping zone curves was less than 0.03 foot, thus eliminating the possibility of significant vertical gradients during the pumping tests. In addition, there are clearly diurnal effects in pumping tests 2 and 3 that would attribute any of the difference in the non-pumping curves to natural variability. Because of this, non-pumping zone curves could be used as the "non-pumping" curves for the pumped zone.

Based on the factors discussed above, radial flow into the pumping well was assumed. This assumption is believed to be valid for such a highly permeable porous medium, which the data in this study supports as an appropriate model for the coral aquifer underlying the facility. The storage coefficient is defined as the amount of water lost from a unit volume of aquifer during pumping; it cannot exceed the value of the effective porosity. The storage coefficients obtained from the pumping tests represent 32, 45 and 60 percent of the reported value of effective porosity of the aquifer.

SUMMARY AND CONCLUSIONS

Approximately two months' of ground-water elevation data for the twelve well clusters were compiled in a graphical format and analyzed in several different forms to ascertain the horizontal and vertical flow regime, tidal influences and the effect of injection wells. The data collected at the facility compared extremely well with predicted hourly Pacific Ocean stage data. Three pumping tests were conducted to determine aquifer hydraulic parameters and the effects of vertical flow gradients during the pumping test period. A summary of the most significant conclusions are given below:

- Average horizontal gradients in the upper, middle and lower zones were 0.00018, 0.00015 and 0.00087, respectively. The average vertical gradient between the upper-middle zone and the middle-lower zone were 0.0042 and 0.0180, respectively. All average vertical gradients were in the downward direction. The vertical gradients within each well cluster remained relatively constant and fluctuated consistently about a mean value.

- There are two different scales for which the flow regime is valid: the local scale (limited to the areas near the cluster wells; hundreds of feet), and the regional scale (thousands of feet). There was a net average horizontal gradient toward the Pacific Ocean from the well clusters in the upper zone. There appears to be a local reversal in flow direction due to the influence of the injection wells, compared to a regional flow toward the Pacific Ocean. Therefore, ground-water flow varies spatially; i.e., the ground-water flow direction is dependent upon the horizontal position of the injection wells within the aquifer.
- The pumping tests indicated increasing hydraulic conductivity with depth, which is most likely the result of increased interconnected porespace with increasing depth within the uppermost aquifer.

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