N.A. Water Systems

April 25, 2008

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Mr. Mark Purcell
Superfund Division (6SF-RL)
U.S. Environmental Protection Agency
1445 Ross Avenue, Suite 1220
Dallas, TX 75202

Mr. Myron Fliegel
U.S. Nuclear Regulatory Commission
11545 Rockville Pike
#2 White Flint, Mail Stop T8F5
Rockville, MD 20852

Re: Recommendations and Summary of Hydrogeologic Analysis
Evaluation of Groundwater Flow in Zone 3 for the Design of a Pumping System to Intercept and Recover Impacted Groundwater
United Nuclear Corporation's Church Rock Tailings Site, Gallup, New Mexico
Administrative Order (Docket No. CERCLA 6-11-89)
Materials License No. SUA-1475

Dear Messrs. Purcell and Fliegel:

Introduction

On behalf of United Nuclear Corporation (UNC), N.A. Water Systems has prepared this report regarding UNC's Mill and Tailings Site near Gallup, New Mexico. The subject of this report was discussed at the annual Church Rock multi-agency meeting that was held on March 12, 2008 in Santa Fe, New Mexico.

This report presents recommended well layouts for hydraulic capture at the leading edge of seepage-impacted groundwater in the Zone 3 hydrostratigraphic unit at the Church Rock Site. The recommendation is based on analyses of groundwater drainage rates and flow patterns prior to and during the pumping of wells in Zone 3, which began

N.A. Water Systems, LLC
120 Radnor Road
State College, PA 16801 USA
Tel: 814-231-2170 • Fax: 814-231-2174
Web site: www.veoliawaterst.com

(most recently) in early 2005. A summary of this hydrogeologic analysis follows the recommendations.

Recommendations

Two pumping well array layouts have been designed as options for the hydraulic capture of impacted groundwater from Zone 3 at the Church Rock Site. The primary objective of the proposed pumping arrays is to intercept the plume of impacted groundwater before it reaches the Section 36 boundary. It is for this reason that the proposed wells are arrayed near to and down-gradient of the most northern known location of impacted groundwater (well NBL-1). Recovery of impacted groundwater is a secondary objective.

The two optional layouts were developed to accomplish the primary objective, while taking into account previously experienced limitations of the productivity of Zone 3 and the tendency of well yields to degrade with time. Two optional layouts were prepared, because of uncertainty in the applicability of empirical information about these limitations to the vicinity of the proposed wells.

The less extensive of the options includes three wells aligned parallel to the estimated piezometric potential line approximately 60 feet down-gradient of well NBL-1. These three pumping wells are provisionally identified as NW-1, NW-2, and NW-3. The array spans a distance of 322 feet (at 161 feet spacing) perpendicular to the estimated current direction of groundwater flow. The predicted piezometric surface configuration from pumping these wells for 15 months is shown in Figure 1 and for 27 months in Figures 2 and 2B. Both predictions were based on the conservative assumption that the initial yield from the wells would be 1 gallon per minute (gpm). It was also assumed that the yield would degrade with time at the same rate as that experienced from the onset of pumping in nearby well PB-2. The scenarios shown in Figures 1 and 2 also incorporate continued pumping from well PB-2, as well as RW-A, RW-11, and RW-16. The rates of pumping from each of those wells were projected to degrade at rates derived from empirical data (discussed below). The coordinates of wells NW-1 through NW-3 are listed in Table 1.

The configurations of the predicted piezometric surfaces shown in Figures 1 and 2 show evidence of the influence of the pumped wells. However, these configurations do not lead to the conclusion that complete capture (between the wells of the array) is certain. The water level drawdown predicted in the near vicinity of the pumped wells is approximately 9 feet or about 40 percent of the estimated saturated thickness of Zone 3 in this vicinity during October 2007. Approximately 5 feet of drawdown is predicted midway between the hypothetical wells. This may be enough to indicate the possibility of continuous hydraulic capture between the wells of the array.

Analogous predictions based on a five-well hypothetical array are shown in Figures 3 and 3B. The projected piezometric surface configurations for the five-well array lead to an unambiguous prediction of complete capture between the wells of the array. The only change from the three-well scenarios is the addition of two wells, each initially yielding 1 gpm. The locations of the two additional hypothetical wells are designed to "fill" the gaps between the three wells of the prior scenario, but are offset to the up-gradient side of those wells (NW-4 and NW-5 in Table 1). This was done to reduce the tendency for overdraft of the available drawdown and to effect a greater inflection of the piezometric surface in the up-gradient direction. This increases the breadth of flow that is redirected into the combined capture zone of the wells. However, the predicted drawdown in the vicinity of the pumped wells increases in this scenario, such that the saturated thickness remaining is predicted to be as little as six feet. With the likelihood of well inefficiencies such a drawdown outside the well may portend more rapid than assumed degradations of well yields. Therefore, the 5-well array may represent the closest practical limit of pumped well spacing.

It is worth noting that the contributions of wells RW-11, RW-16, and RW-A to the predicted piezometric surface configurations in the area of the proposed well arrays are not substantial. The pumping of PB-2 has a greater influence, the absence of which could be simulated if desired.

Pilot testing is probably the best available method to determine which of the two alternatives may be better in practice. If the five wells were installed, then the two up-gradient wells could be employed for water level monitoring as the three down-gradient wells are pumped for a period of several months. Data collected from the pilot pumping could be used to determine whether it is advisable then, or at some future time, to expand the pumping regime to all five wells.

Hydrogeologic Analysis

The recommendations made in the previous section are based on various predictions of future pumping at existing wells (e.g. PB-2, RW-11, RW-A, and RW-16) and at hypothetical wells located further down-gradient in the vicinity of Well NBL-1. The predictions were made with a computer program based on analytical functions (an analytical model). The analytical functions account for several characteristics of Zone 3, including that it is unconfined, bounded on the east, has an inclined water table, and will be pumped from multiple locations at time-variable rates. The accuracy of these predictions depend on knowledge of constituent properties (e.g. hydraulic conductivity), boundary conditions (e.g. the eastern limit of saturation), the distribution of saturated thickness and its time-dependence on natural drainage as well as pumping, the slope of the water table, and future rates of yield degradation at pumped wells.

The primary purpose of the hydrologic analyses was to develop the best possible input data for the analytical model. These analyses were for the most part empirical, based on measurements of water levels in monitoring wells (2000-2008), well pumping rates (2005-2008), and aquifer test data developed in the Phase I Full Scale Hydraulic Fracturing Report (MACTEC, Final Report, Phase I Full Scale Hydraulic Fracturing, June 2006) and in In-Situ Alkalinity Stabilization Pilot Study (ARCADIS BBL, June 2007). While the input data were empirically derived the analytical model is based on a well function for sloping unconfined aquifers derived by Hantush (Hydraulics of Wells, in Advances in Hydroscience, vol. 1, p. 368, Academic Press, 1964). Image wells were used to simulate a no-flow boundary at the eastern limit of Zone 3 saturation. Superposition, involving multiple well pumping stress and recovery periods, was used to simulate pumping rates that degrade steadily through time.

The analyses begin with a mapping of the base of the Zone 3 hydrostratigraphic unit. The mapping of structure contours on the base of Zone 3, shown in Figure 4, is based on interpretations of drilling logs at the control points shown in the figure. Estimates of saturated thickness were made by subtracting the Zone 3 base elevations from piezometric surface elevations. The Zone 3 piezometric surface elevations are estimated from quarterly measurements of well water levels. These measurements are the bases of maps presented in annual reports (most recently in N.A. Water Systems, January 2008). They were also the basis for estimates of groundwater flux, pumping drawdown, and gravity drainage made for this report.

Plots of saturated thickness as a function of time are shown for two sets of Zone 3 wells in Figures 5 and 6. The plots show data from wells identified by their proximity to Zone 3 wells (distinguished by a RW prefix) that were pumped regularly after January 10, 2005. The data span the period from June 2000 through October 2007. June 2000 was selected as a starting time for analysis of drainage, because this was when the former Zone 3 pumping system was shut down. The shutdown was followed by an approximate two-year period of modest water level changes (either recovery or lowering) at most wells. Progressive reduction of saturated thickness began in or about April 2002 at most wells. The reduction of saturated thickness prior to January 2005 is interpreted to represent gravity drainage, promoted by the inclination of Zone 3.

Trend lines were fit to the pre-pumping drainage data at each of the monitored wells, including those not shown in Figures 5 and 6. The fitted trends were used to estimate the rate of gravity drainage throughout the monitored area of Zone 3, and to project future drainage. For example, forward projections of these trends were used to estimate water level drawdown attributable to the pumping after January 2005. Drawdown was estimated by subtracting measured saturated thicknesses from those projected on the basis of pre-pumping drainage rates. The purpose in doing this is to quantify the fluxes of groundwater induced independently by gravity drainage and pumping.

Figure 7 is a contour map showing the estimated piezometric surface in Zone 3 prior to the initiation of sustained pumping in January 2005. Hydraulic gradient vectors plotted on the same map illustrate the directions of gravity drainage. The theory of groundwater flow predicts that in a uniform, homogeneous system the direction of drainage should be dictated by the slope of that system. A comparison of Figures 4 and 7 shows that this is not the case in the northern part of Section 36, where the hydraulic gradient vectors are oblique to the structure contours on the base of Zone 3. This indicates that heterogeneities of hydraulic conductivity, historic recharge, or both factors must be responsible for the eastward rotation of hydraulic gradients relative to the structural slope in the northern part of Section 36. (There were relatively few wells in the northern part of Section 36 at the time represented in Figure 7. However, the north-northeastward convergence of impacted groundwater in Zone 3 and recent water level measurements in monitoring well NBL-2 indicate that the eastward rotation of hydraulic gradients shown in the northern part of Section 36 is probably accurate.)

Armed with empirical information on the distribution of hydraulic gradients, saturated thickness, and rates of drainage it is possible to estimate variations of the transmissive capacity (e.g. hydraulic conductivity) in Zone 3. The Darcy flow equation can be used for this purpose. The equation, written in terms of flux in one dimension, is:

$$Q = -k * i * A$$

where,

Q is the volumetric flux

k is the hydraulic conductivity

i is the hydraulic gradient, and

A is the wetted cross-sectional area

The flux and hydraulic conductivity are the principal unknowns in this equation. The hydraulic gradient and saturated thickness (the vertical dimension of A) have been empirically estimated, as illustrated in the preceding figures. The horizontal dimensions of three cross-sectional areas of flow are mapped as lines (labeled sections) in Figure 7. The lines are oriented approximately perpendicular to the hydraulic gradients (and interpreted flux directions). The two more northerly lines span a breadth of the flow system that is estimated to be equivalent to the most up-gradient line (labeled south section). The interpretation is that any groundwater flux that traverses the south section must also traverse the more northerly sections. To this flux would be added any groundwater that drains by gravity between the section lines (i.e. the change of stored groundwater).

There are relatively few wells providing drainage data south of the south section line shown in Figure 7 (not all are shown). The amount of drainage into Zone 3 from the Southwest Alluvium, if any, is also unknown. However, well test data from the In-Situ Alkalinity Stabilization Study has provided an independent estimate of the hydraulic conductivity (5 X 10^{-5} cm/s) on the western side of the south section line. (This value of hydraulic conductivity is less by an order of magnitude than that previously interpreted to be representative of Zone 3 materials. Investigation of the mineralogy of the local Zone 3 materials indicated pore clogging (by clay), which was interpreted to be a reaction product of tailings-derived acidity with native feldspar.) If this value is assumed to be applicable to the whole of the south section then it can be integrated with the saturated thickness and hydraulic gradient data to estimate the flux, Q, traversing that section line from the south. This was done by calculating the flux across 33 divisions of the 1642-foot section line using the Darcy flow equation. The calculated sum or total flux is 96.7 ft^3/day or 723 gallons per day (gpd) or 0.5 gpm (see attachment for calculation details). This flux must pass through each of the more northerly lines. To that flux would be added groundwater derived by gravity drainage.

Gravity drainage rates were estimated for each of the monitoring wells (e.g. as shown in Figures 5 and 6). The map distribution of those rates is shown in Figure 8. There is a clear pattern of increasing drainage rates from southeast to northwest. This trend is attributable in part to increases of saturated thickness. However, normalizing the drainage by dividing by saturated thickness does not entirely remove this trend. It is likely that hydraulic conductivity (the other factor of transmissive capacity) also increases in the western areas of Zone 3, where it has not been degraded by reactions with tailings impacted groundwater.

Drainage volumes can be calculated by factoring the rates shown in Figure 8 over time. However, the porosity of the Zone 3 materials must be factored in the calculation of the volume of water drained. An estimate of this porosity was made by comparing the known volume of water pumped from Zone 3 wells with the volume of Zone 3 estimated to have been dewatered by pumping (independently of contemporaneous gravity drainage). Estimates of water level drawdown from pumping were made for each of the wells monitored between January 2005 and January 2006. The map distribution of these estimates is shown in Figure 9. The total volume of dewatering calculated from the combined cone of depression (using Surfer, Version 8, Golden Software) is 7,780,500 ft^3 and the volume of groundwater pumped from wells during the same period was measured to be 457,433 ft^3. Dividing the volume of water by the estimated volume of pumping drawdown gives an estimate of porosity of 5.9 percent, which is applicable as an average over the area affected by pumping (see attachment for calculation details). This estimate is slightly lower than the estimate of 8 percent derived by MACTEC (June, 2006). Although they used a similar method, they calculated drawdown over a shorter period and did not account for contemporaneous gravity drainage.

Estimates of the rates of change of groundwater storage applicable to the period prior to January 2005 were made for the areas between the section lines shown in Figures 7 and 8. For the area between the south and mid-section lines the calculated rate of storage change is -153 ft^3/day and that between the mid- and NBL-section lines is -262 ft^3/day. An estimate was also made for the area between the south section line and the southern subsurface limit of Zone 3. This estimate, which is based on limited well information, is 133 ft^3/day or about 138 percent of the 96.7 ft^3/day flux derived using the Darcy equation. This raises the possibility that most, if not all, of the flux from the south is derived from gravity drainage within Zone 3 rather than drainage across the buried part of Zone 3 beneath the Southwest Alluvium.

The Darcy flux estimate of flow across the south section line was used in calculations of the total flux across the two more northerly section lines. Those estimates, which account for the accumulations from changes of storage, are 250 ft^3/day (1.3 gpm) across the mid-section line and ***512 ft^3/day (2.7 gpm) across the 1200-ft long NBL section line. The latter estimate represents the total flux from the area of seepage impact without any pumping.*** This flux estimate, which is based on conditions in January 2005, will decrease with time, more or less proportionally to the ongoing reduction of saturated thickness.

Having estimates of the total flux across each of the section lines it is possible to integrate this with the saturated thicknesses and hydraulic gradients to estimate hydraulic conductivity. Using the Darcy equation in a process similar to that employed at the south section line (except that average hydraulic conductivity rather than flux is the unknown to be solved for) the average hydraulic conductivity is estimated to be 2.16 x 10^{-4} cm/sec at the mid section and 2.95 x 10^{-4} cm/s at the NBL section (see attachment for calculation details).

The difficulties that have been experienced extracting groundwater by pumping wells are understandable given the very low density of groundwater flux (less than 3 gpm over a breadth of more than 1200 feet) in Zone 3. Furthermore, the well yields have degraded as a result of clogging by suspended solids and precipitated solids. The combination of decreased saturated thickness and clogging at well screens is likely to have progressively reduced the efficiency of pumped wells. Empirical measures of the rates of yield degradation were made using pumping records. Those estimates are shown in Figures 10 to 13 for pumped wells that were still in service after October 2007. The roughly linear relationship of yield degradation to the log of time is characteristic of all the pumped wells, including those not shown in the figures. This is partly attributable to the typically linear relationship of pumping dewatering (and transmissivity reduction) to the log of time.

The empirical data developed by these analyses are sufficient to construct the analytical model used to predict the future configurations of piezometric surfaces and hydraulic gradients based on pumping from hypothetical well arrays. A final step was taken to test the analytical model and to provide some independent verification of the empirically derived hydraulic conductivity and porosity estimates. The same analytical model used to test hypothetical pumping scenarios was first used in an inverse solution to estimate an average transmissivity and storage parameter for the drawdown caused by historic pumping between January 2005 and January 2006.

The time-drawdown data for each monitored well was estimated using the method illustrated by Figures 5 and 6. This gave estimates of drawdown through time that are independent of contemporaneous gravity drainage. The inverse solution was formed by a simultaneous fit to all of these data using the same well function (Hantush, 1964) used for the hypothetical pumping scenario predictions. Also used were the same methods of superposition for pumping rate changes (including recovery), and image wells to represent the eastern no-flow boundary. The resulting best-fit estimates are an average transmissivity of 25.5 ft^2/day and a specific storage of 0.11.

The transmissivity value is comparable to the empirical estimates of hydraulic conductivity times saturated thickness. For example, the average hydraulic conductivity estimated for the NBL section (which is closest to the area of interest for the predictive scenarios) is 2.95 x 10^{-4} cm/s or 0.84 ft/day. Multiplying by an average saturated thickness of roughly 25 feet results in an estimated average transmissivity of 21 ft^2/day, which is remarkably similar to the model-derived estimate. The specific storage of 0.11

or 11 percent is 1.86 times the empirically derived estimate of 5.9 percent porosity, but closer to the specific storage of 8 percent reported by MACTEC (also based on pumping test data). The best-fit hydraulic properties derived using the analytical model, and described here, were also used for the predictive models. This was done in recognition that the analytical model, while constructed to be as accurate as feasible, is an approximation. Therefore, the hydraulic properties that make the output of the model fit best to empirical data are also likely to make the most accurate predictions. On the other hand, the empirically derived hydraulic conductivities and porosity are likely to be the more accurate measures of those properties. The differences of the estimates are extremely small given the uncertainties inherent in applying such analyses to a flow system that deviates significantly from "textbook" assumptions.

Closing

UNC has selected the five-well option (described earlier) and is planning on drilling the wells during May or June 2008. Water-level data collected during the first several months of pilot pumping will be used to determine whether it is advisable then, or at some future time, to expand the pumping regime to all five wells. To keep to an aggressive schedule, UNC seeks your concurrence to proceed at your earliest possible convenience.

If you have any questions please do not hesitate to contact me (814-231-2170 x 236) or James Ewart (412-809-6719).

Very Truly Yours,

Mark D. Jancin, PG
Project Manager

James A. Ewart, PhD, PG
Technical Consultant

Attachments

MDJ: dll-2091

cc: Earle Dixon, NMED
David Mayerson, NMED
Diane Malone, Navajo Nation EPA
Roy Blickwedel, GE
Larry Bush, UNC

TABLE 1

Locations of Hypothetical Wells Used for Zone 3 Pumping Scenarios

Well ID	X-coordinate (feet)	Y-coordinate (feet)	Distance from NBL-1 (feet)	Direction Azimuth (degrees)*	Estimated Depth (ft bgs)
NW-1	62275	77820	160	94.8	~205
NW-2	62125	77895	62	8.5	~205
NW-3	61980	77950	179	310.6	~205
NW-4	62178	77805	68	114.6	~205
NW-5	62030	77859	90	286.6	~205

* direction based on coordinate north, not magnetic north

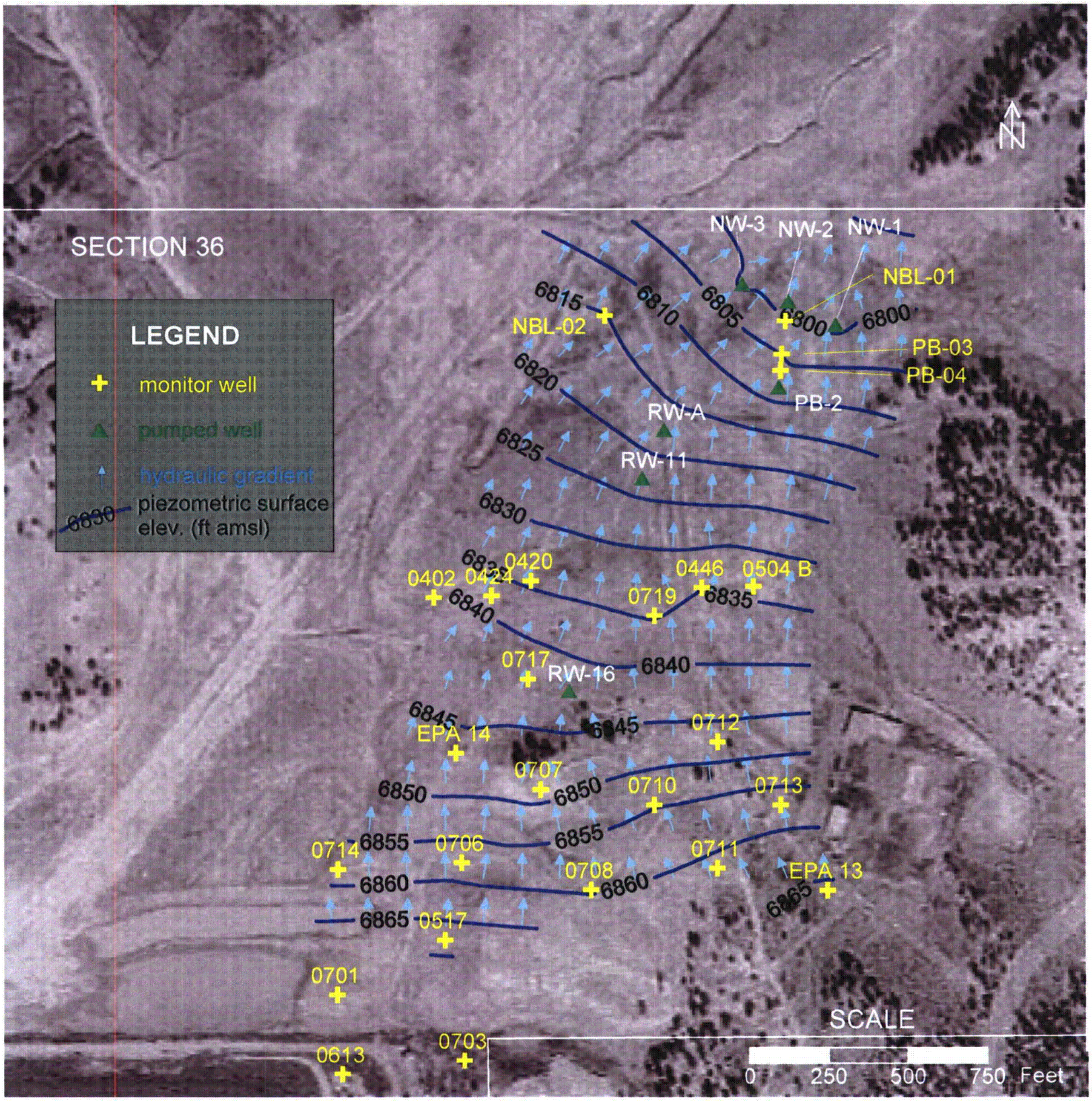

FIGURE 1
Piezometric surface elevations in Zone 3, projected to October 10, 2009, based on continued pumping of PB-2, RW-11, RW-16, and RW-A with degrading rates, addition of 3 hypothetical wells NW-1 through 3, each intitially at 1 gpm starting June 30, 2008

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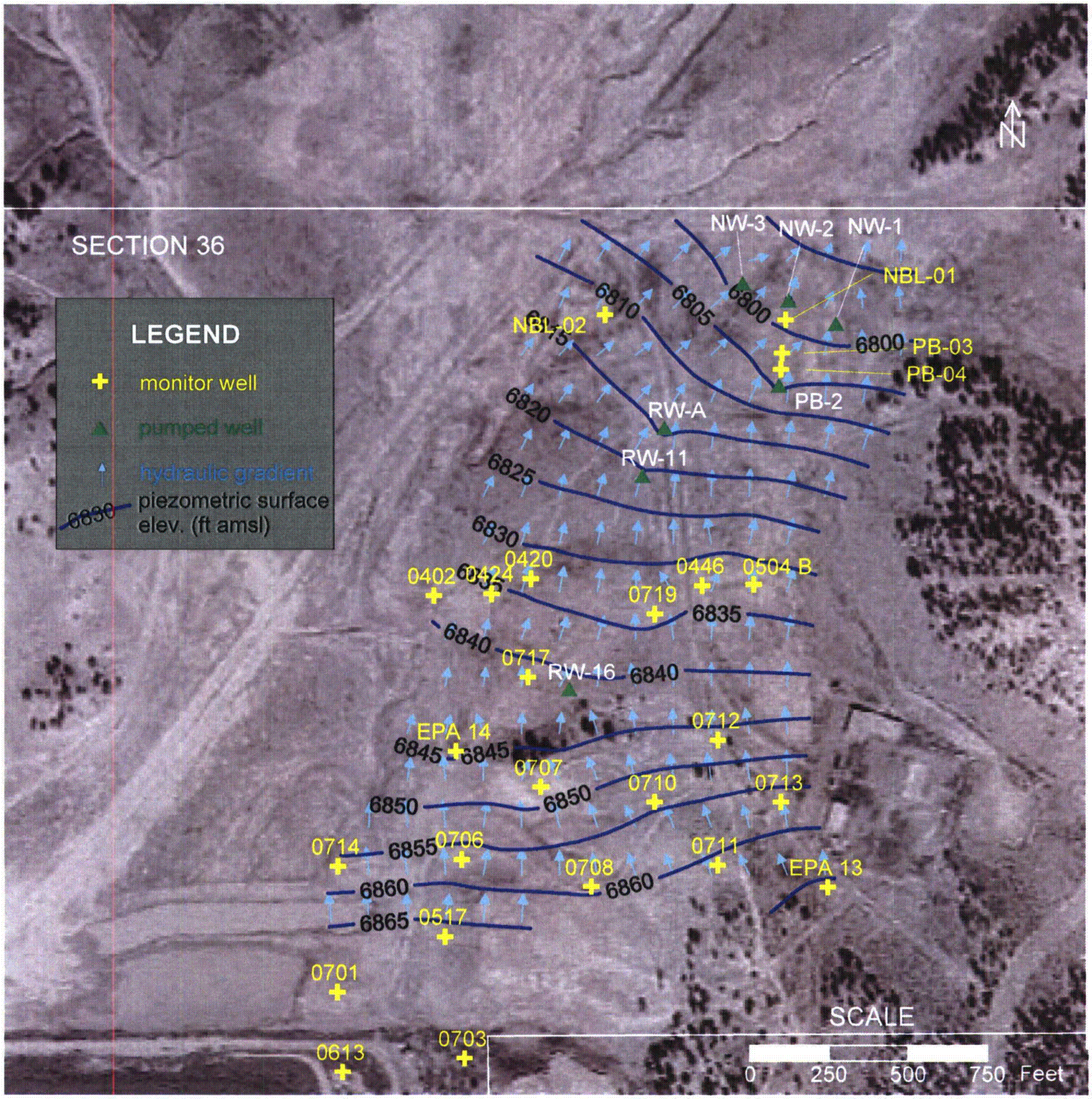

FIGURE 2
Piezometric surface elevations in Zone 3, projected to October 10, 2010, based on continued pumping of PB-2, RW-11, RW-16, and RW-A with degrading rates, addition of 3 hypothetical wells NW-1 through 3, each intitially at 1 gpm starting June 30, 2008

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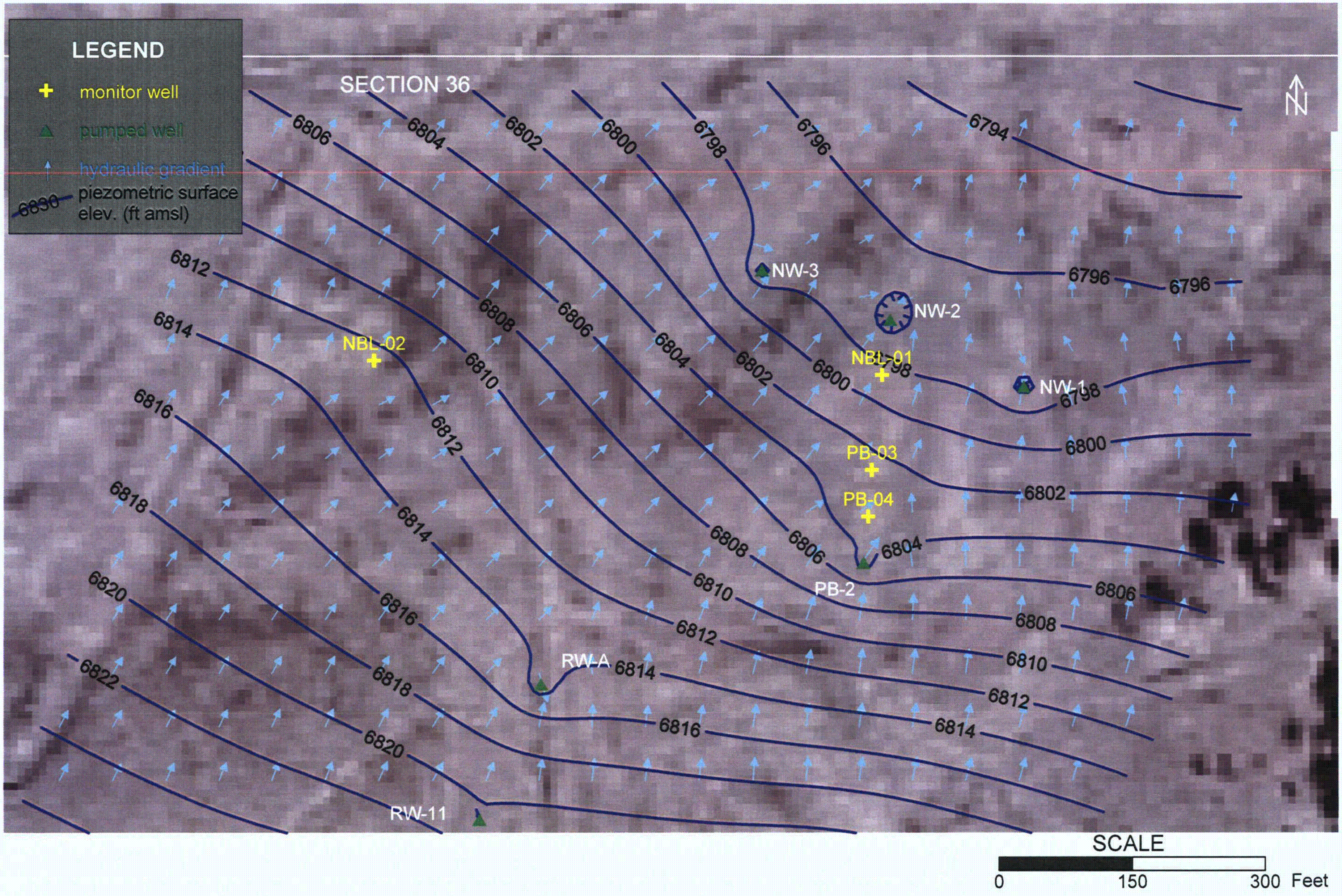

FIGURE 2B

Detail of piezometric surface elevations in Zone 3, projected to October 10, 2010, based on continued pumping of PB-2, RW-11, RW-16, and RW-A with degrading rates, addition of 3 hypothetical wells NW-1 through 3, each intitially at 1 gpm starting June 30, 2008

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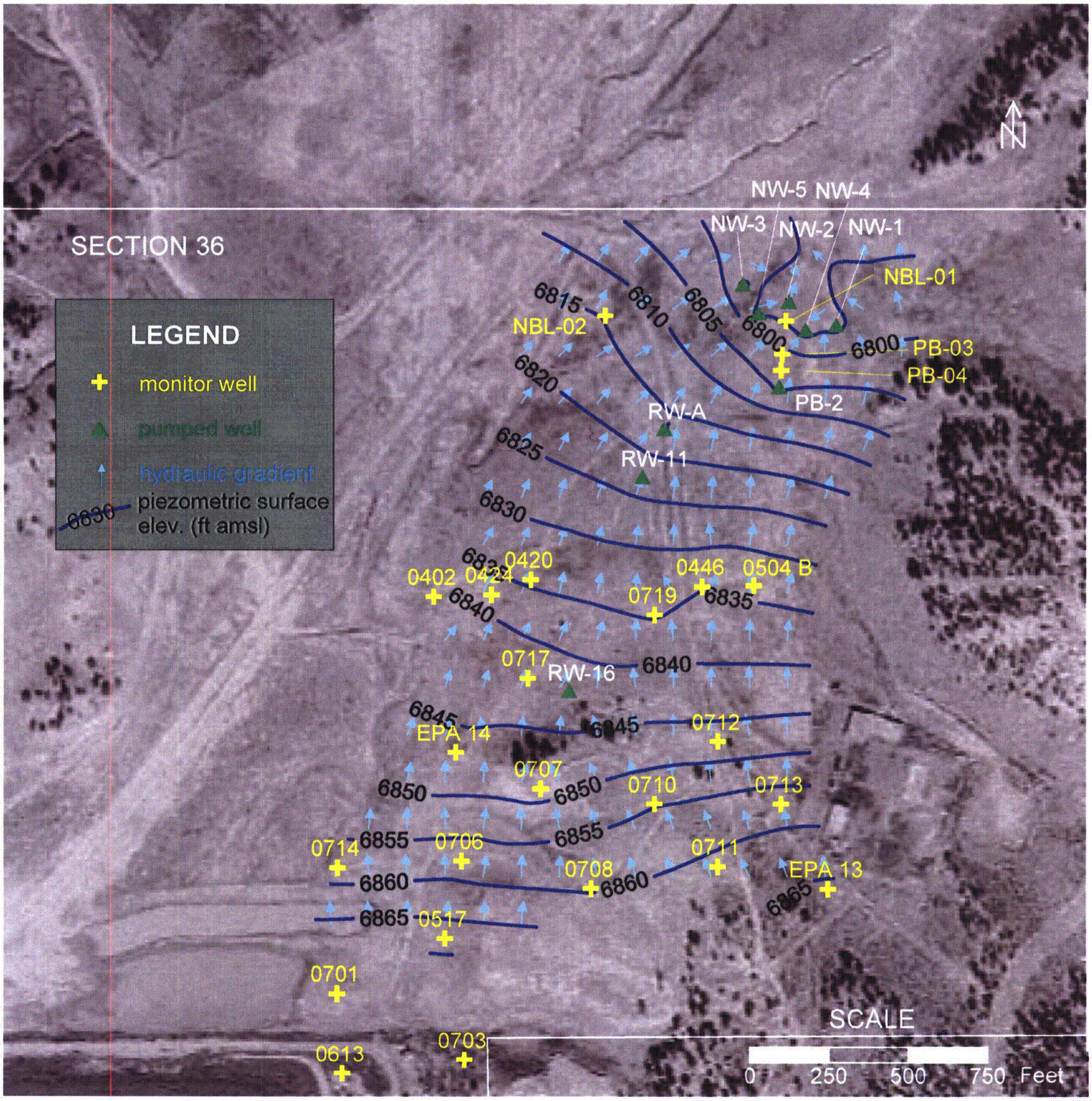

FIGURE 3
Piezometric surface elevations in Zone 3, projected to October 10, 2009, based on continued pumping of PB-2, RW-11, RW-16, and RW-A with degrading rates, addition of 5 hypothetical wells arrayed near NBL-1, each intitially at 1 gpm starting June 30, 2008

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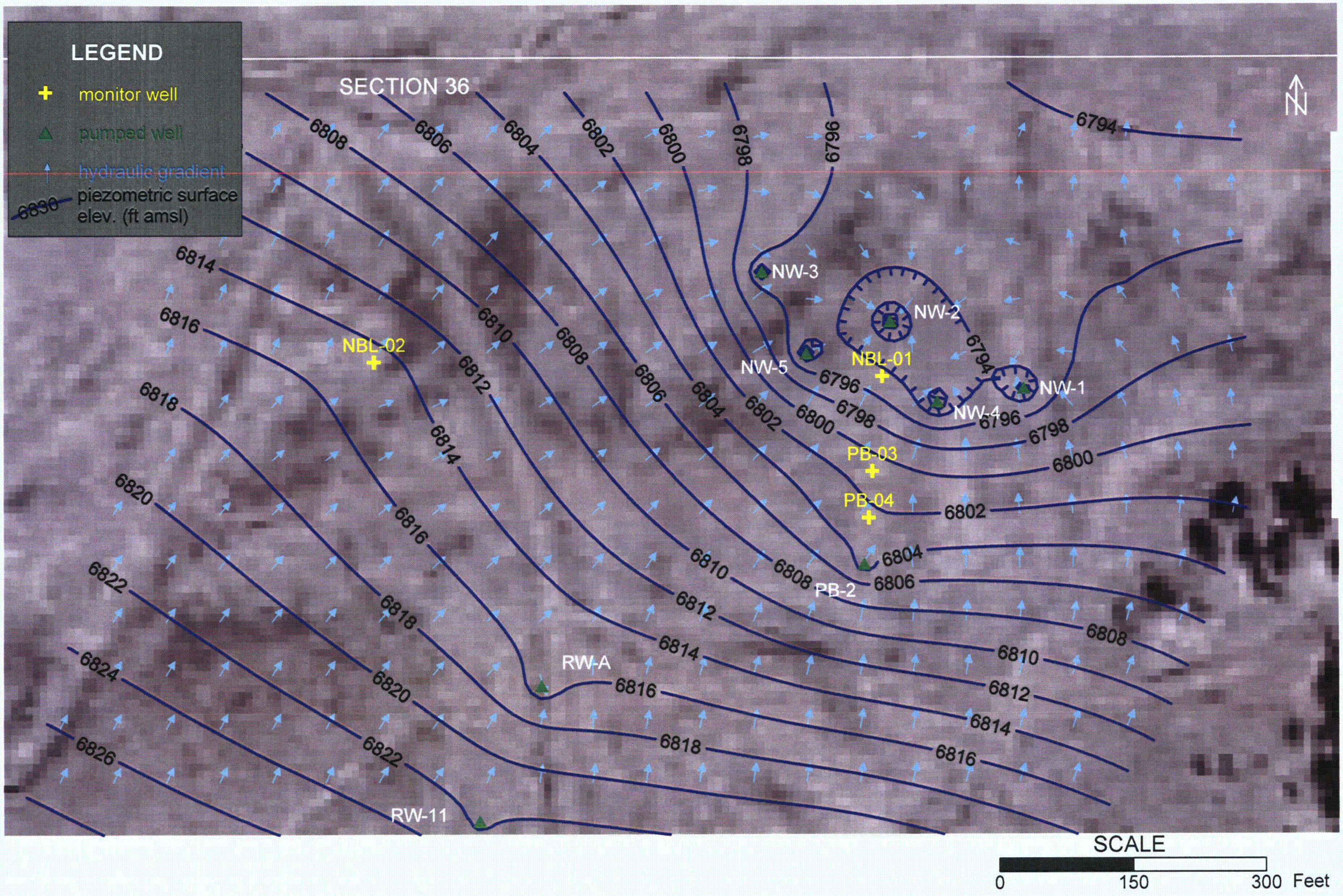

FIGURE 3B
Detail of piezometric surface elevations in Zone 3, projected to October 10, 2009, based on continued pumping of PB-2, RW-11, RW-16, and RW-A with degrading rates, addition of 5 hypothetical wells arrayed near NBL-1, each intitially at 1 gpm starting June 30, 2008

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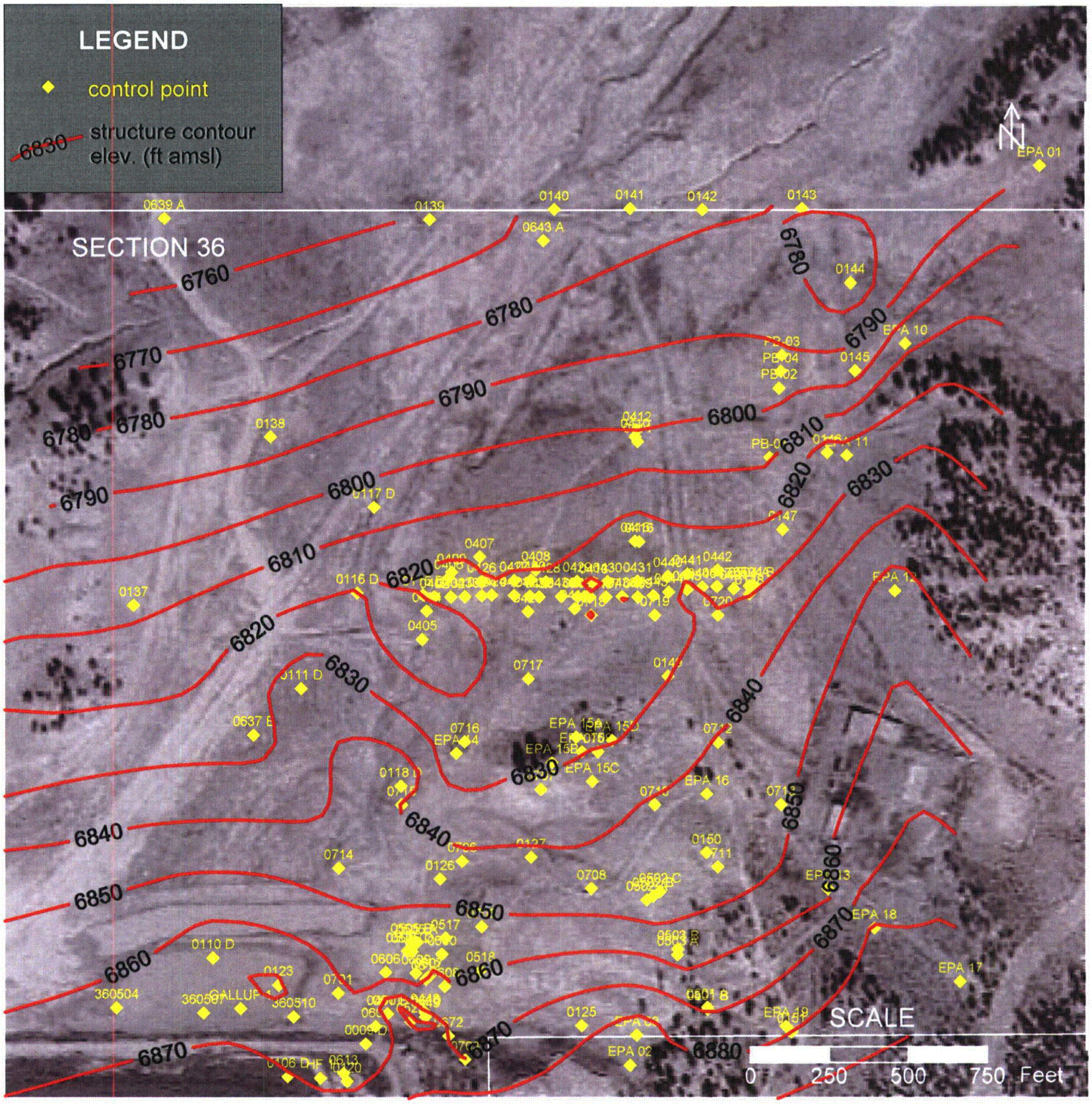

FIGURE 4
Contour map of the elevation of the base of Zone 3, control points based on drilling logs are shown by yellow symbols

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FIGURE 5
Changes of Zone 3 Saturated Thickness near Southern Frac Wells Since June 1, 2000
used to estimate pre-pumping drainage rate (April 02 - Jan 05) and pumping drawdown (Jan 05 - Jan 06)

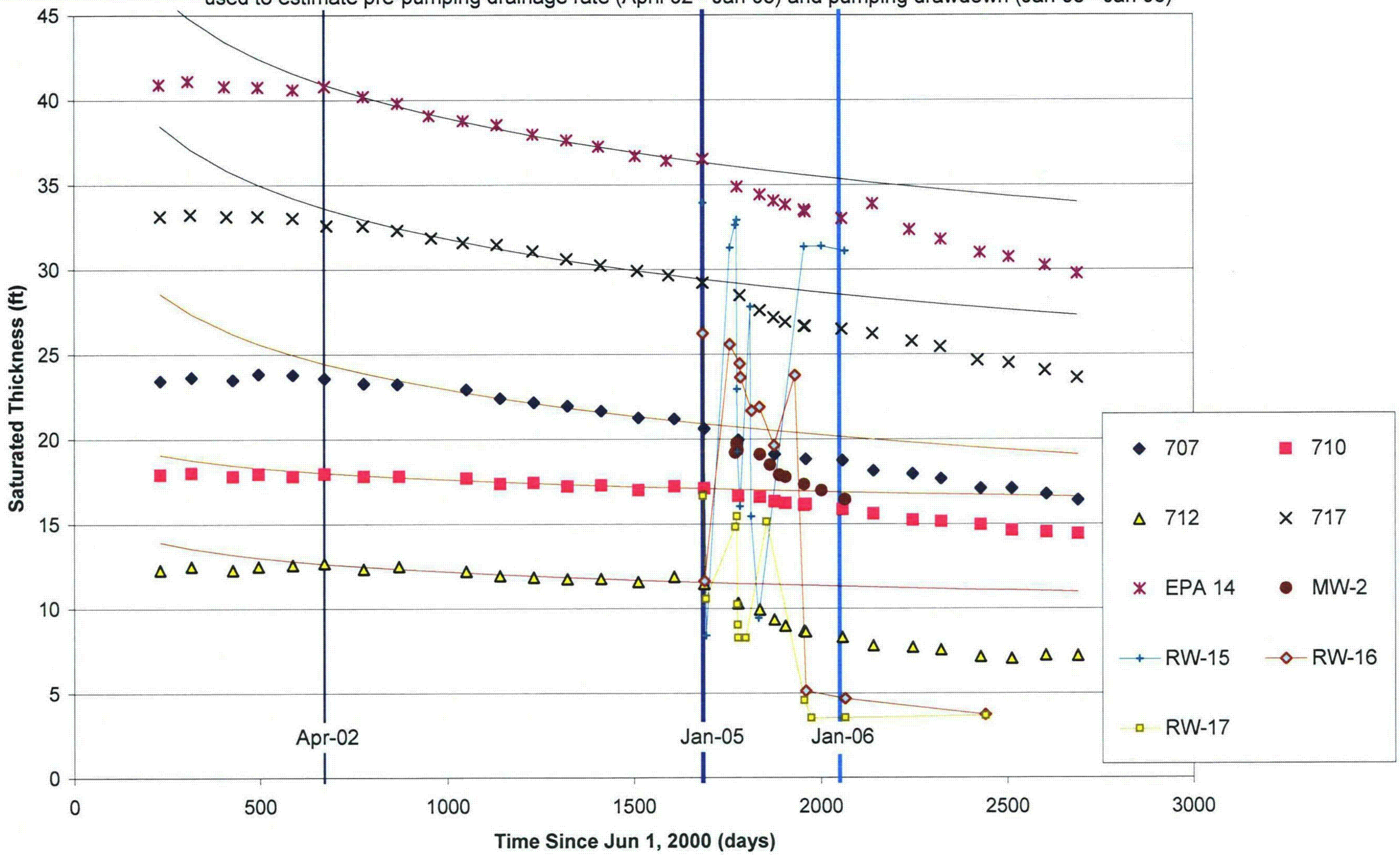
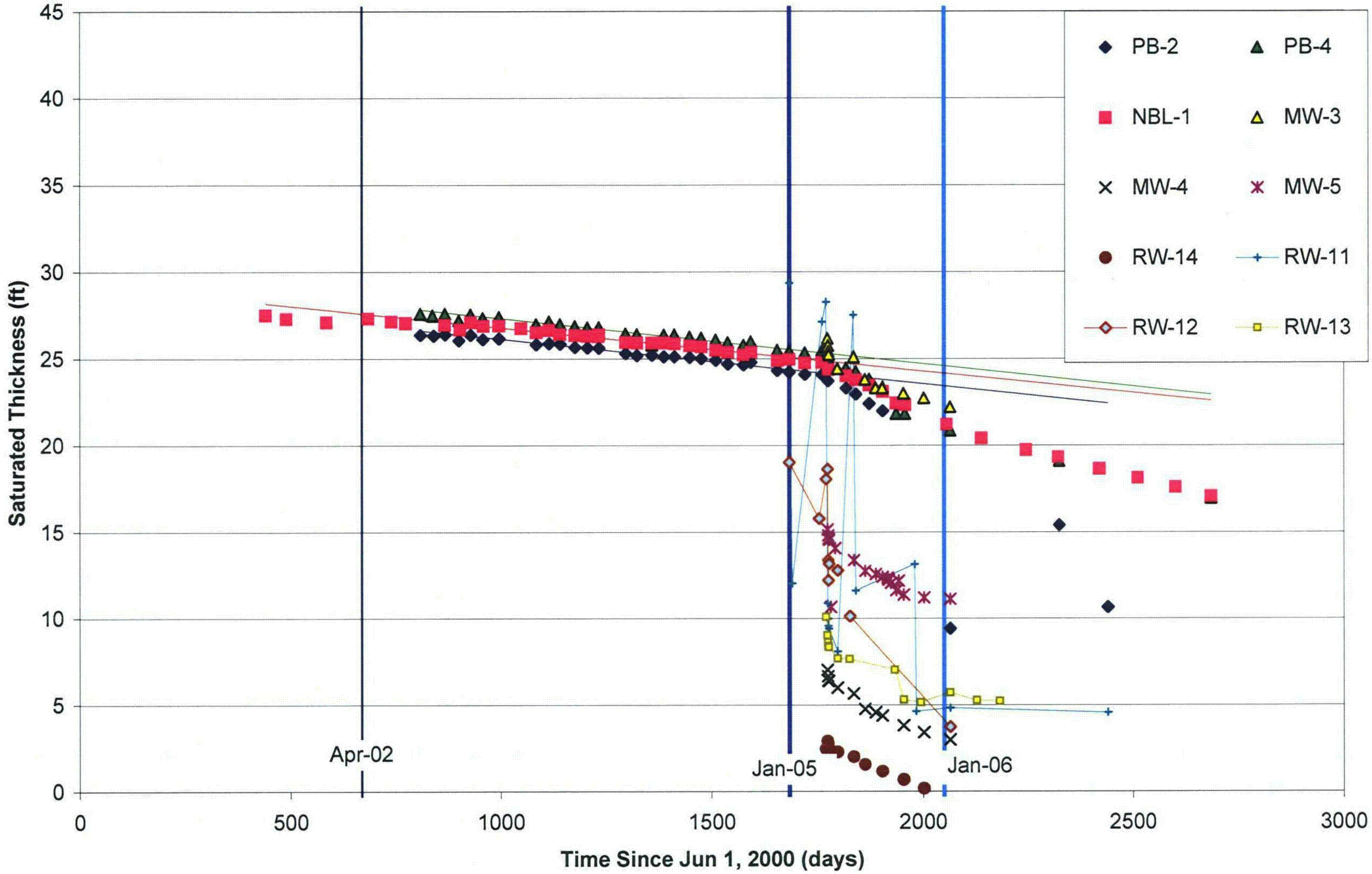


FIGURE 6

Changes of Zone 3 Saturated Thickness near Northern Pumped Wells Since June 1, 2000

used to estimate pre-pumping drainage rate (April 02 - Jan 05) and pumping drawdown (Jan 05 - Jan 06)



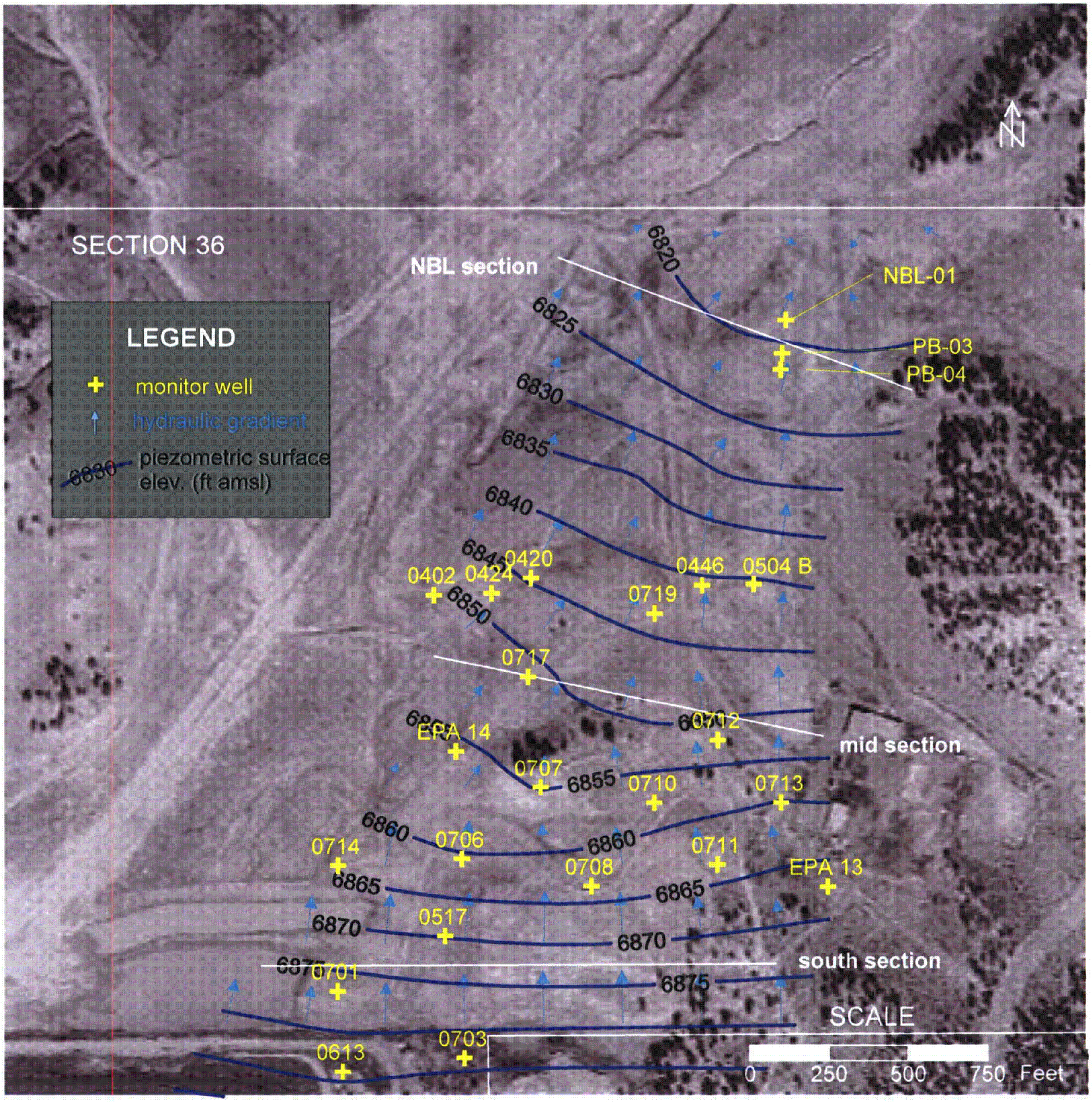


FIGURE 7
Piezometric Surface Elevations in Zone 3, based on January 2005 measurements, made prior to sustained pumping

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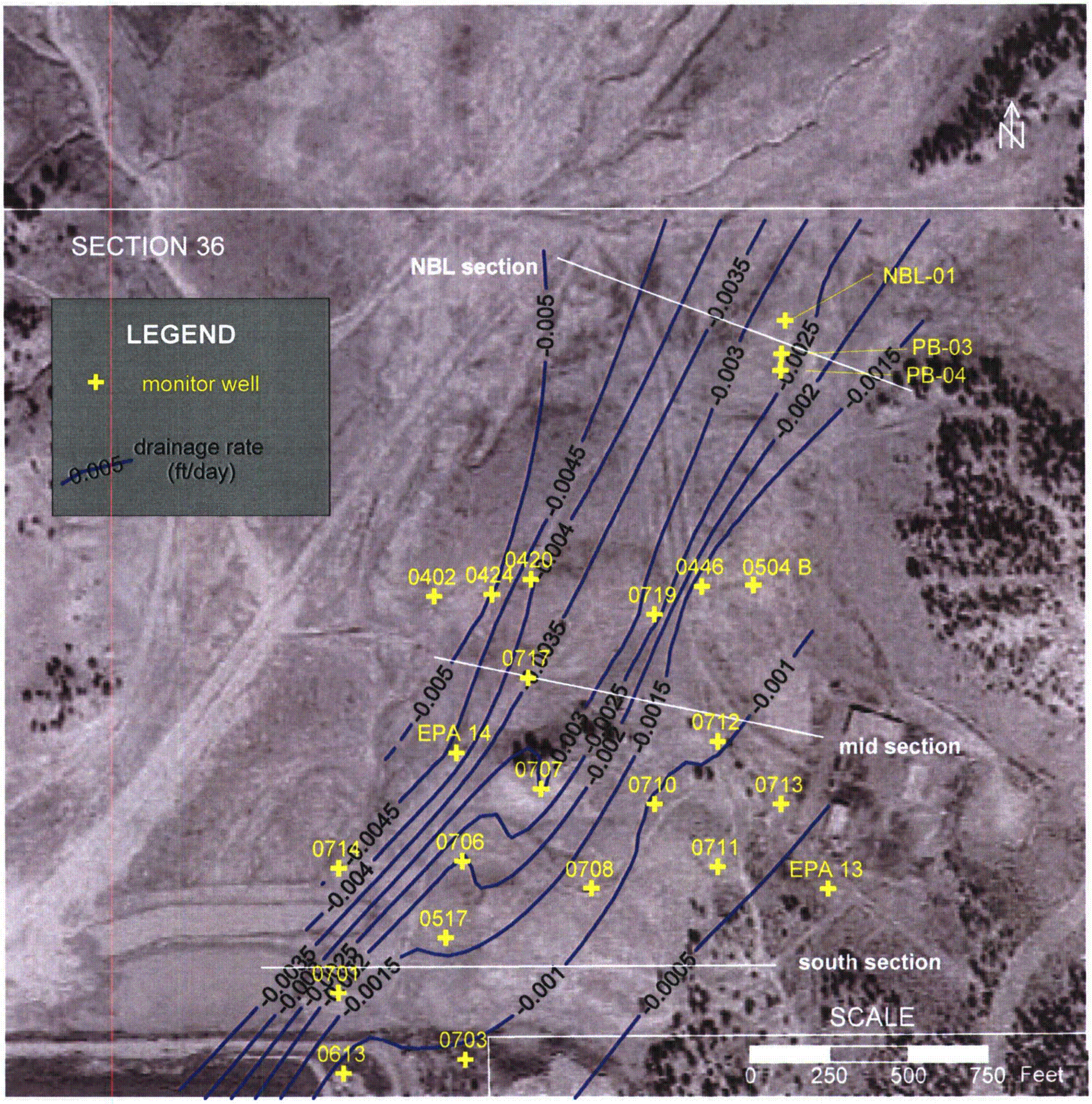

FIGURE 8
Pre-Pumping Drainage Rate in Zone 3
based on 2002-2005 measurements in (ft/day)

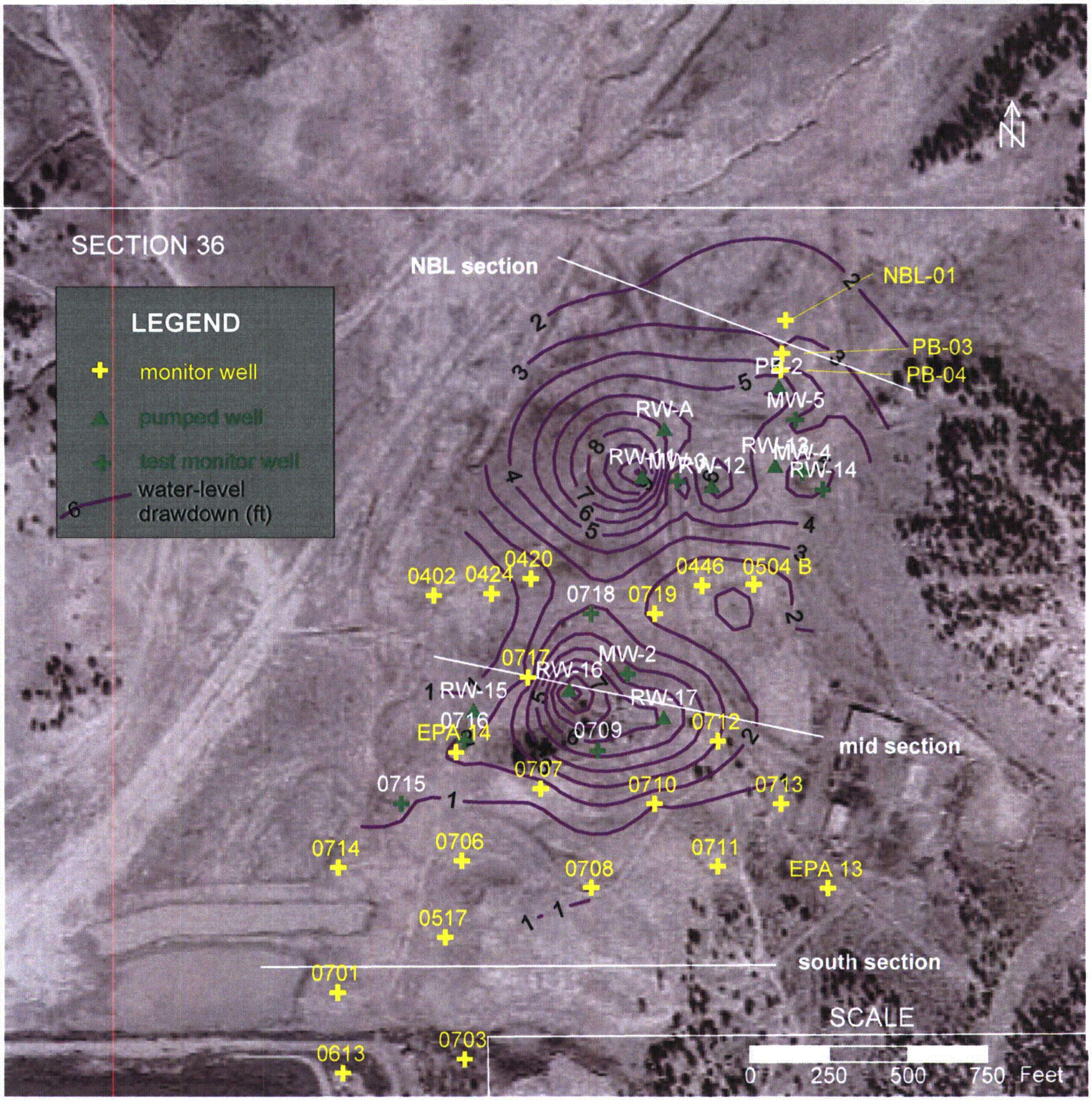

FIGURE 9
Estimated Drawdown from Pumping in Zone 3, between January 2005 and January 2006

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FIGURE 10
Empirical Fit and Projection of Pumping Rates from Well RW-11, based on monthly average pumping 2005 - 2007

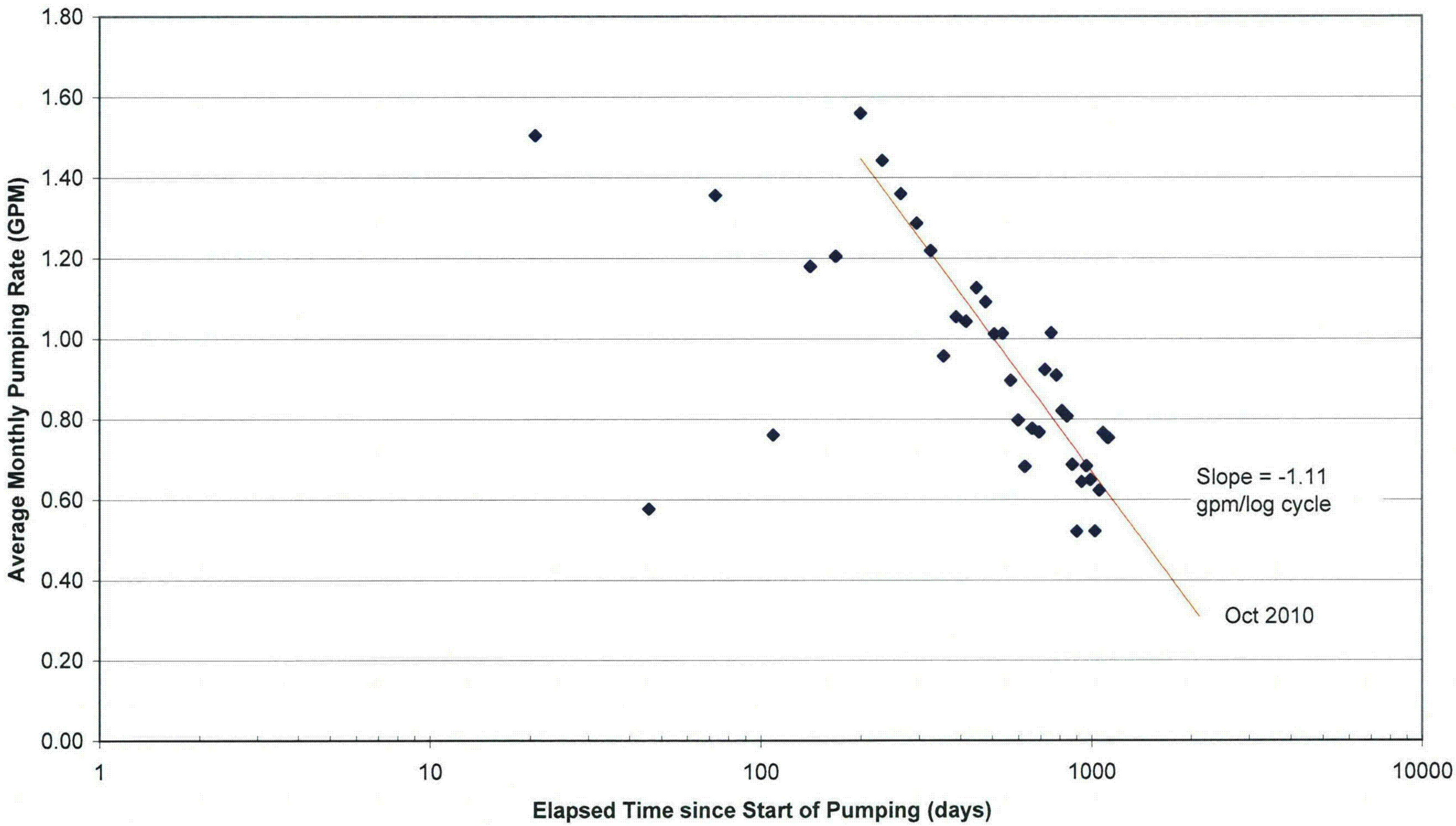


FIGURE 11
Empirical Fit and Projection of Pumping Rates from Well RW-16, based on monthly average pumping 2005 - 2007

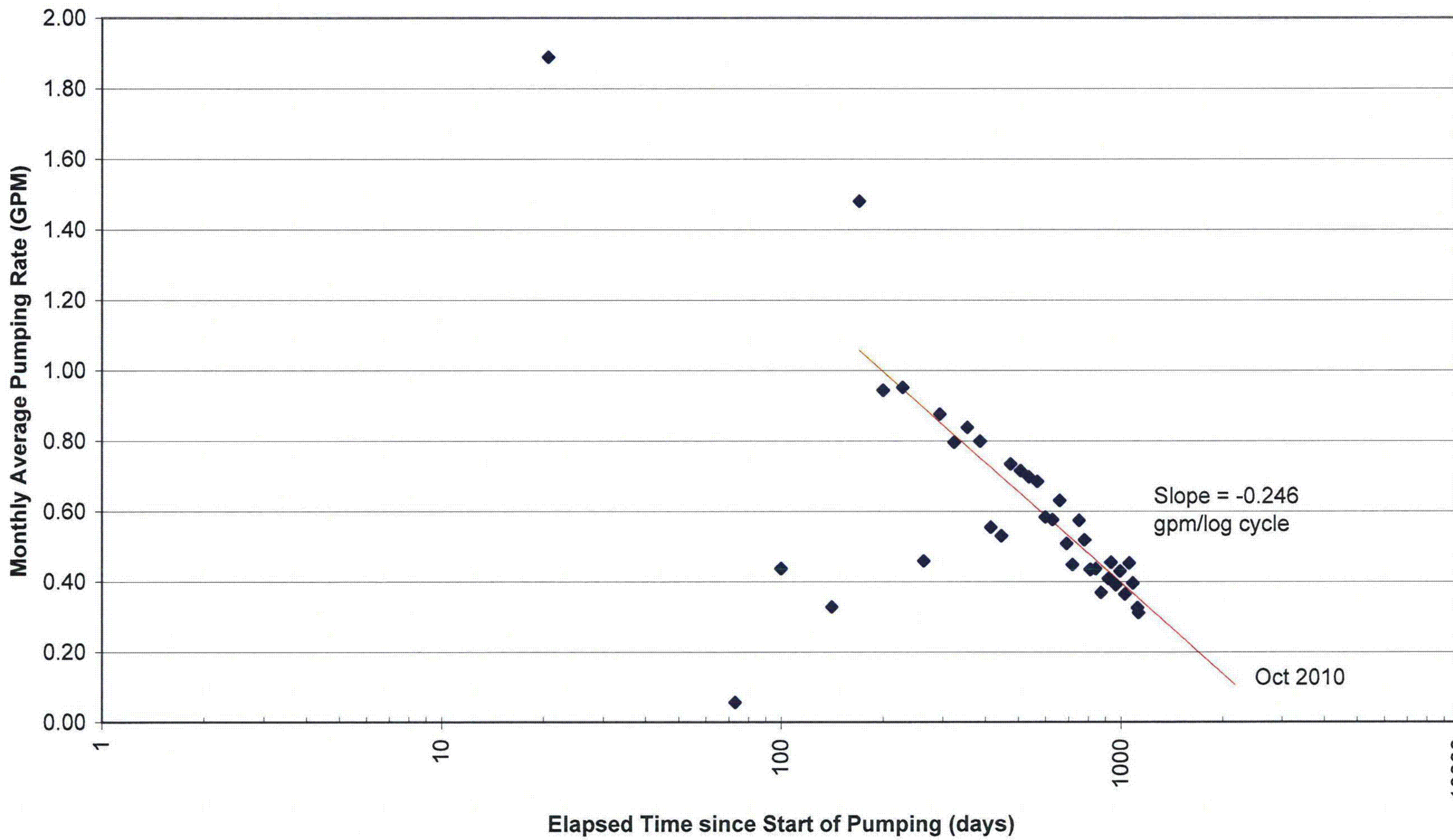


FIGURE 12
Empirical Fit and Projection of Pumping Rates from Well RW-A, based on monthly average pumping 2007-2008

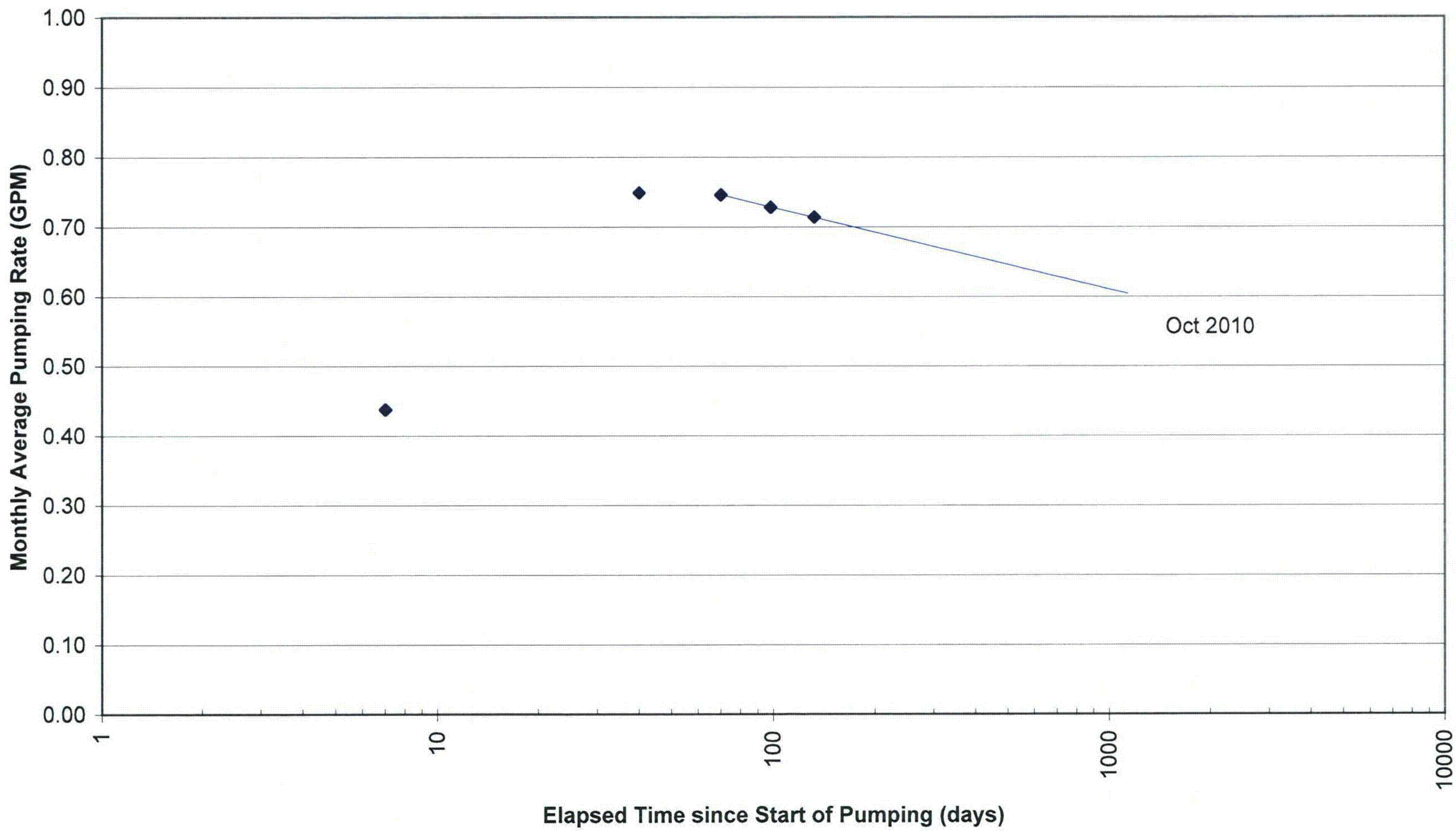
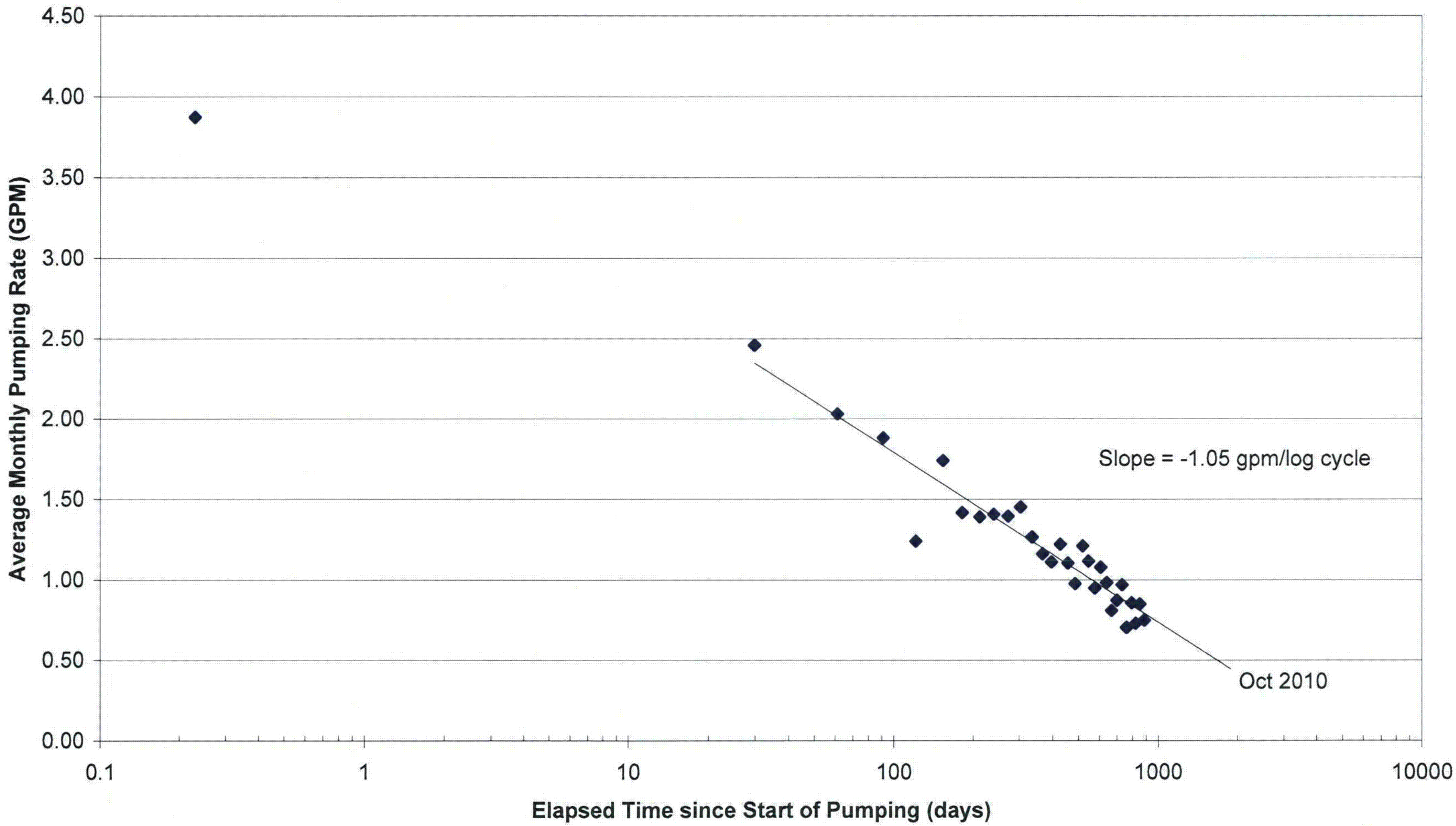


FIGURE 13
Empirical Fit and Projection of Pumping Rates from Well PB-2, based on monthly average pumping 2005 - 2007



Estimated Pre-Pumping Groundwater Flux across Three Saturated Cross Sections of Zone 3

Based on conditions measured on January 10, 2005.

Pre Pumping Drainage Rate

	Aquifer Volume	Porosity	Water Volume
southern area (south of southern section)			
	2273 ft^3/day	0.0588	133.6 ft^3/day
			1000 gal/day
mid area (between southern and mid sections)			
	2606 ft^3/day	0.0588	153.2 ft^3/day
			1,146 gal/day
north area (between mid section and NBL section)			
	4459 ft^3/day	0.0588	262.2 ft^3/day
			1,961 gal/day

Estimated Flux across Section Lines

South Section

Darcy Formula Estimate based on hydraulic conductivity of 1.42E-01 ft/day, 5.00E-05 cm/s

96.7 ft3/day
722.9 gal/day

Drainage rate estimate

133.6 ft3/day
978 gal/day

Mid Section

249.9 ft3/day
1869 gal/day

North Section

512.0 ft3/day
3830 gal/day 2.659645

Estimated Hydraulic Conductivity at Section Lines

South Section

1.42E-01 ft/day (based on well testing by BBL)
5.00E-05 cm/s

Mid Section

6.13E-01 ft/day (based on above estimated fluxes and Darcy formula)
2.16E-04 cm/s

North Section

8.37E-01 ft/day (based on above estimated fluxes and Darcy formula)
2.95E-04 cm/s

Estimation of Zone 3 Porosity from Pumping Drawdown

Time Period January 10, 2005 to January 25, 2006

Pumping Induced Drainage Volume

Estimate of volume based on pumping induced drainage

7780516 ft^3

Volume of water pumped

Well	badger #	Start Date	End Date	Start Pump (gal)	End Pump (gal)	Total Pump (gal)	Total Time (min)	Average Pumping Rate (gpm)
PB-02	32631438	8/31/05	1/25/06	0	397,167	397,167	211,050	1.9
RW-11	29660744	1/10/05	1/25/06	100,329	751,131	650,802	546,210	1.2
RW-12	29607642	1/25/05	1/25/06	0	347,265	347,265	525,480	0.7
RW-13	?	3/22/05	1/25/06	0	474,579	474,579	444,015	1.1
RW-15	29607641	1/10/05	9/27/05	0	728,068	728,068	373,380	1.9
RW-16	29607650	1/10/05	8/26/05	16	237,730	237,715	327,966	0.7
RW-16	?	9/15/05	1/25/06	641	163,304	162,663	189,120	0.9
RW-17	29607649	1/10/05	1/25/06	356	414,195	413,839	546,200	0.8
MW-5	?	4/18/05	4/28/05	89,480	98,985	9,505	14,605	0.7
Total						3,421,602 gallons		
						457,433 cubic feet		

Porosity Calculation

Volume of water pumped / Aquifer volume drained

0.058792

5.88%