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A Conceptual Model of Groundwater Flow at the Midway, Utah Fish Hatchery as Constrained by Geochemical, Physical Hydrogeological, and Geophysical Methods

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A CONCEPTUAL MODEL OF GROUNDWATER FLOW AT THE MIDWAY, UTAH FISH HATCHERY AS CONSTRAINED BY GEOCHEMICAL, PHYSICAL HYDROGEOLOGICAL, AND GEOPHYSICAL METHODS

by

Camille Durrant

A thesis submitted to the faculty of

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GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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This thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

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As chair of the candidate’s graduate committee, I have read the thesis of Camille Durrant in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

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ABSTRACT

A Conceptual Model of Groundwater Flow at the Midway, Utah Fish Hatchery as Constrained by Geochemical, Physical Hydrogeological, and Geophysical Methods

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Department of Geology

Master of Science

In addition to a loss of potential revenues from Utah's $393 million sport fishing industry, the state expends millions of dollars every year on costs associated with whirling disease mitigation and prevention. A state fish hatchery at Midway, Utah was closed when the shallow unconfined aquifer being used for fish culture by spring discharge was deemed to be contaminated by whirling disease. An alternative water source may exist in a confined aquifer below this contaminated unconfined aquifer. However, the complex hydrostratigraphy presents a challenge in determining if this source is a viable resource for fish culture. Geological, physical, chemical, geophysical, and isotopic data were combined to create a conceptual model of the groundwater flow at

the site and to determine the interactions this confined aquifer may have with the contaminated aquifer.

This model divides groundwater at the hatchery into a shallow unconfined system, an upper confined system, and a lower confined system. The shallow unconfined system is characterized by a water table ~1m below ground surface, several active springs, fast travel times, modern water mixed with ancient hydrothermal water, relatively high TDS, and relatively enriched isotopic values. The confined aquifers have a smaller hydrothermal component, relatively depleted isotopic values, lower TDS, and modern recharge components.

Two orthogonal shallow high-resolution seismic reflection profiles indicate substantial heterogeneity in the subsurface at the level of the confined systems at the hatchery. Several north-south trending normal discontinuities were interpreted as possible faults from the seismic profile oriented as a dip line, whereas the strike profile shows discontinuous layering without noticeable faulting. A well log profile for the site shows discontinuous tufa layers amid heterogeneous alluvium material. These tufa layers separate upward leaking confined aquifers from the unconfined system. It is only through the integration of several methods that such mixed systems, can be understood. In this study, the lower confined aquifer was found to be a sufficient and safe resource through the integration of numerous methods.

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TABLE OF CONTENTS

INDEX OF FIGURES

INDEX OF TABLES

APPENDICES

INTRODUCTION

During the past fifty years *Myxobolus cerebralis*, a parasite that causes whirling disease in salmonid fish, has spread so that it now infects hundreds of streams in the northeastern and western United States. Whirling disease causes deformities, and premature death in fish. Waters infected with whirling disease can effectively be considered permanently “contaminated”. Thus, the spread of *M. cerebralis* is a crucial threat to watersheds and fish hatcheries.

Utah sport fishing was estimated to be $393 million industry in 2001 (US department of Interior, 2001). Thus, the spread of whirling disease in Utah elicits great concern. In addition to lost potential revenues, the state of Utah expends millions of dollars every year on costs associated with whirling disease mitigation and prevention. Unfortunately, an increasing number of private and state owned fish hatcheries in Utah have found evidence of *M. cerebralis*. A Utah state fish hatchery in Midway, Utah was closed in 2000 due to *M. cerebralis* contamination. Midway is located in Wasatch County, ~70 km southeast of Salt Lake City, Utah (Figure 1, Figure 2). Prior to closing, the Midway fish hatchery supplied over 20% of Utah’s rainbow trout, the predominant game fish for the state (Chuck Bobo, Utah Divison of Wildlife, personal communication). Water from the hatchery was supplied by several springs, the most important of which is termed Headspring (Figure 3). In March of 2000, a small number of fish in a section of the hatchery tested positive to *M. cerebralis*. It was presumed that *M. cerebralis* was introduced via transdrainage canal water (Willis, 2002). Subsequently, the fish at the hatchery were destroyed and the hatchery was closed. In order to reopen, a water source that does not admit surface or groundwater contaminated with the *M. cerebralis* organism had to be found. Confined groundwater beneath the hatchery site is one possible source. However, the complex hydrostratigraphy of the area along with the mixing of thermal and possibly contaminated surface waters present many challenges (Carreón et al., 2003). The issue of pumping waters without causing further mixing and contamination makes the problem even more complex.

The purpose of this study is to determine if an adequate resource of clean isolated groundwater exists in a confined aquifer below the contaminated unconfined groundwater at the Midway fish hatchery. The investigation included geological, physical, chemical, geophysical, and isotopic methods to characterize the groundwater systems at the site. The study also presents a general model for approaching complex hydrostratigraphic problems involving mixing across multiple confining boundaries.

Regional Geologic Setting

Midway, Utah is in the Heber Valley, on the east side of the Wasatch Range. Heber valley is a half-graben basin (Willis and Willis 2000). It is flanked by several down-to-the-east faults on the west side, and down-to-the-south faults (Charleston-Nebo thrust fault and Deer Creek detachment fault) on the south (Willis and Willis, 2000; Baker, 1976; Bromfield et al. 1970). The Dutch Hollow fault has been mapped north of Midway (Baker, 1970; Kohler, 1979; Willis and Willis, 2000). One down-to-the-east, north-south trending normal fault has been observed by Willis and Willis (2000) ~1 km west of the hatchery (Figure 2). The precise locations of many of these faults have not been well constrained (Willis and Willis, 2000).

The Midway area is overlain predominantly by alluvium and hot spring tufa deposits. These deposits are underlain and surrounded by fractured and folded

Pennsylvanian Weber Quartzite and Mississippian to Triassic age sedimentary rocks of the Wasatch Range, mostly limestone, sandstone, and shale (Willis, 2000; Bromfield et al., 1970; Baker 1970; Hintze, 1997; Kohler, 1979). A geologic map for the study area (Figure 2) was modified from Willis and Willis (2000).

Hydrogeologic Setting

Many of the aforementioned faults are suspected conduits for thermal water. Hot springs in the area have been active for an extended period of time, as evidenced by thick layers of tufa. Tufa mounds or craters north of the hatchery mark the active surficial discharge sites for the thermal water (Willis and Willis, 2000; Baker, 1970). Carreón et al. (2003) suggests the entire Midway groundwater system is the result of mixing to varying degrees amid these isotopically depleted, high TDS, thermal spring waters and isotopically enriched, cold, surface waters.

METHODS OF STUDY

The hydrostratigraphy in the subsurface was defined by drilling 4 production wells (PW) and 6 monitoring wells (MW) (Table 1). The locations of these wells are shown in Figure 3. A series of pump tests, using observation well responses, and step tests were performed to determine aquifer and well characteristics. Water samples were collected from shallow unconfined (surface-10 m), upper confined (9-45 m), and lower confined (45-119 m) horizons. As shown below, samples from wells and springs were analyzed for solutes, stable isotopes, radioisotopes, and chlorofluorocarbons. The subsurface was further defined through P-wave seismic surveys. Dye and Bacteria tracer tests demonstrated the mechanisms by which waters flow in the shallow unconfined aquifer.

Aquifer Performance Test Methods and Analysis

Step-drawdown tests were run on PW-2 and PW-3 by the methods described in Batu (1998), Sanders (1998), and Driscoll, (1986). Step-drawdown tests were not run on PW-1 due to limitations associated with fish culture at the hatchery. Another goal of the step tests was to determine the discharge that can be maintained by each pumping well in order to keep drawdown above a confining layer at 10 m. This 10 m criterion will ensure upward pressure gradients are maintained and contaminated surface waters will not leak into the confined aquifer, as discussed below.

Constant rate pumping tests were run on PW-1, PW-2 and PW-3, using pumping well and monitoring well water level data, to estimate aquifer transmissivity and storativity values and identify boundary conditions. Pumping rates were adjusted to maintain the 10 m criterion. Observation well responses were analyzed using the methods of Theis (1935), Lohman (1993), Batu (1998), and Driscoll (1986) and with the testing package Aquifer Test Pro 3.5. ArcGIS 9 ArcMap was used to plot radii to apparent boundaries.

Chemistry

Water quality and isotopic data from Carreón et al. (2003) was supplemented with additional water samples collected from springs and wells at the hatchery. An error in charge balance of $\leq$5% was considered acceptable.

Stable Isotopes

Water samples were analyzed for stable isotopes δD_{VSMOW}, and $\delta^{18}O_{VSMOW}$, and HCO_3 was analyzed for $\delta^{13}C_{PDB}$ using a Finnigan Delta^{plus} isotope ratio mass spectrometer equipped with a GasbenchII and HDevice using methods similar to Carreón (2000). δD_{VSMOW} and $\delta^{18}O_{VSMOW}$ were measured against calibrated laboratory standards as described in Nelson (2000) and Nelson and Dettman (2001). Reproducibility was determined by replicate internal laboratory standard analysis. Values of uncertainty were <1‰ for δD_{VSMOW} and <0.21‰ for $\delta^{18}O_{VSMOW}$.

Radioisotopes

Water was analyzed for ^{14}C by first precipitating bicarbonate in the form of $BaCO_3$. This was then synthesized to benzene after the methods of Noakes (1963). Beta decays were then counted with a PerkinElmer Quantalus Liquid Scintillation Counter (LSC) 1220 and converted into percent modern carbon (pmc). This process is similar to the methods described in Clark and Fritz (1997), Polach and Stipp (1967) and Stuvier and Polach (1977). Water was analyzed for tritium also using a PerkinElmer Quantalus Liquid Scintillation Counter (LSC) 1220. Samples were prepared and enriched similar to the University of Waterloo Environmental Isotope Laboratory method (EIL, 1998).

Chlorofluorocarbons

Chlorofluorocarbon (CFC) samples were collected in accordance to the USGS Reston Chlorofluorocarbon Laboratory new CFC bottle sampling method (USGS, 2003) at PW-3, MW-1, and Headspring (Figure 3). Chlorofluorocarbon samples were analyzed at the University of Miami RSMAS tritium laboratory as described in RSMAS (2003) and Warner et al. (1985).

Geophysical Methods

The common depth point (cdp) seismic reflection technique was used to characterize the subsurface stratigraphy and help identify faults. Two primary wave (P-wave) surveys were performed at the hatchery. Field recording was performed using a geometrics NZ-II and Geode seismograph system. Line 1, approximately 270 m long, was surveyed along a line on the north-south hatchery road (Figure 3). The source was produced by striking a 7 kg sledge hammer against a metal plate. This was field stacked three times and recorded by 24 28-Hz geophones spaced 3.05 m apart to provide a 12-fold cover.

Line 2, approximately 370 m long, was located along the shoulder of the east-west road, north of the hatchery (Figure 3). The P-wave source was produced with a 45 kg accelerated weight drop. This was field stacked two times and recorded on 28-Hz geophones at 3.05 m intervals. Each shot was recorded by 72 geophones to provide a nominal fold of 36. The data were processed using Landmark Graphics, Inc. ProMAX2D™ software. The data processing followed a routine series of steps including geometry assignment, noisy trace editing, static correction, velocity analysis, normal move-out correction, first-break trace muting, cdp stacking, deconvolution, and random noise suppression.

Tracer Test Methods

As partially reported in Carreón et al. (2003) and McIntosh (2002), dye and bacteria tracer tests were conducted at Midway fish hatchery. Rhodamine WT (RWT) dye was injected into Fox Den, a sinkhole feature in the tufa platform ~800 m northeast of Headspring. Fluorescein dye was injected into irrigation water being used to flood irrigate a pasture adjacent to Fox Den. Dye was accumulated on charcoal packets at the Hatchery. Dye concentrations were measured at Ozark Underground Laboratory in Protem, Missouri, and were averaged over the time interval each charcoal packet was in place.

In conjunction with one round of dye, cultured bacteria (DA-001 and OY-107) were simultaneously introduced as particulate tracers. DA-001 was injected into Fox Den, whereas OY-107 was injected into the irrigation water with the fluorescein dye. Ferrographic capture was used to monitor bacterial concentrations as described in McIntosh (2002). These bacteria were engineered to be a conservative tracer for *M. cerebralis* spores. DA-001 and OY-107 bacteria are an order of magnitude smaller than *M. cerebralis* spores. The bacteria also have a near neutral surface charge, to prevent sorption.

Gain-Loss Methods

Flow measurements were taken at the hatchery on a creek carrying raceway effluent to a pond south of hatchery raceways during July of 2000 (Figure 3). Measurements were done using a Flow-Mate portable flowmeter.

SITE HYDROGEOLOGY

Potentiometric gradients are upward (Table 2, Figure 4). This is consistent with increasing flows in a creek carrying raceway effluent to a pond south of hatchery raceways (Figure 3). An unconfined aquifer occurs above a first tufa layer ~10 m below the ground surface (Figure 4). The water table is ~1 m below land surface as evidenced by shallow monitoring wells, MW-4, MW-5 and MW-6 (Table 2).

The area between the first and second tufa layers is designated as the upper confined aquifer. Only MW-1 is completed in this horizon. The water level in MW-1 is typically ~0.2-1 m above ground surface (Table2, Figure 4). The area below the second tufa layer is designated as the lower confined aquifer. Wells completed in this horizon include: MW-2, MW-3, PW-1, PW-1.5, PW-2, and PW-3. This aquifer has typical head values~1-4 m above the ground surface (Table 2, Figure 4).

The two main streams that flow near the hatchery, Provo River and Snake Creek, are considered to be gaining systems as they flow by the study area (Baker, 1970). The Provo River gains as much as 50% as it flows through the study area. Similarly, Snake Creek gains flow along its course near the study area (Carreón et al., 2003).

Aquifer Tests

It is important that the pumping of wells, in the lower confined horizon, does not induce drawdown below the first tufa layer ~10 m. The 10 m criterion will ensure upward pressure gradients are maintained and contaminated waters will not leak into the confined aquifers. Step drawdown tests were performed on wells PW-2 and PW-3 to determine the maximum pumping rates that will satisfy the 10 m criterion at the pumping wells. PW-2 can pump ~5670 L/min (1500 gal/min) and PW-3 can pump ~8130 L/min (2150 gal/min) without exceeding the critical 10 m of drawdown. All three production wells (PW-1, PW-2 and PW-3) can be pumped simultaneously for a total of ~13980 L/min (3700 gal/min), without exceeding 10 m of drawdown. Drawdown within pumping wells PW-2 and PW-3 is shown for various pumping rates, up to the maximum safe rate, in Figure 7. As expected, well efficiencies decline with increased pumping rate (Figure 8).

Results of the constant rate observation well response tests are summarized in Table 3. Typical time-drawdown plots are shown if Figure 9. On average, transmissivity of the lower confined aquifer is about 5-6 x 10^3 m^2/day, and storativity averages about 3 x 10^{-4}. Distance-drawdown graphs for wells PW-2 and PW-3 are shown for various durations of time using the aforementioned safe pumping rates for PW-2 and PW-3 and a pumping rate of 3440 L/min for PW-1 (Figure 10).

Analyses of the observation well data indicate that recharge or constant head boundaries occur (Table 3). Figure 12, shows circles around the observing wells with the radii of the circle being the calculated distance from the observing well to the recharge boundary.

Geochemical Results

Average solute compositions for the groundwater systems at the hatchery are listed in Table 4. The systems include the unconfined and upper and lower confined aquifers. These are compared to Midway area streams and thermal groundwaters from Carreón (2003). Stiff diagrams for these systems show surface and upper and lower confined waters are less evolved than the unconfined aquifer and thermal groundwaters (Figure 12).

The confined aquifers and area streams are a calcium-bicarbonate type with a mean TDS of 235 mg/L for streams, 354 mg/L for the lower confined aquifer, and 511 mg/L for the upper confined aquifer (Table 4). The unconfined aquifer is a calcium-mixed anion type water with a mean TDS of 888 mg/L. The thermal waters are a sodium-sulfate type with a mean TDS of 2098 mg/L.

Stable isotopic compositions are plotted relative to the global meteoric water line after Craig (1961) in Figure 13. It is apparent that the confined aquifers are more depleted in $\delta^{18}O_{VSMOW}$ and δD_{VSMOW} than the shallow unconfined aquifer. The upper and lower confined aquifers plot with area thermal waters. The unconfined aquifer waters are more enriched than the confined and hydrothermal waters but more depleted than area stream waters.

Apparent Ages

Modeled ^{14}C mean residence ages are compared with tritium and chlorofluorocarbon apparent recharge ages in Figure 14. The shallow unconfined system has 4-9 tritium units (TU). The upper confined system at MW-1 has ~6 TU. The lower confined system has 6-9 TU. These tritium values indicate all groundwater systems have a modern (post 1951) recharge component (Clark and Fritz, 1997). Conversely, radiocarbon age (^{14}C) data suggests all systems have a component of old groundwater with the unconfined system having the oldest radiocarbon ages (Table 5).

Chlorofluorocarbon results also suggest a modern recharge component for all three systems (Figure 5). These results indicate apparent recharge ages of <20 years for the unconfined system, and between about 31 and 36 years for the confined systems (Table 6). Apparent CFC recharge ages are within a year of each other for duplicate samples. Thus, the values reported in Table 6 are the average values for samples at each site.

Tracer Test Results

Dye tracer tests showed dye, introduced ~800 m up gradient of the hatchery at Fox Den reached the hatchery within a day. The dye introduced into water flood irrigating a pasture adjacent to Fox Den took a little longer to reach the hatchery and exhibited more dilution than the Fox Den dye. Nevertheless, dye concentrations from both the pasture and Fox Den reached the hatchery within 2 days (Figure 15).

Bacteria injected in the irrigation water flood irrigating the field were not detected at the hatchery during the tests. The bacteria injected into the Fox Den were observed at the hatchery within a day, about the same time as the RWT dye (Figure 15) (McIntosh 2002). Although detected at numerous places in the unconfined system, during the 40-50 day time period of monitoring, the dye and bacteria tracers were not detected in the wells penetrating the confined aquifers (Carreón et al., 2003).

SITE GEOLOGY

A conceptual image of the subsurface was developed by analysis of the geophysical and well log data. The data indicate appreciable heterogeneity at the study site.

Well Logs

The subsurface consists of discontinuous layers of sand, gravel, cobble, tufa, and tufa cemented sediments (Figure 4). Baker (1970) characterized the tufa to be permeable and water transmissive. However, at the hatchery a 5-10 m thick tufa layer at ~10 m below ground surface separates the unconfined aquifer from underlying confined units. This tufa and tufa deeper in the subsurface provide additional confinement with depth. Although not readily apparent from well logs, due to the cable tool manner in which drilling occurred, clay present in the subsurface may be providing confinement in addition to the tufa. A second tufa layer at ~40 m may also be continuous (Figure 4). Other continuous tufa layers are not apparent from the well logs and the geophysical data. Attempts to draw cross sections from well logs throughout the greater Midway area confirm that great heterogeneity exists throughout the valley.

Geophysical

Images of the subsurface from the analysis of the P-wave surveys (Figures 4 and 5) likewise confirm subsurface heterogeneity. The north-south line 1 depicts layers and lenses thinning and pinching out and a general lack of continuity (Figure 5). The east-west line 2 shows more continuity. It shows continuous reflectors on the west end of the line (Figure 6). However, toward the middle of survey these reflectors are interrupted by discontinuities. Lines were drawn (Figure 6B) to illustrate these discontinuities, based on several criteria: (1) lateral termination of reflections mimicked by reflectors above and below, (2) abrupt changes in attitude mimicked by reflectors above and below, and/or (3) displacement/offset of reflectors at discontinuities mimicked by reflectors above and below. These discontinuities could be north-south trending faults. Thus, line 1 is perpendicular or oblique to and intersects several possible faults, whereas line 2 runs parallel to the faults thus, faults are not seen.

The apparent north-south orientation of these possible faults is consistent with geologic interpretations of faulting in the valley (Willis and Willis, 2000; Baker, 1970; Peterson, 1970). Peterson (1970) did a gravity survey of Heber and Rhodes Valleys. He noted that “the steeper gravity gradients along the west and south edges of Heber Valley may reflect faulting”. It is also possible that the discontinuities observed in line 2 represent lateral heterogeneity, due to depositional features associated with tufa and stream channels, rather than faulting.

Because a lighter hammer was used, the P-wave line 1 survey involved a higher frequency than the line 2 survey. The lower part of the line 2 suggests that the subsurface is more homogenous and continuous below ~1580 m. It is possible that the reflector at ~1535 m is indicative of bedrock, since below this depth the reflectors are more uniform, straight and consistent. Other wells or geological data that would be deep enough to be used to correlate bedrock are unavailable in the vicinity of the hatchery. Bedrock is probably not seen on the line 2 record. This may be due to some of the P-wave signal being absorbed by the road base fill material.

The vertical resolution for the seismic sections is a function of seismic velocity of the medium and the frequency of reflecting signal. Based on a velocity of 1000 m/s and a maximum frequency of 100 Hz, the Raleigh Criterion or ¼ wavelength criterion for vertical resolution is 2.5 m. Thus, small layers and lenses thinner than 2.5 m would not readily be seen in either of these lines.

DISCUSSION

A conceptual model of groundwater flow in the vicinity of Midway fish hatchery includes three groundwater systems: an unconfined system, an upper confined system, and a lower confined system (Figure 16). The hatchery area is a locus of discharge for all three systems, thus appreciable mixing occurs.

Unconfined Aquifer

At the hatchery the unconfined aquifer extends from ~1 m below the ground surface to a depth of ~10 m. At the hatchery the water table is ~1 m below ground surface. North and west of the hatchery, the unconfined aquifer occurs in an upland tufa mound (Figure 3) and is above the hatchery ground surface elevation (Figure 17). The aquifer discharges at the base of the tufa mound as evidenced by Headspring and seepage elsewhere along the base of the tufa mound. At the hatchery the aquifer occurs in tufa and coarse sand and gravel. It is bounded on the bottom by the tufa layer at ~10 m that is approximately 6-12 m thick.

During summer months of up gradient irrigation the water table rises. This water table response rapidly influences Head Spring discharge, typically within 8-12 hours of up gradient flood irrigation (Chuck Bobo, Utah DWR, personal communication). Average headspring discharge during the 1999 water year irrigation period (April-August) was ~60% greater than during non-irrigation times (Novemeber-March) (Carreón et al., 2003). Likewise, dye tracer tests showed travel times from sources ~800 m away to the hatchery within a few days. Bacteria engineered to be a conservative tracer for *M. cerebralis* showed similar results when injected into a sinkhole feature in the tufa. However, the bacteria were filtered out when the tracer was applied to a field adjacent to Fox Den via an irrigation ditch. This suggests that the fractured tufa acts like a conduit rather than a filter, and does not provide significant filtration for *M. cerebralis* or other particles.

CFC and tritium results show the unconfined water has a component of modern recharge (Figure 14). CFC-12 concentrations for Headspring waters, when using a recharge temperature of 6.8°C, exceed the current atmospheric level (are supersaturated). This could indicate Headspring waters are slightly contaminated with respect to CFC-12. Possible causes of CFC-12 contamination include sources of solvents, refrigerants, sewage treatment facilities, chlorinated water, and others (Happell, electronic comm., 2004).

Of the three hatchery aquifer systems, the shallow unconfined system has the highest TDS and is the most isotopically enriched (Table 4). This aquifer consists of a young (modern) component mixed with the old (2500-5800 yrs) thermal water described in Carreón et al. (2003). Carreón et al. (2003) also found the thermal component at

Headspring to be between 13% and 30%. This estimate is consistent with the chemistry and radiocarbon modeled ages of this study.

This hydrothermal water most likely discharges into the unconfined aquifer up gradient (north) of the hatchery, and mixes with modern surface waters and waters from the confined systems leaking upward into the unconfined system. Thus, the shallow unconfined aquifer is a mixture of the youngest and oldest water components at the hatchery.

Upper Confined Aquifer

The upper confined aquifer (~15-40 m below ground surface) is characterized by sand, gravel, discontinuous tufa layers, and tufa cemented sediments. This aquifer is artesian. The static head is typically 0.2-1 m above the ground surface at MW-1. Isotopic data suggests a large component of older enriched water contributes to this system. Some thermal water (though to a smaller extent than in the unconfined aquifer) is contributing to this upper confined aquifer. Another component consists of modern recharge, perhaps <36 yr. This modern water is isotopically more depleted than the unconfined waters and the streams in the area.

Lower Confined Aquifer

The lower confined aquifer is penetrated by several wells. The deepest well, PW-3, penetrates a depth of ~119 m. At this depth bedrock was not reached. Therefore, the lower extent of this aquifer is unknown. However based on line 1, bedrock may be ~135 m below ground surface, defining the lower extent of the aquifer. Subsurface materials of the lower confined aquifer include sands, gravels, tufa, tufa cemented sediments, cobbles, and even large boulders. This aquifer is highly artesian with heads <4 m above the surface and flow rates of 37.8 L/s. The aquifer exhibits large (5-6 x 10^3 m^2/day) transmissivities. The lower aquifer exhibits the smallest contribution of ancient thermal water of the three aquifer systems at the hatchery. It is also characterized by isotopically depleted waters; it also has a modern recharge component.

Interactions

The three aquifer systems at the hatchery are not isolated systems. The lower system bears the same isotopic signatures for recharge time, temperature and elevation as the upper confined aquifer. It is likely that the two aquifers share the same recharge area. The aquifer systems with relatively depleted isotopic signatures likely represent recharge at a higher elevation and colder temperature than found at the hatchery. The Wasatch Mountains several Km north of the site, are a likely recharge area. The isotopic signature of the unconfined aquifer likely represents a lower recharge elevation as well as mixing between the enriched stream waters with the relatively depleted hydrothermal and confined aquifer waters.

As evidenced by well logs and seismic results, there is a lot of heterogeneity in the subsurface. However, between about 45 m and 50 m below ground surface all penetrating hatchery wells encounter some tufa. The tufa, as evidenced by tracer tests and hydraulic responses to irrigation has very high horizontal hydraulic conductivities. However, the low vertical hydraulic conductivity of the tufa causes increased confinement and higher hydraulic heads in the deeper wells. It is apparent from pump tests that there is communication and upward leakage between the lower confined aquifer and the upper confined aquifer. Similarly the unconfined system receives leakage from the confined aquifers.

Resource Potential

The lower confined aquifer has large transmissivity values. It is clear that the capacity of this aquifer is sufficient for fish culture. As discussed, the wells (especially PW-3) can be pumped over long time intervals without causing appreciable amounts of drawdown in the aquifer (Figure 10).

It is apparent from the combined results of the step drawdown tests and the constant rate tests that the cone of depression, caused by pumping, is very steep within the pumping well and quite shallow away from the well. For example, using the safe pumping limit for PW-3 (8130 L/min), the drawdown within the well would be ~10 m, while 100 m away drawdown would be ~.7 m. Thus, the limiting factor in keeping drawdown above the upper tufa layer is drawdown in the well bore of the pumping well itself.

The production wells at the hatchery have not been monitored for seasonal effects. However, measurements of other wells in the area indicate a seasonal effect is probable (Baker 1970; USGS 2004). It is critical that the pumping wells be monitored closely throughout the year, when pumped, to ensure upward gradients are maintained and the 10 m criterion is upheld. Using the most efficient well, PW-3, and pumping at conservative rates will preserve upward gradients.

It should be noted that this study did not test the lower confined aquifers for triactinomyxons (TAMs) or other components of whirling disease. Ongoing tests for whirling disease are done via fish culture at the hatchery. Properties of whirling disease inherent in the aquifers may be retained with pumping.

Boundaries

The apparent multiplicity of recharge boundaries is problematic. In order to pinpoint a boundary location triangulation should be used. Unfortunately, hatchery wells are roughly linear in spatial alignment, which does not permit triangulation. Therefore, the locations identified for the boundaries (Figure 12) are only possibilities. From overlapping radii in Figure 12, the boundaries appear to be north of the hatchery. This is consistent with the potentiometric map created by Carreón et al. (2003) showing that groundwater flows to the hatchery from the north.

Boundaries indicate possible facies changes, discontinuities, geological structures (faults, lenses, confining layers, barriers), or recharge or discharge sources within aquifer flow domain (Şen 1995). The boundaries in this study, interpreted from pump test results are all constant head or recharge boundaries. This further qualifies the lower confined aquifer as a sufficient long term resource for fish culture. Typical recharge boundaries represent increases in aquifer thickness, increases in aquifer permeability from increasing grain size, encountering a recharge source (lake, stream, gravel channel), or leakance from adjacent aquifers (Weight and Sonderegger 2001). Given the valley’s half graben setting, there are many likely sources. The unconsolidated sediments, and therefore the aquifer, would be thicker nearest the down-and-to-the-east faults on the west side of the valley. This could explain possible recharge boundaries inorthwest of the hatchery. Also, this geology has created the setting for which area streams (Provo River and Snake Creek) have created channels and deposited sediments over the course of their existences. Streams can create areas of coarser sediments and higher hydraulic conductivities and thus explain possible recharge boundaries throughout the valley.

Applications

A principal strength of this study is the integration of several methods to characterize a mixed system. Analyses similar to those performed at Midway fish hatchery can be applied elsewhere to evaluate water sources beneath contaminated systems. If upward gradients exist the lower water could be a plausible alternative to the surface water. The study also presents a possible general model for approaching complex hydrostratigraphic problems involving mixing across multiple confining boundaries. This study also brings attention to tufa layers in the area. The role of tufa in the system is twofold. The pressure head of the lower wells and pump test results indicate that the tufa at the hatchery functions as a confining layer. Conversely tracer tests and previous studies suggest tufa is permeable and water bearing. Tufa at the hatchery functions as both a confining layer, with low vertical hydraulic conductivity, and a conduit that transmits water horizontally, high horizontal hydraulic conductivity. This illustrates the crucial nature of maintaining upward gradients at the hatchery. The tufa may not act as a sufficient barrier to downward leakage, and possible contamination, if upward pressure gradients are not maintained.

The case study at Midway also illustrates the importance of analyzing mixed systems using a variety of methods. Looking at the results of only one or two techniques can lead to misinterpretations. For example, the radiocarbon data at Midway suggests the water that is emitted by Headspring is very old. Without tritium, tracer tests, or CFC results decisions regarding the water resource could be based on false assumptions.

CONCLUSIONS

It is important to evaluate mixed systems using a variety of methods and techniques. By combining several geochemical, physical hydrogeological, and geophysical methods, it is possible to understand the groundwater flow at Midway fish hatchery. There is appreciable heterogeneity at Midway fish hatchery, both in hydrostratigraphy and the water's chemical and isotopic characteristics. The subsurface at the site is characterized by semi-discontinuous tufa and alluvium layers bisected by north-south trending discontinuities, possibly faults. Waters at the hatchery represent mixtures between old, hydrothermal, high TDS, depleted water and modern, low TDS, enriched water. The shallow unconfined system is a mixture of both of these end-members, containing elements of both the oldest and the youngest waters. The upper and lower confined systems are composed of a smaller component of the thermal end-member along with cold, low TDS, modern waters. Solutes, isotopes and hydrothermal components decrease with aquifer system depth.

The lower confined aquifer has large transmissivity values and can be pumped for extended periods of time without causing appreciable amounts of drawdown in the aquifer. The cone of depression, however, is very steep in the well itself. Therefore, pumping wells should be monitored closely to ensure that drawdown in the well bore remains above the shallow tufa layer (~10 m). A drawdown of less than 10 m is critical to ensure no vertical leakage of the contaminated unconfined aquifer to the clean confined aquifers below. By keeping this drawdown above the tufa layer, an upward pressure gradient is maintained and no contamination of the confined aquifers should occur.

Despite the complexity of groundwater at Midway fish hatchery it is important to remember that groundwater and aquifer characteristics are controlled by the fundamental principles and parameters of hydrogeology. Water movement is caused by pressure gradients, from high to low hydraulic head. This understanding is crucial in keeping uncontaminated aquifers clean. Upward pressure gradients must be maintained during production.

The integration of several methods helps mitigate the confounding effects of heterogeneity. It is only through the integration of several methods that such mixed systems, can be understood. In this study, the lower confined aquifer was found to be a sufficient and safe resource through the integration of methods.

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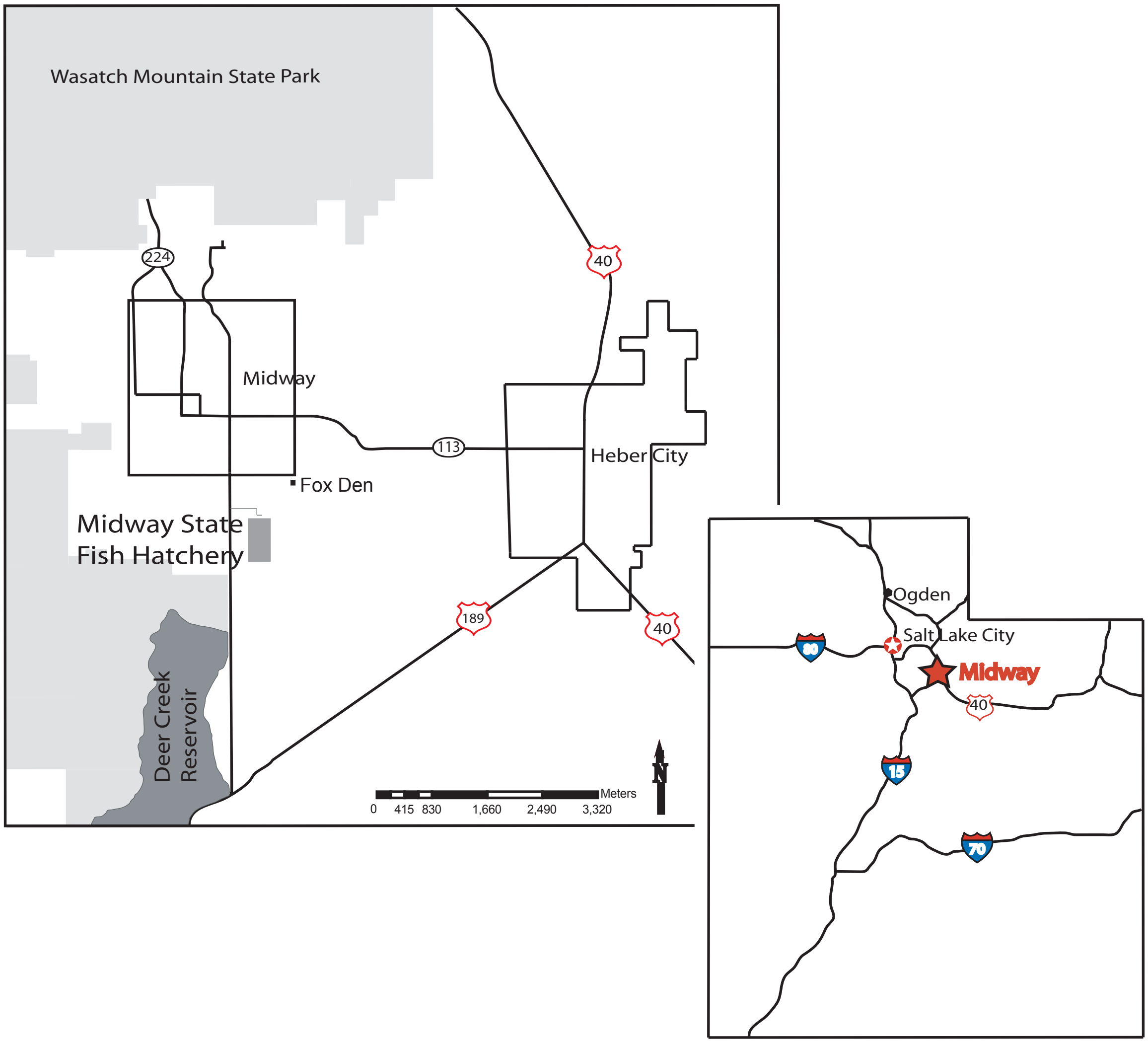


Figure 1 Midway Hatchery, one of Utah's state fish hatcheries is located in Midway, Utah.

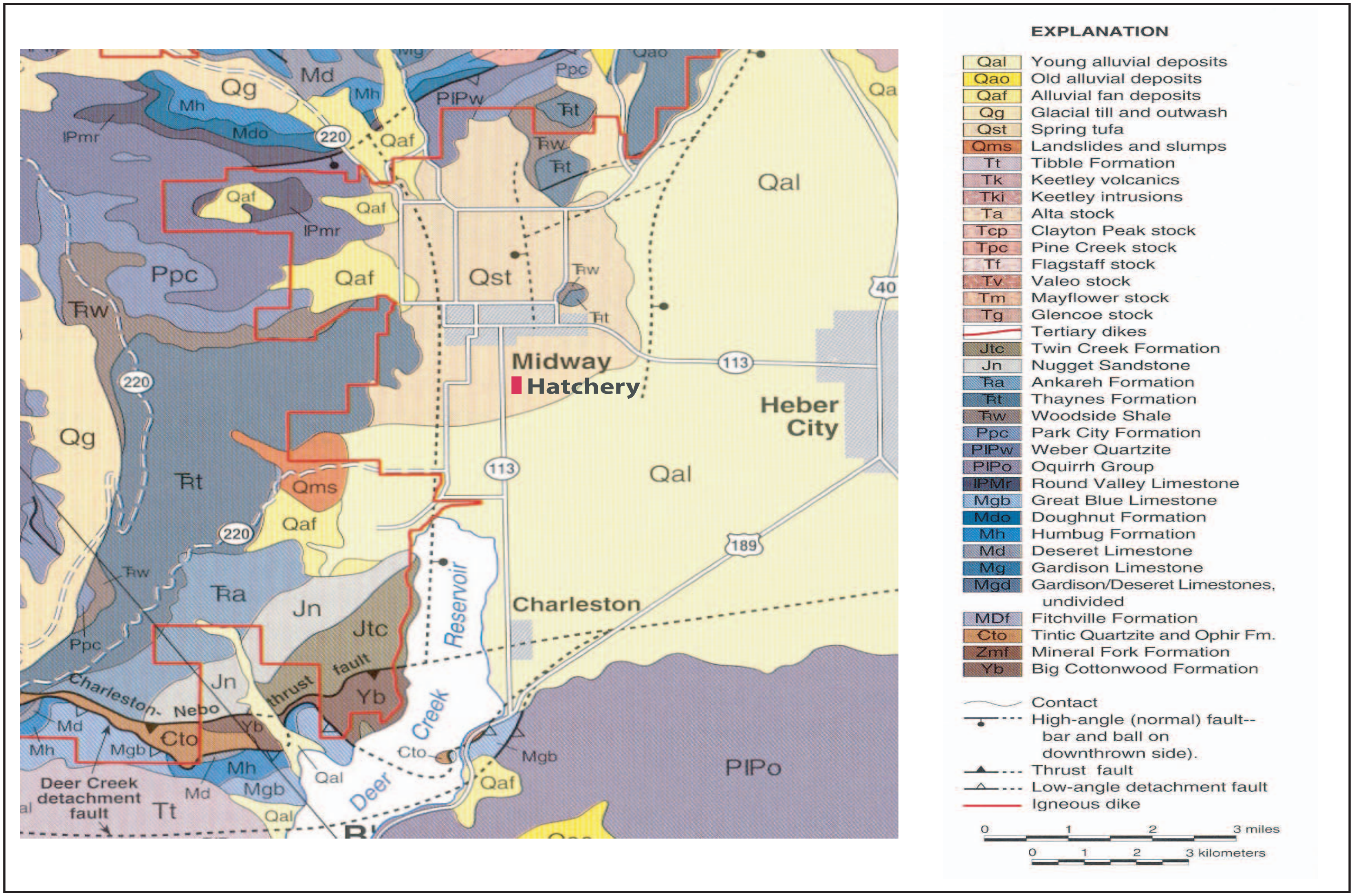


Figure 2 Geologic map for the greater Midway area. Modified from Willis and Willis (2000).

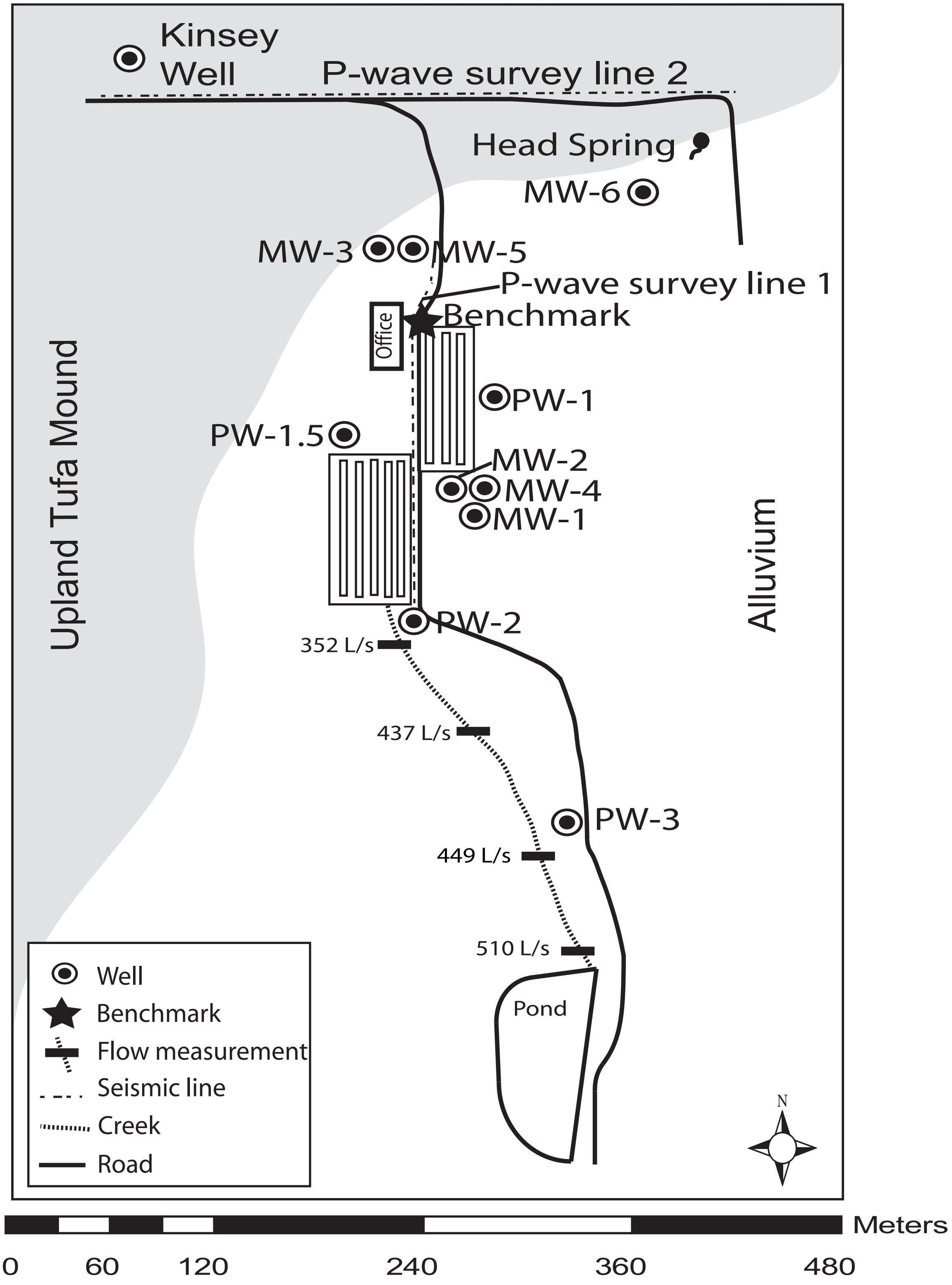


Figure 3 Site map of Midway Fish Hatchery, Utah. This Map shows the locations of pumping wells (PW), monitoring wells (MW), headspring, seismic lines, flow measurements, and the upland tufa mound.

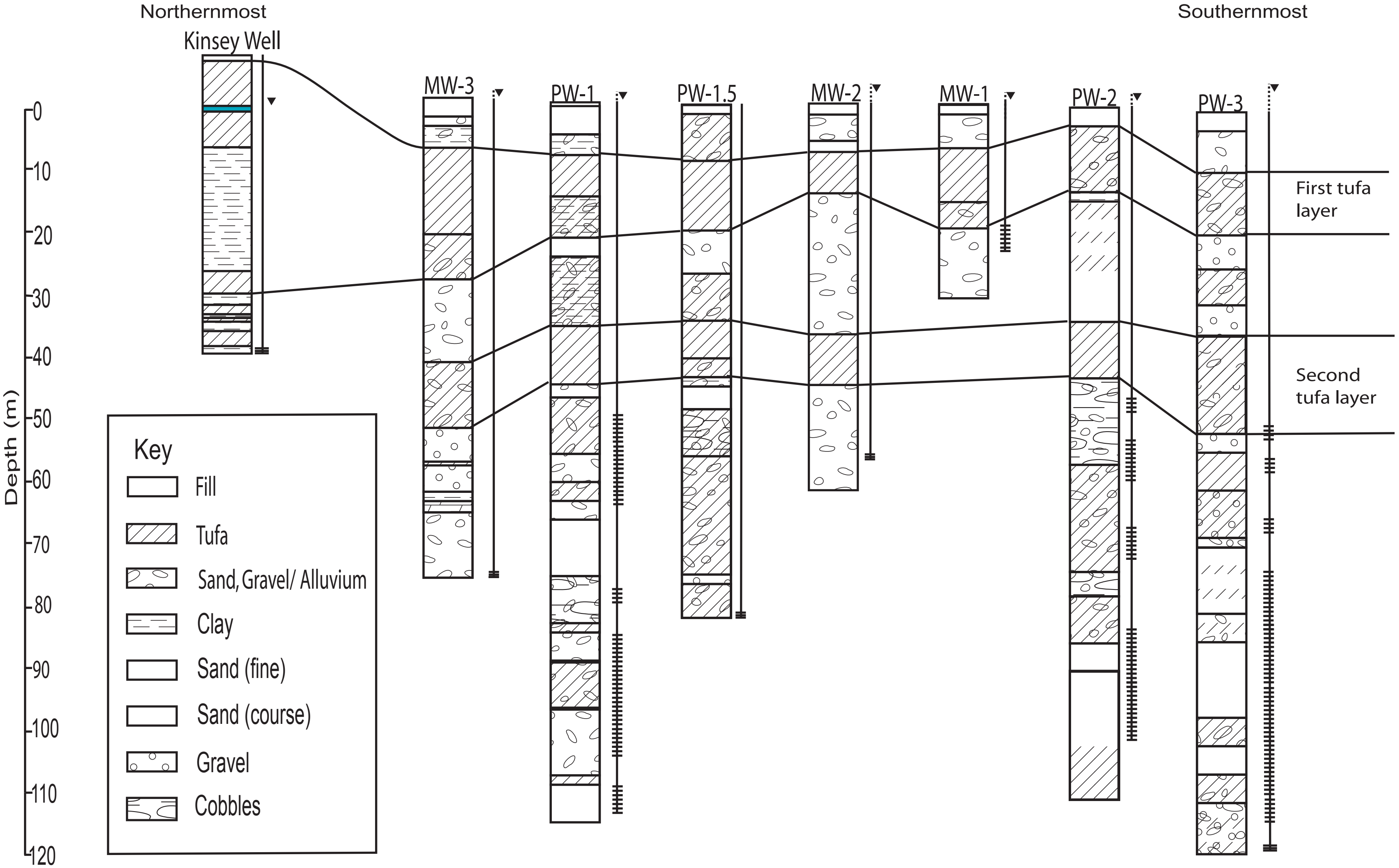


Figure 4 It is apparent from monitoring wells (MW) and production wells (PW) at Midway fish hatchery, shown with screened intervals,that hydraulic gradients increase with well depth. See Figure 3 for well locations.

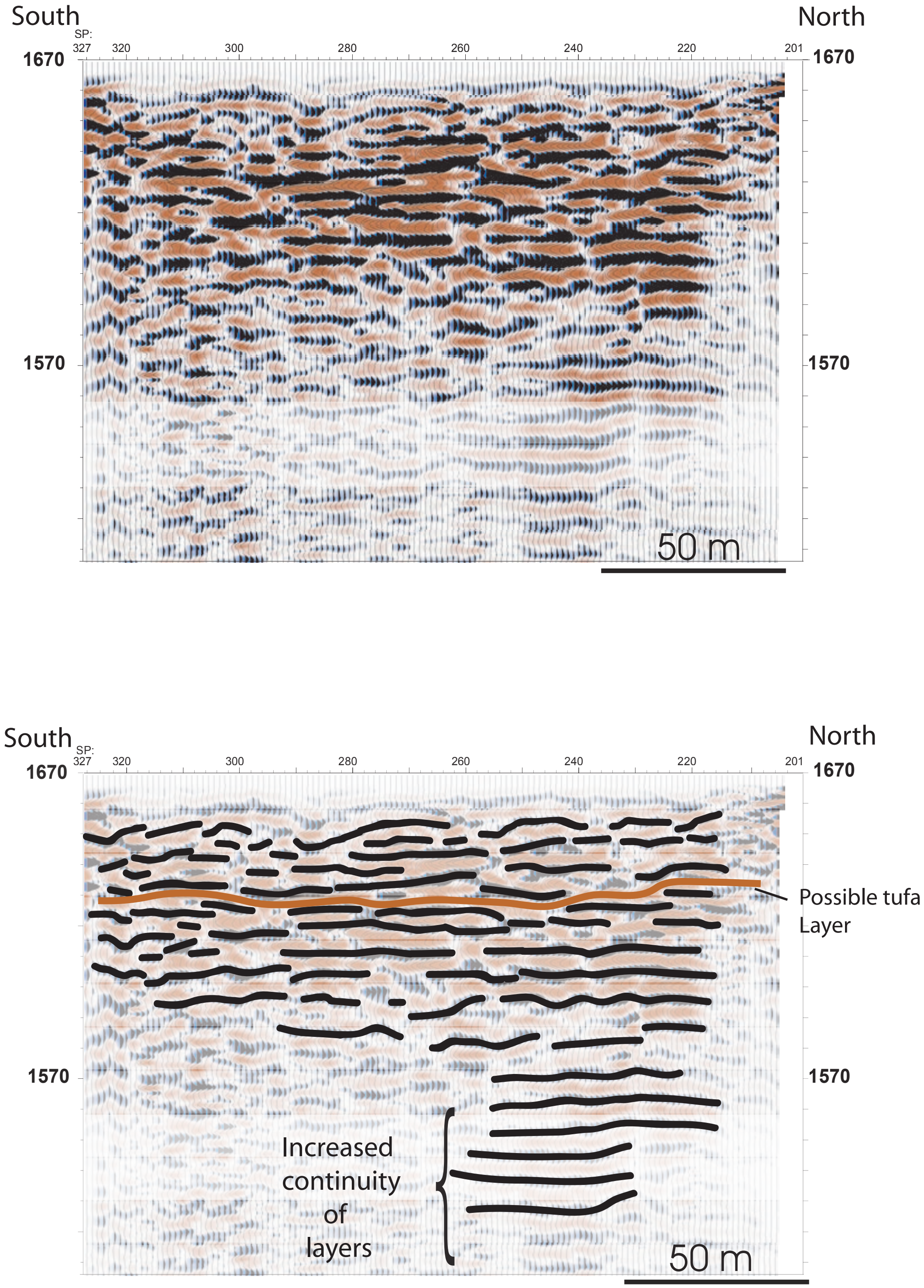
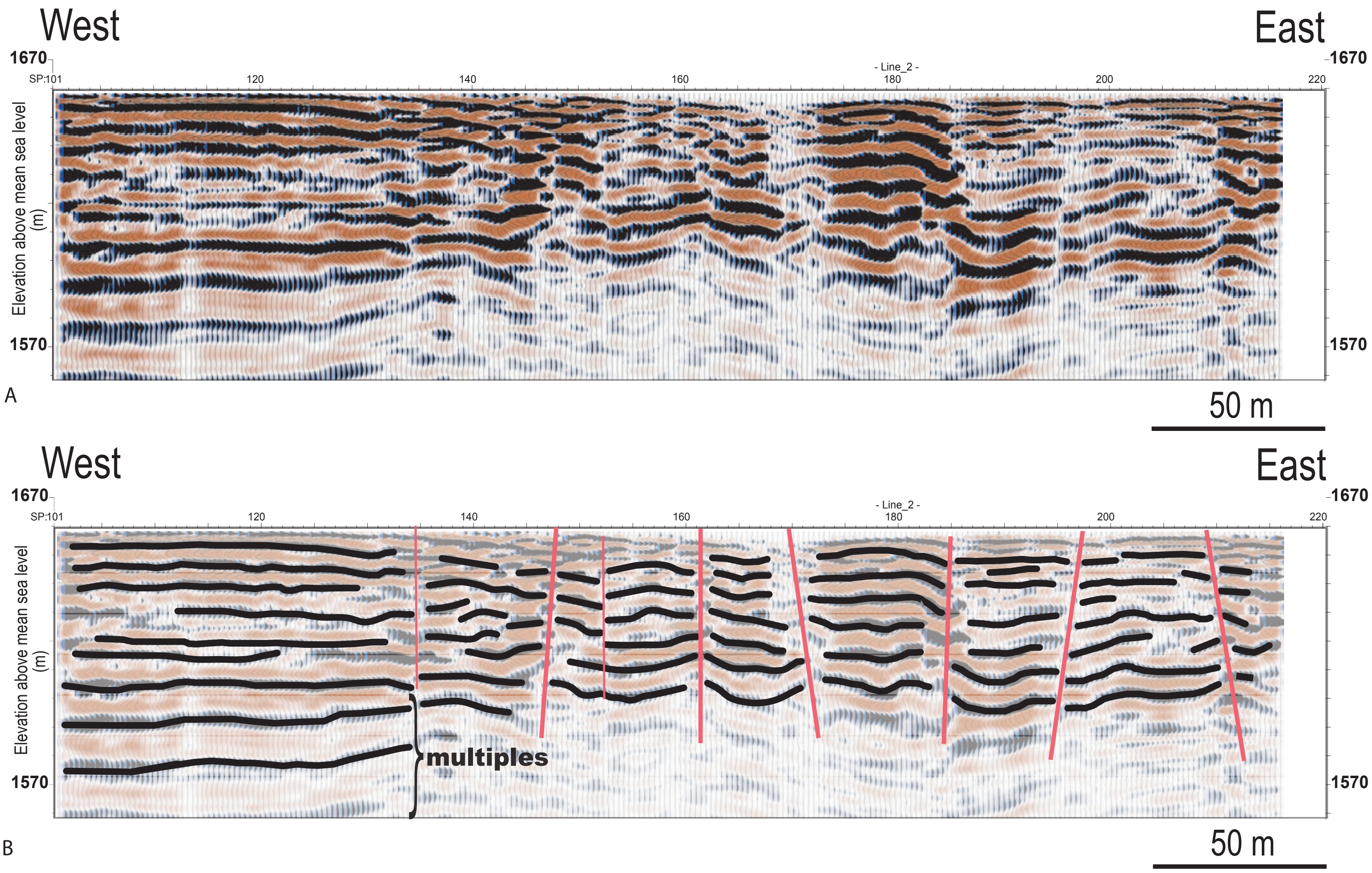


Figure 5 P-wave seismic line 1 is a north-south trending line characterized by subsurface hetrogeneity as shown in A) uninterpreted data and B) interpreted data. A reflector at ~40 m is a possible tufa layer. See Figure 3 for the location of this line.



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trending discontinuities, interpreted at breaks in continuity, offset, and attitude. See Figure 3 for the location of this line.

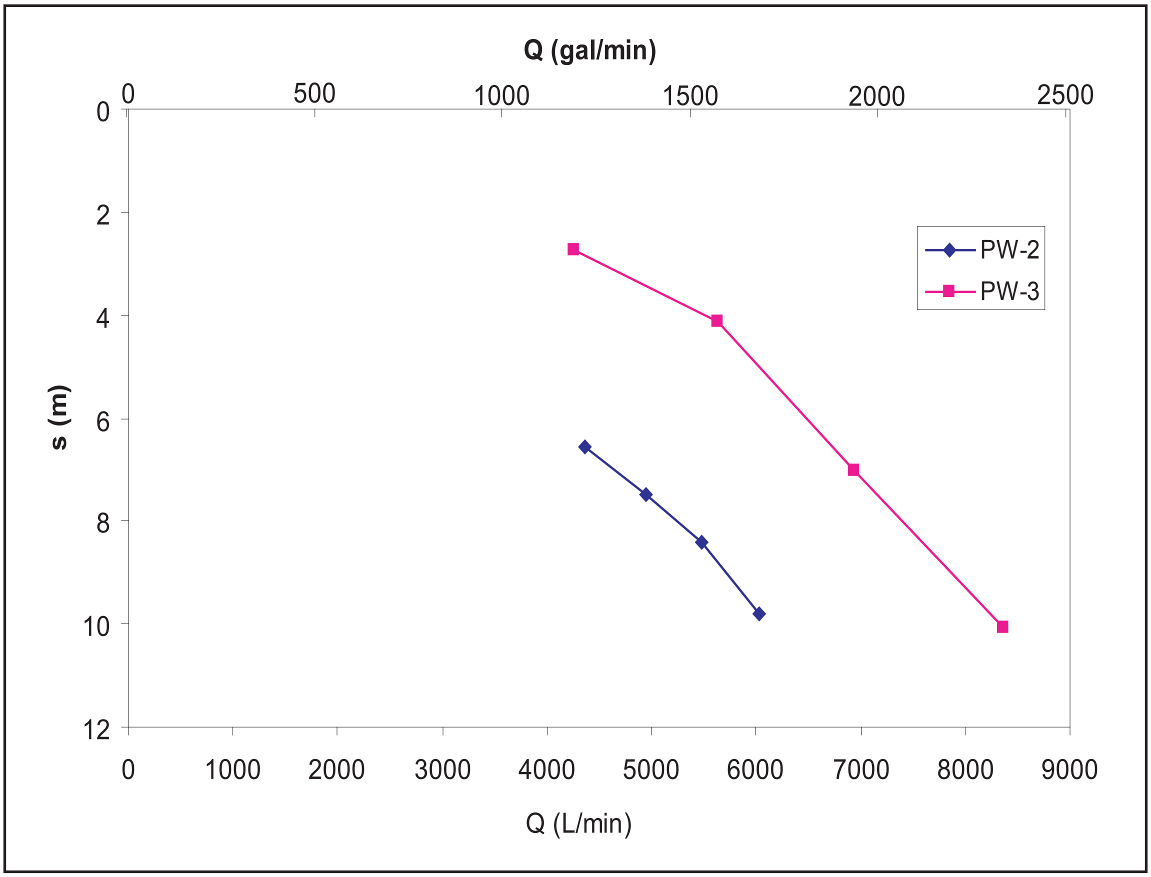


Figure 7 Drawdown in pumping wells PW-2 and PW-3 after 30 min of pumping at the rate shown indicate drawdown within the well bore is much greater than in the aquifer itself.

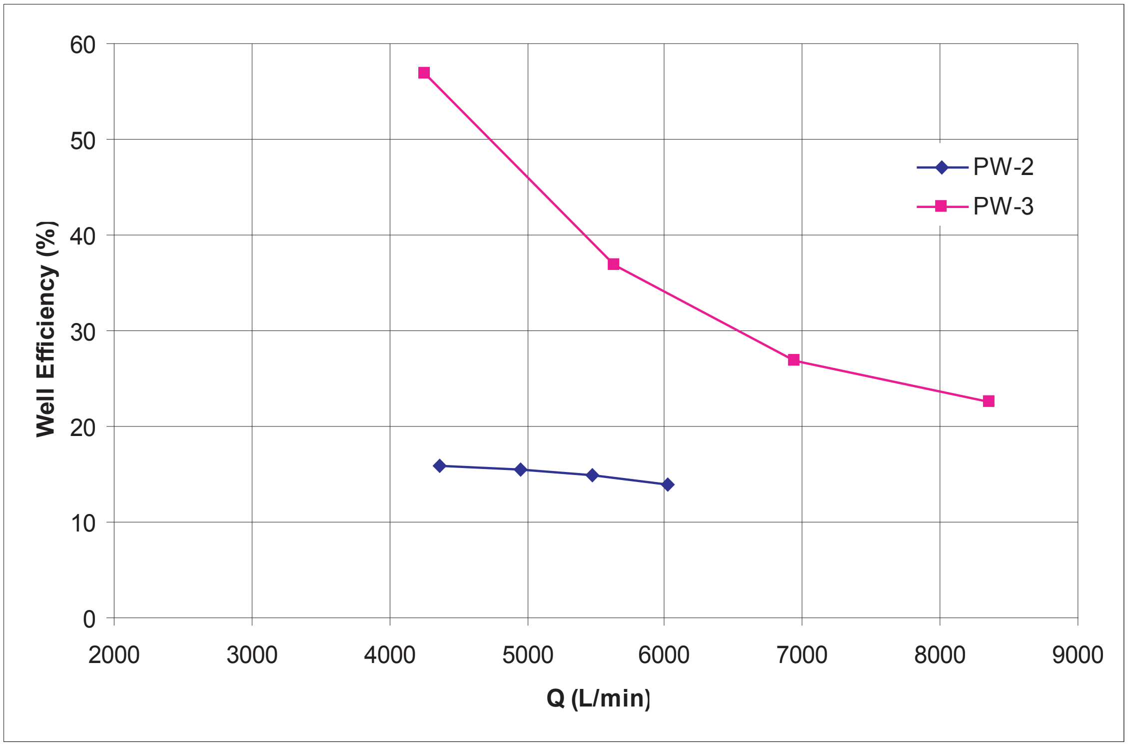
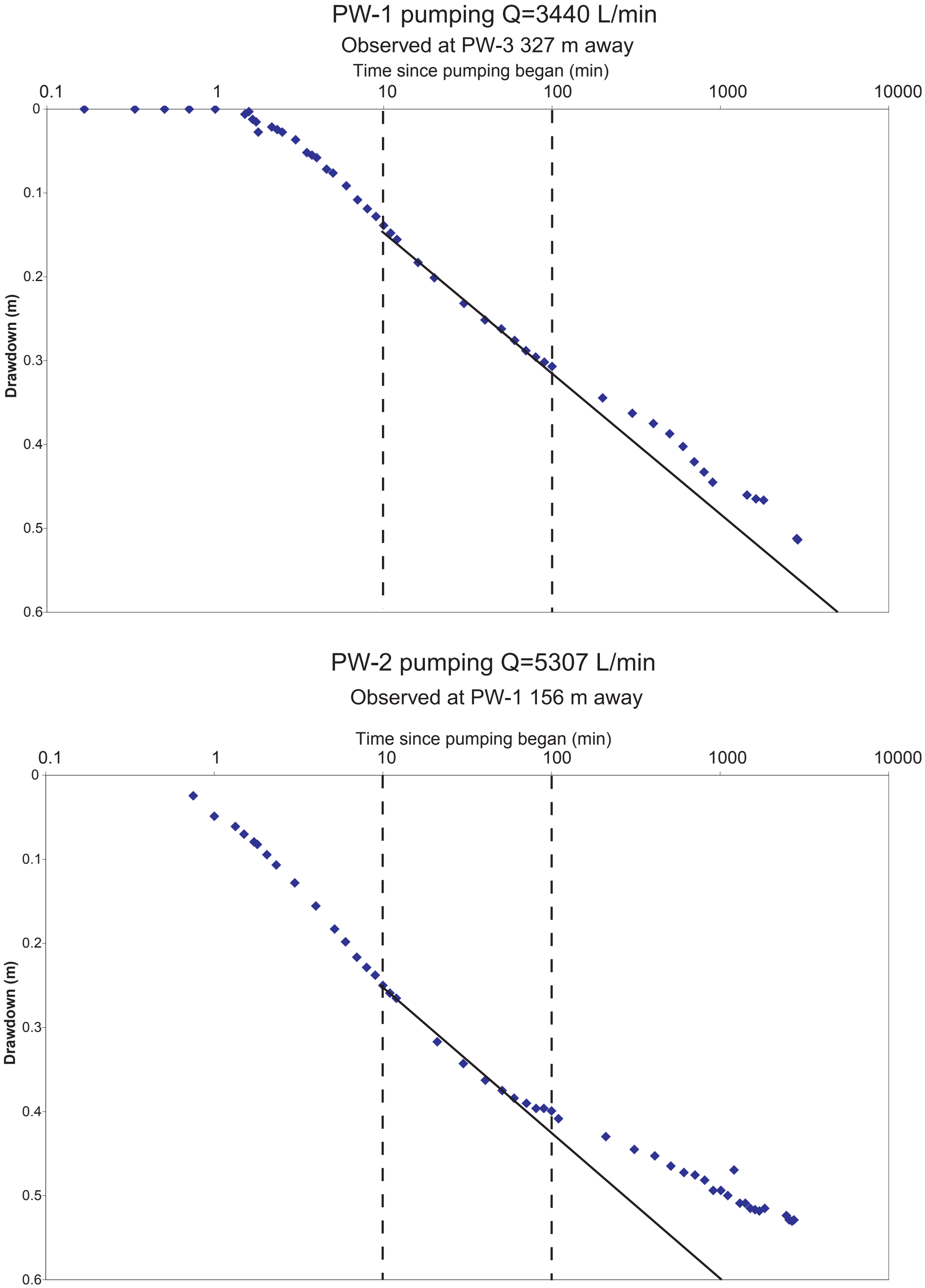


Figure 8 Well efficiencies decrease with increased pumping rate. PW-3 is the most efficient well at the hatchery.


PW-1 pumping Q=3440 L/min

Observed at PW-3 327 m away

PW-2 pumping Q=5307 L/min

Observed at PW-1 156 m away

Figure 9 Typical time-drawdown curves show a lessening slope, which suggests recharge boundary conditions are present.

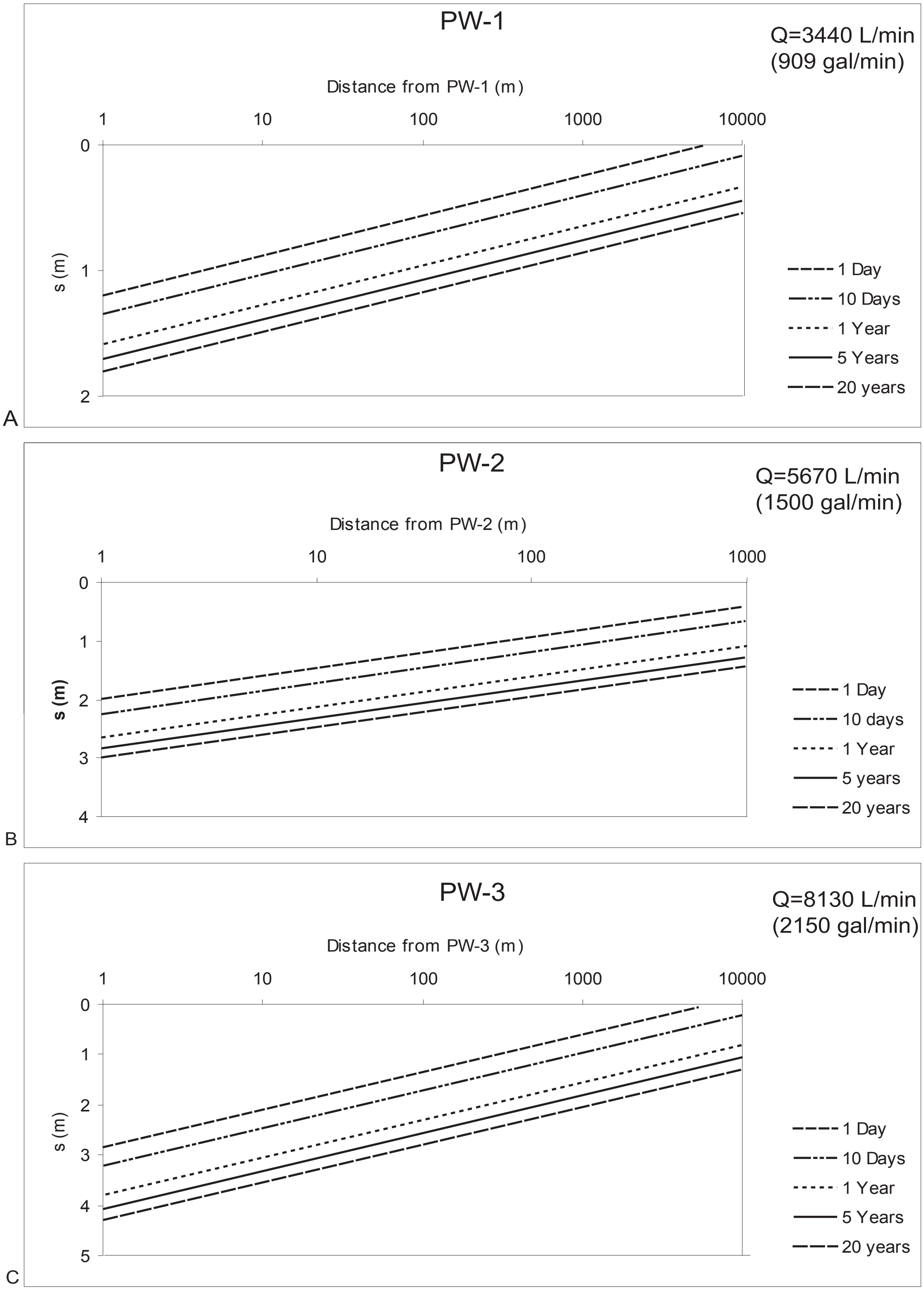


Figure 10 Distance drawdown graphs show the cone of depression caused by pumping for 1 day, 10 days, 1 year, 5 years, and 20 years for A) PW-1 pumping at 3440 L/min, B) PW-2 pumping at 8130 L/min, and C) PW-3 pumping at 8130 L/min.

	Boundary,	Pumping Well,	(Observed At)
○	First	PW-2	(PW-1)
○	First	PW-3	(PW-1)
○	Second	PW-2	(PW-1)
○	First	PW-1	(PW-2)
○	First	MW-2	(PW-2)
○	First	MW-2	(PW-3)
○	Second	PW-3	(PW-1)
○	1st	MW-3	(PW-3)
○	Second	PW-1	(PW-2)
○	Second	MW-2	(PW-2)

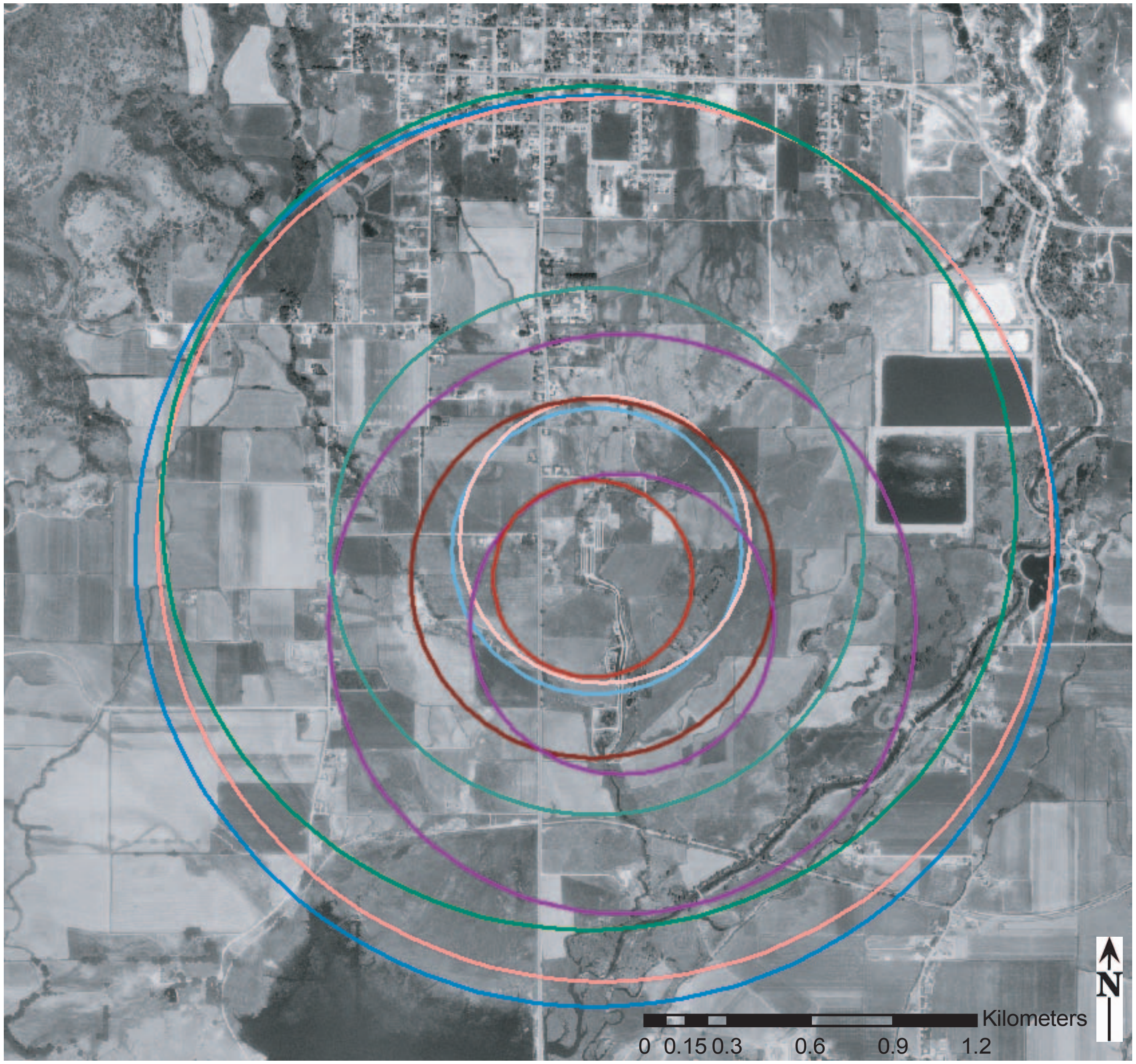


Figure 11 Several boundaries are observed. However, the lack of spatial variation among wells does not allow for triangulation. Therefore, the boundaries found in this study can only be interpreted as possibilities.

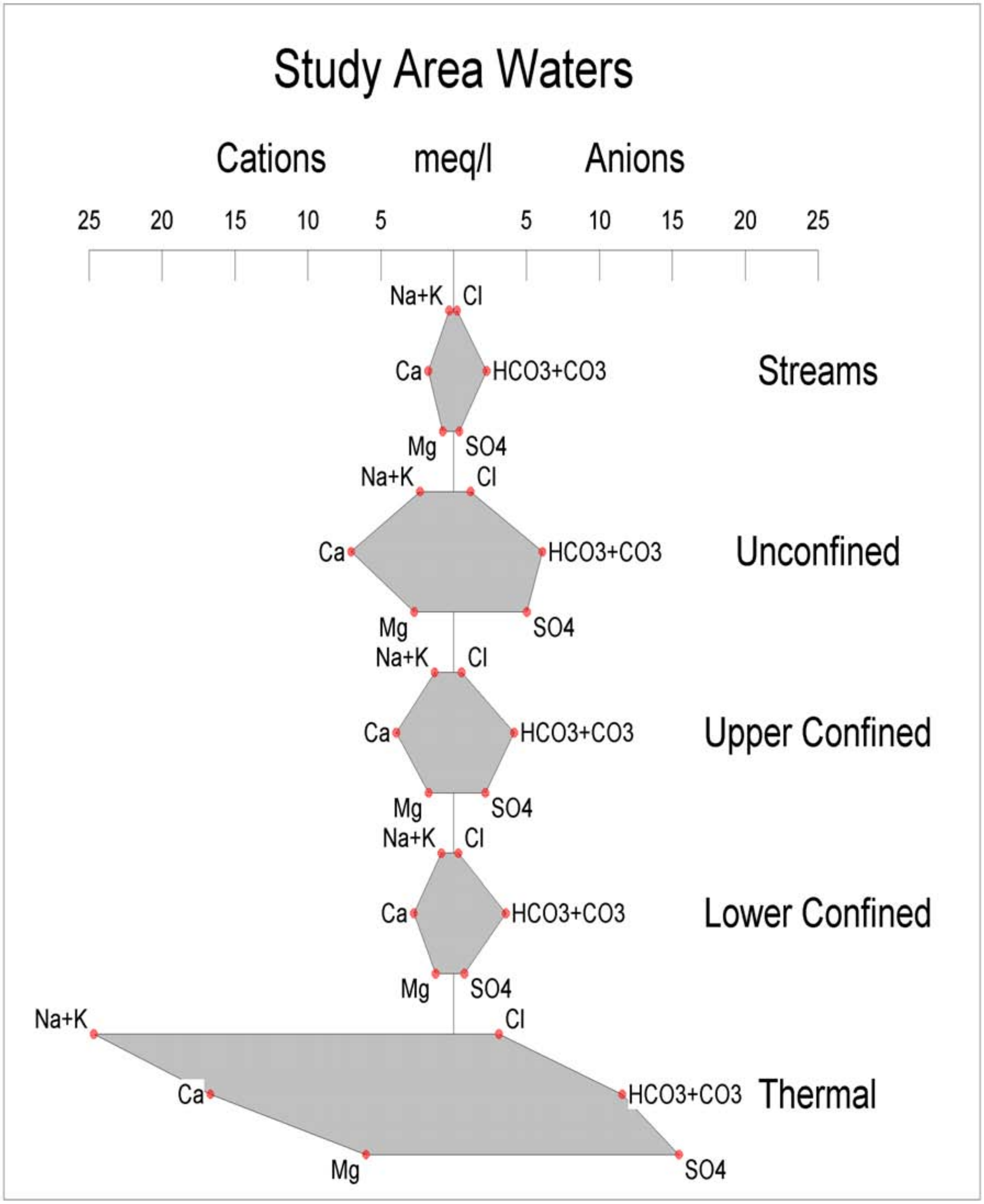
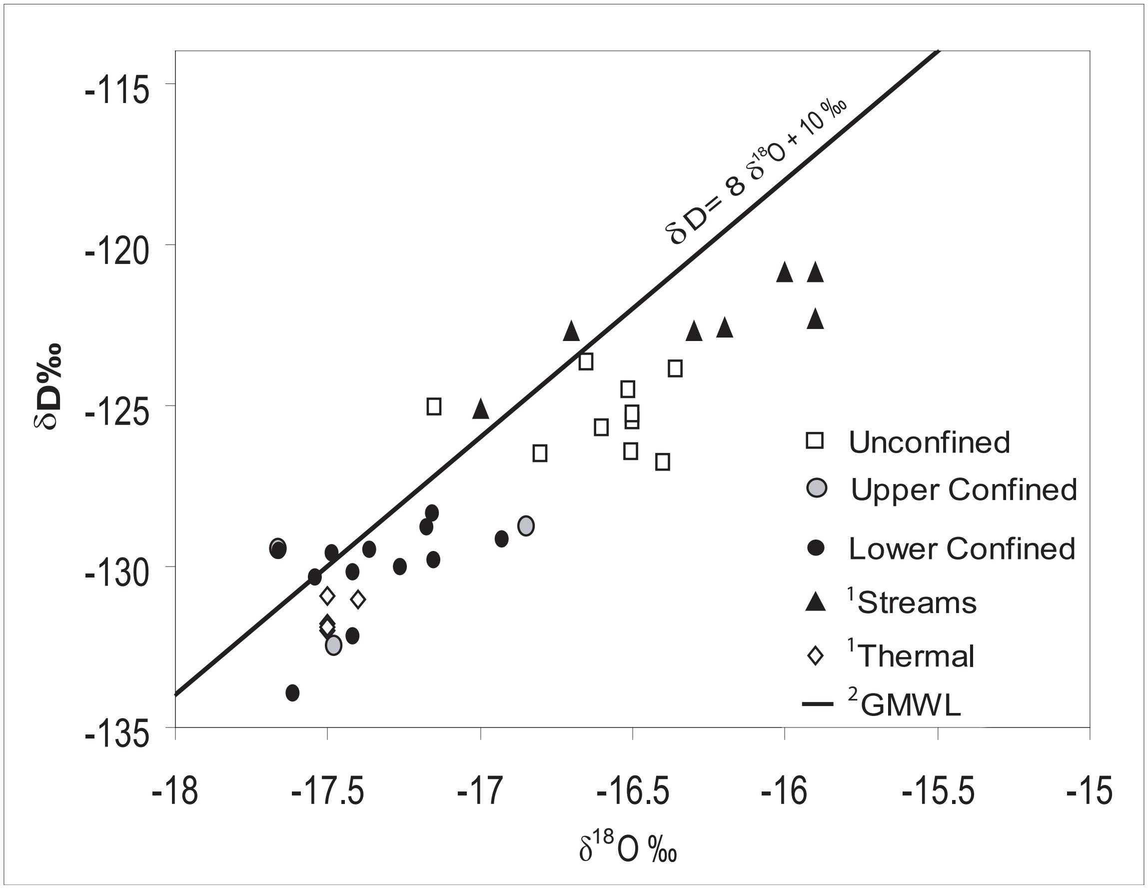


Figure 12 Stiff diagrams of hatchery aquifers compared with area streams and thermal waters from Carreón et al. (2003) show the unconfined aquifer has the largest component of thermal water.



[1] From Carreón et al. (2003)
[2] From Craig (1961)

Figure 13 The upper and lower confined aquifers have similar isotopic signatures. It is likely these systems share the same recharge area and age. Thermal waters bear a similar signature to the confined aquifers. The unconfined system is more enriched than the confined aquifers. Area streams represent an enriched end-member.

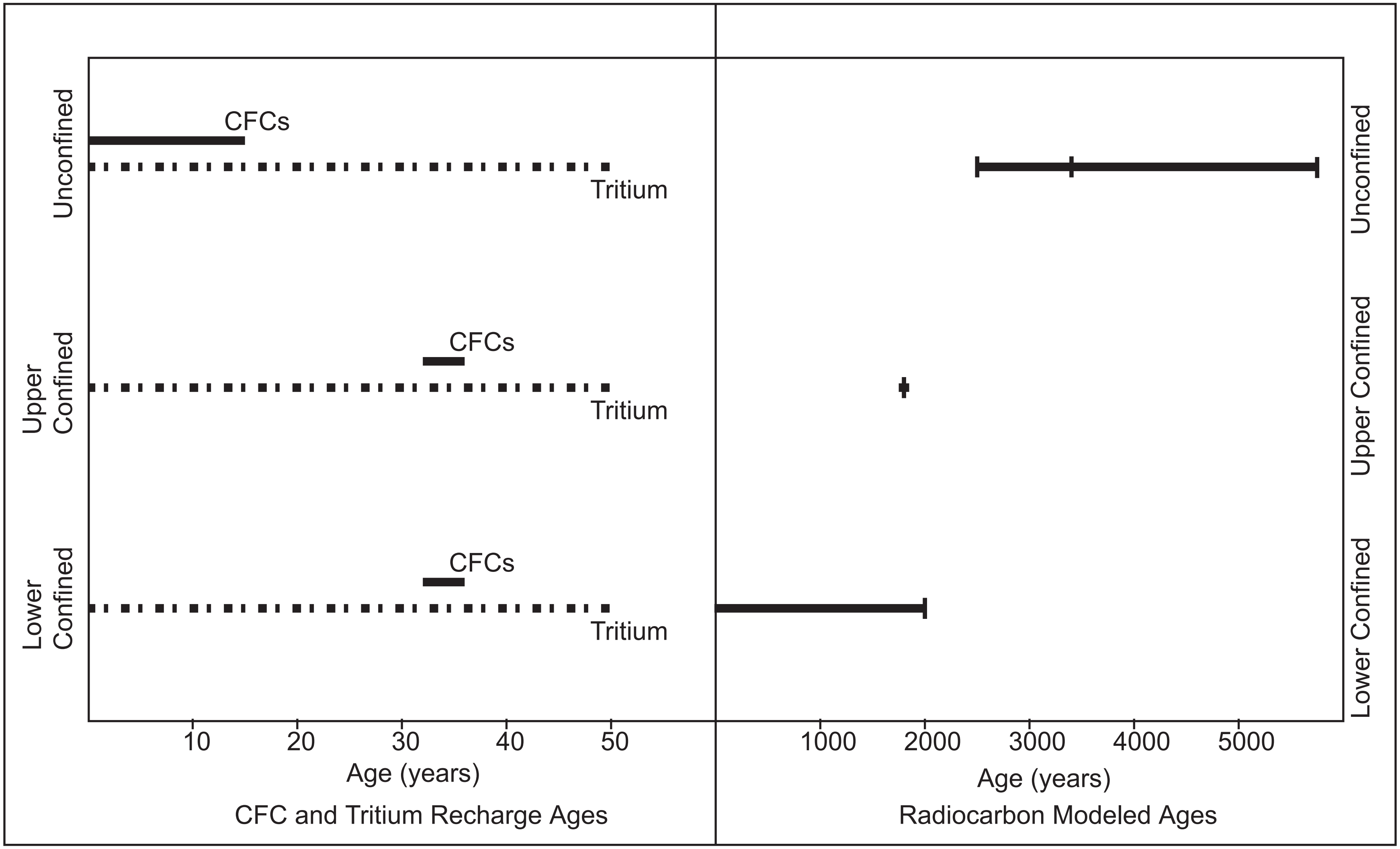


Figure 14 Apparent recharge and modeled ages from CFC, tritium, and radiocarbon results show hatchery aquifers are mixed systems with young and modern components.

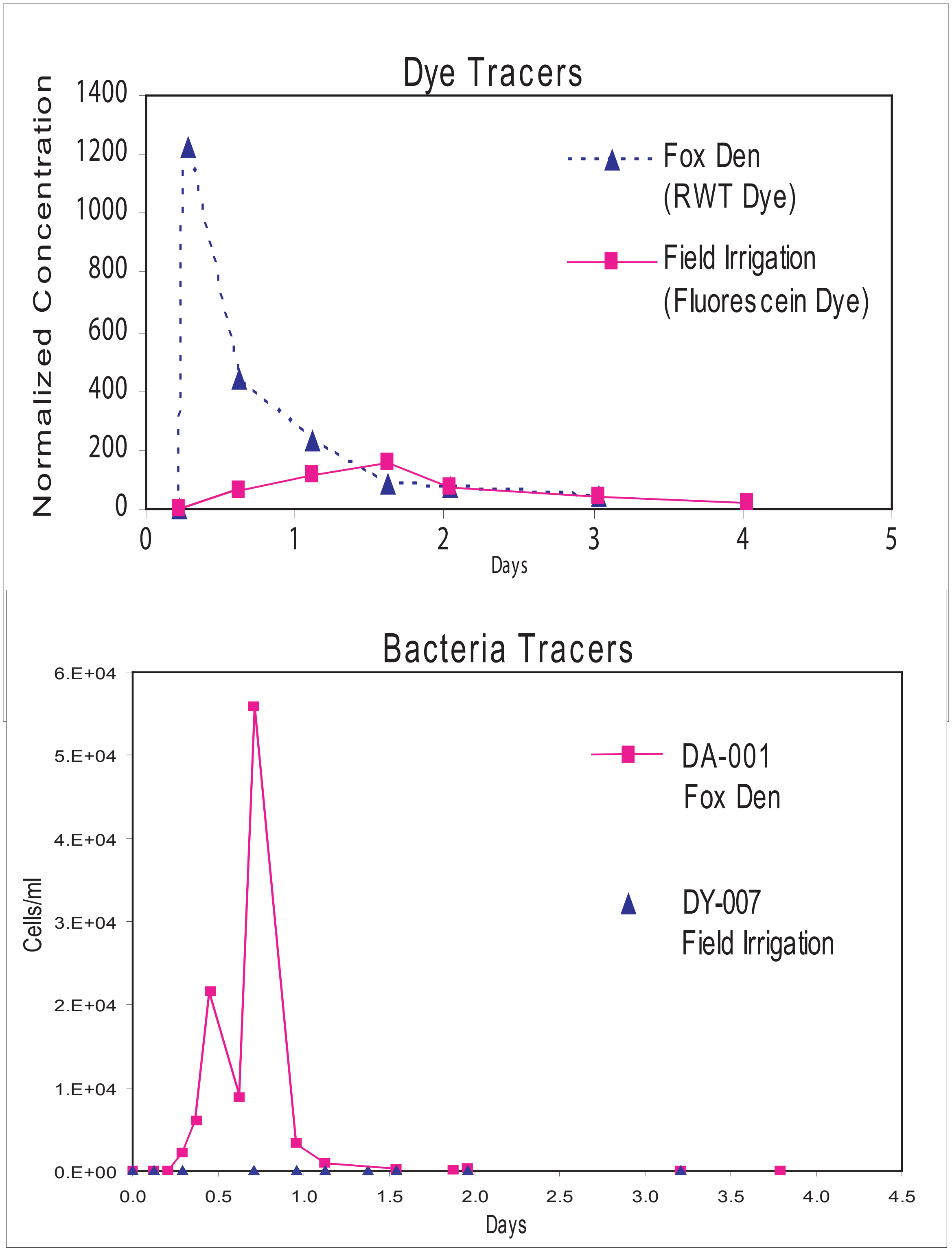


Figure 15 Dye and bacteria tracer test results show travel of tracers from Fox Den a sinkhole feature in the tufa mound ~800 m away to Headspring within 2 days. Bacteria applied to field was not tetected at the hatchery. Data from Carreón et al. (2003) and McIntosh (2002).

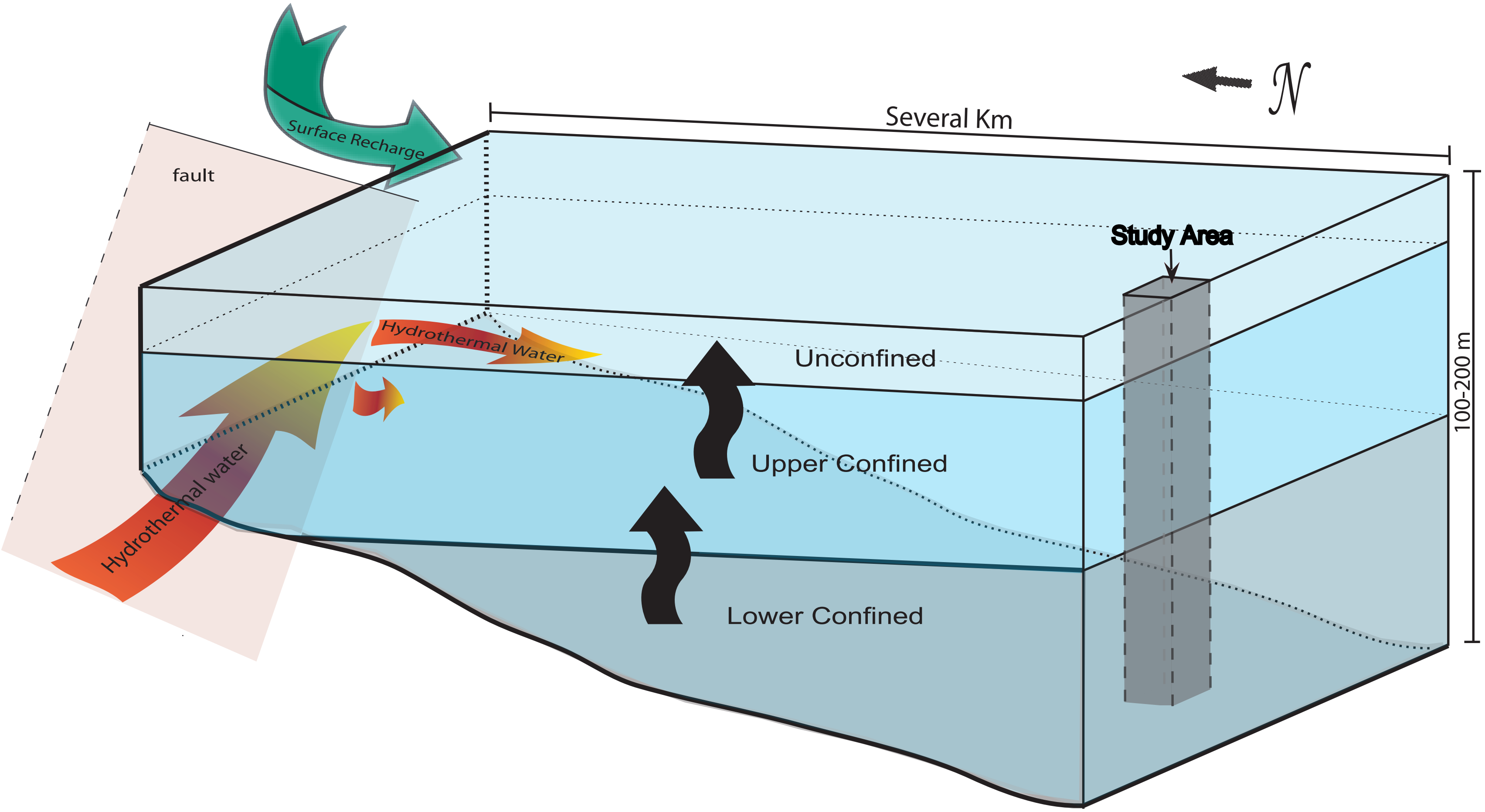


Figure 16 A conceptual model of groundwater flow in the greater Midway area illustrates an unconfined aquifer, an upper confined aquifer and a lower confined aquifer. Hydrothermal water flows up faults and mixes with unconfined system, upgradient of study area. Upward gradients exist and the lower confined aquifers leak upward. Not to scale.

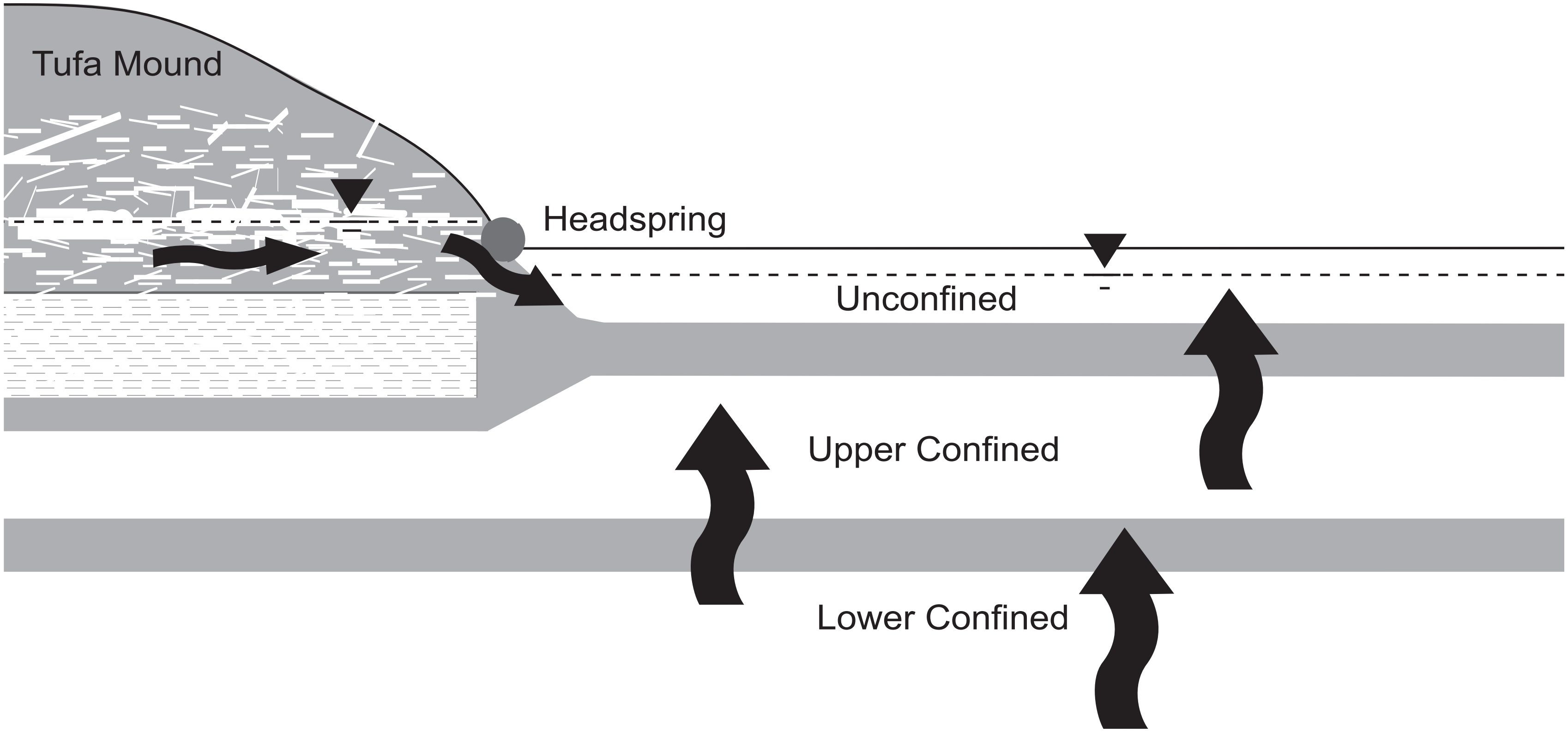


Figure 17 A conceptual model of the unconfined aquifer illustrates the water table north of the is in the fractured tufa of the upland tufa mound (see Figure 3 for location). At the hatchery the water table is below the ground surface. Springs at the base of the tufa mound act as drain and contribute tufa water to the unconfined aquifer. The confined aquifers also contribute to the unconfined system by leaking upward. Not to scale.

Aquifer	Well	Northing (m)	Easting (m)	[1]Approx ground elev (m)	[1]Collar elevation (m)	[2]Stickup (m)	[2]Well Depth (m)	[2]Screen Intervals (m)
Unconfined	MW-4	4482476	460289	-0.68	0.42	1.10	6.7	0.6 - 6.7
Unconfined	MW-5	4482648	460247	1.20	1.80	0.61	7.0	0.9 - 7.0
Unconfined	MW-6	4482716	460418	1.19	1.50	0.30	7.0	0.9 - 7.0
Upper Confined	MW-1	4482646	460295	-0.76	0.47	0.43	33.8	20.7 - 23.8
Lower Confined	MW-2	4482688	460282	-0.57	0.56	1.13	57	56.7 - 57.0
Lower Confined	MW-3	4482853	460252	1.02	1.81	0.79	39.6	39.3 - 39.6
Lower Confined	PW-1	4482732	460313	-0.37	1.02	1.39	117.7	51.8 - 66.1 77.7 - 80.8 84.4 - 105.2 109.7 - 112.8
Lower Confined	PW-1.5	4482715	460222	-0.32	0.31	0.63	83.2	82.9 - 83.2
Lower Confined	PW-2	4482583	460267	-1.23	0.21	1.44	112	47.2 - 50.3 56.4 - 64.0 68.6 - 74.7 78.6 - 80.2 83.2 - 102.1
Lower Confined	PW-3	4482411	460377	-2.08	-0.23	0.91	119	50.3 - 53.3 57.9 - 62.5 67.1 - 70.1

[1] Relative to local datum at N 4482592 E 460274 about 1660 m above mean sea level. Located at the northwest corner of concrete raceway (Figure 3)

[2] Relative to ground surface

Table 1 Monitoring wells (MW) and pumping wells (PW) and screen intervals at Midway fish hatchery

Aquifer	**MW-4** Ground Surface Elev: -0.68 m		**MW-5** Ground Surface Elev: 1.2 m		**MW-6** Ground Surface Elev: 1.19 m	
	Date	Water Level (m)	Date	Water Level (m)	Date	Water Level (m)
Unconfined	5/24/2002	-0.39	5/24/2002	-0.67	5/24/2002	0.00
	5/26/2002	-0.40	5/26/2002	-0.69	5/26/2002	0.00
	5/28/2002	-0.41	5/28/2002	-0.70	5/28/2002	-0.02
	5/30/2002	-0.40	5/30/2002	-0.66	5/30/2002	-0.02
	6/3/2002	-0.35	6/3/2002	-0.55	6/3/2002	0.05
	6/5/2002	-0.32	6/5/2002	-0.52	6/5/2002	0.07
	6/5/2002	-0.32	6/5/2002	-0.53	6/5/2002	0.06
	6/6/2002	-0.34	6/6/2002	-0.56	6/6/2002	0.04
	6/6/2002	-0.34	6/6/2002	-0.56	6/6/2002	0.04
	6/6/2002	-0.35	6/6/2002	-0.56	6/6/2002	0.04
	6/7/2002	-0.35	6/7/2002	-0.59	6/7/2002	0.02
	6/7/2002	-0.35	6/7/2002	-0.59	6/7/2002	0.01
	6/10/2002	-0.35	6/10/2002	-0.59	6/10/2002	0.01
	6/12/2002	-0.36	6/12/2002	-0.61	6/12/2002	0.00
	6/17/2002	-0.32	6/17/2002	-0.57	6/17/2002	0.04
	6/20/2002	-0.34	6/20/2002	-0.64	6/20/2002	-0.01
	6/22/2002	-0.35	6/22/2002	-0.64	6/22/2002	-0.02
	6/24/2002	-0.36	6/24/2002	-0.68	6/24/2002	-0.02
	6/26/2002	-0.36	6/26/2002	-0.69	6/26/2002	-0.02
	7/1/2002	-0.32	7/1/2002	-0.66	7/1/2002	0.02
	7/8/2002	-0.34	7/8/2002	-0.69	7/8/2002	-0.01
	7/10/2002	-0.35	7/10/2002	-0.73	7/10/2002	-0.03
	7/22/2002	-0.36	7/22/2002	-0.74	7/22/2002	0.01
	8/2/2002	-0.42	8/2/2002	-0.79	8/2/2002	-0.04
	8/12/2002	-0.40	8/12/2002	-0.78	8/12/2002	-0.04
	8/14/2002	-0.39	8/14/2002	-0.77	8/14/2002	-0.03
	8/20/2002	-0.38	8/20/2002	-0.88	8/20/2002	-0.21
	11/19/2002	-0.48	11/19/2002	-0.98	11/19/2002	-0.30
	1/6/2003	-0.49	1/6/2003	-0.98	1/6/2003	-0.28
	3/28/2003	-0.51	3/28/2003	-1.09	3/28/2003	-0.32
Upper Unconfined	**MW-1** Ground Surface Elev: -0.76 m					
	Date	Water Level (m)				
	8/30/2004	0.91				
	9/29/2004	0.95				
Lower Confined	**MW-2** Ground Surface Elev: -0.57 m		**MW-3** Ground Surface Elev: 1.02 m		**PW-2** Ground Surface Elev: -1.23 m	
	Date	Water Level (m)	Date	Water Level (m)	Date	Water Level (m)
	2/11/2004	2.01	2/11/2004	0.91	4/14/2004	3.30
	4/14/2004	2.54	4/14/2004	2.07	4/20/2004	3.31
	4/20/2004	2.54	4/20/2004	0.92	8/25/2004	3.08
	8/25/2004	2.40	8/25/2004	1.02	8/30/2004	3.14
	8/30/2004	2.45	8/30/2004	1.08		
	9/29/2004	2.88				
	PW-1 Ground Surface Elev: -0.37 m		**PW-3** Ground Surface Elev: -2.08 m			
	Date	Water Level (m)	Date	Water Level (m)		
	2/11/2004	2.08	9/29/2004	4.45		
	8/25/2004	2.40				
	8/30/2004	2.39				

Table 2 Water levels in wells relative to ground surface.
Ground surface elevation is relative to local benchmark (Figure 3)
See Figure 3 for well locations.

Hand Calculations		**Theis Method**		**Boundaries**	
Pumping Well	**Observing Well (OW)**	**Transmissivity (m^2 day^{-1})**	**Storativity**	**Radius from OW to Boundary 1 (m)**	**Radius from OW to Boundary 2 (m)**
PW-1	PW-2	2.4 E+03	2.7 E-04	374	684
PW-1	PW-3	3.1 E+03	2.0 E-04	572	1105
PW-2	MW-2	5.0 E+03	5.1 E-04	545	1738
PW-2	PW-1	5.2 E+03	3.7 E-04	546	1685
PW-3	MW-1	3.3 E+04	7.6 E-03	--	--
PW-3	MW-2	7.7 E+03	5.0 E-04	1003	--
PW-3	MW-3	8.7 E+02	2.8 E-05	1608	--
PW-3	PW-2	1.1 E+04	3.6 E-04	--	--

Aquifer Test® Results		**Theis Method**		**Cooper-Jacob Method**	
Pumping Well	**Observing Well (OW)**	**Transmissivity (m^2 day^{-1})**	**Storativity**	**Transmissivity (m^2 day^{-1})**	**Storativity**
PW-1	PW-2	2.0E+03	3.2 E-04	3.3E+03	2.1E-04
PW-1	PW-3	3.4E+03	2.0 E-04	4.9E+03	1.3E-04
PW-2	MW-2	4.9E+03	4.8 E-04	5.1E+03	4.8E-04
PW-2	MW-3	5.9E+03	3.9 E-05	4.9E+03	5.2E-05
PW-2	PW-1	5.4E+03	4.1 E-04	6.1E+03	3.2E-04
PW-3	MW-2	7.9E+03	5.3 E-04	1.0E+04	4.0E-04
PW-3	MW-3	8.7E+03	2.6 E-04	9.4E+03	2.0E-04
PW-3	PW-1	9.3E+03	7.8 E-04	1.6E+04	2.9E-04
PW-3	PW-2	1.1E+04	3.8 E-04	1.0E+04	3.3E-04
PW-3	MW-1	2.7E+04	1.2 E-02	3.3E+04	7.7E-03

Table 3 Transmissivity, storativity and radii to recharge boundaries from time-drawdown, observation well response, pump test results were calculated using a variety of methods.

Aquifer	# of Samples		Conductivity µS/cm	pH	temp °C	Cations (mg/L / meq/L)				Anions (mg/L / meq/L)							$\delta^{18}O$ ‰	δD ‰
						Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	CO_3^{2-}	F^{-}	Cl^{-}	NO_3^{-}	Br^{-}	SO_4^{2-}		
Unconfined	n=4	Mean	1055	7.08	12.07	141.33	32.88	47.57	9.27	1.48	371.00	1.11	41.36	0.65	0.16	241.44	-16.69	-124.60
						7.05	2.71	2.07	0.24	0.02	12.37	0.06	1.17	0.01	0.00	5.03		
Upper Confined	n=3	Mean	674	7.3	13.2	79.27	21.03	26.02	6.57	0.77	252.87	1.34	18.56	0.89	0.09	103.94	-17.33	-130.23
						3.96	1.73	1.13	0.17	0.01	8.43	0.07	0.52	0.01	0.00	2.16		
Lower Confined	n=4	Mean	412	7.5	12.4	52.86	14.47	17.35	3.73	0.50	217.53	1.24	11.28	0.83	0.04	35.00	-17.27	-129.60
						2.64	1.19	0.75	0.10	0.01	7.25	0.07	0.32	0.01	0.00	0.73		
[1]**Streams**	n=15	Mean	234	8.2	12.3	37.45	9.84	6.29	1.84	153.59	0.37	0.07	8.26	0.31	0.00	17.52	-16.26	-122.03
						1.87	0.81	0.27	0.05	2.52	0.01	0.00	0.23	0.00	0.00	0.36		
[1]**Thermal**	n=6	Mean	3200	6.2	40.1	333.55	72.79	129.25	28.81	699.50	0.00	1.66	110.29	0.23	0.44	723.67	-17.68	-131.46
						16.64	5.99	5.62	0.74	11.46	0.00	0.09	3.11	0.00	0.01	15.07		

[1]**From Carreón et al (2003)**

Table 4 Mean Chemistry and Stable Isotopic Values

Sample	$\delta^{13}C_{PDB}$	^{14}C pmc	+-	Modeled age (yrs)
Unconfined				
[1]MFH-1	-8.1	44.4	1.3	2500
[1]MFH-2	-8.9	46.3	1.1	5800
[1]MFH-3	-7.4	33.3	0.9	3400
[2] 15	-6.3	43.7		Mixed-Modern
Upper Confined				
3298	-6.26	45.2	0.6	1800
Lower Confined				
2116	-8.6	42.79	1.1	2000
3879	-11.21	77.7	0.7	Modern
Thermal				
[1]HS-1	-6.1	10.2	1.2	>2300
[1]HS-2	-5.2	12.5	1.2	>3200
[1]HS-3	-6.8	7.8	0.7	>7500

[1] From Carreón et al. (2003)

[2] From Mayo and Louks (1995)

Table 5 Radiocarbon Ages: $\delta 13C_{PDB}$, ^{14}C Percent Modern Carbon (pmc), and Modeled Ages

			Water Concentration Corrected for Purging Efficiency			Equivalent Atmospheric Concentration CFC (pmol/mol)			CFC-Derived Apparent Recharge Age In years before sampling date					
Site	Recharge Elev. (m)	Recharge Temp °C	CFC12 pmol/Kg	CFC11 pmol/Kg	CFC113 pmol/Kg	12.0	11.0	113.0	CFC12 years	error years	CFC11 years	error years	CFC113 years	error years
Headspring	1660	6.8	3.00	4.32	0.25	568.3	208.1	38.3	[1]Supersaturated		21	2	20	2
Headspring	1660	0.0	3.00	4.32	0.25	389.0	136.2	24.1	20	2	28	2	24	2
MW-1	1829	6.8	0.84	1.08	0.03	163.4	52.9	5.1	32	2	35	2	35	4
MW-1	1829	0.0	0.84	1.08	0.03	111.8	34.6	3.2	36	2	38	2	36	4
PW-3	1829	6.8	0.88	1.92	0.02	171.1	94.6	3.6	32	2	31	2	36	4
PW-3	1829	0.0	0.88	1.92	0.02	117.1	61.9	2.3	35	2	34	2	36	4

[1] Supersaturated indicates the equilvalent atmospheric concentration is above the maximum observed atmospheric concentration, implying that there are additional non-atmospheric sources of the CFC.

CFC	Current Atmospheric Value	Max Atmospheric Value
CFC-12	~ 546 pmol/mol	
CFC-11	~ 255 pmol/mol	~ 272 pmol/mol in 1994
CFC-113	~ 79 pmol/mol	~ 85 pmol/mol in 1994

Table 6 Chlorofluorcarbon (CFC) Concentrations and Derived Recharge Ages From Headspring (Unconfined System), MW-1 (Upper Confined System), and PW-3 (Lower Confined System).

The mean annual air temperature of the Midway area is about 6.8°C. However, a large portion of recharge in the Midway area occurs as wintertime snow. Therefore, CFC concentrations were analyzed using an estimate of O°C in addition to the 6.8°C estimate. A recharge elevation of 1829 m was estimated for samples taken from PW-3 and MW-1.

APPENDIX A

Pump Test Data

Constant Rate Time-Drawdown Pump Test

PW-1 Time Drawdown **Q=3440 L/min (909 gal/min)** **Date 9/29/04**

PW-2		PW-3		MW1		MW-2	
Min	s (m)	Time	s (m)	Min	s (m)	Min	s(m)
0	0.000	0.17	0.000	16.53	0.006	16.53	0.695
0.5	0.003	0.33	0.000	27.97	0.015	27.97	0.741
0.75	0.012	0.5	0.000	37	0.024	37	0.765
1.16	0.030	0.7	0.000	47	0.030	47	0.783
1.5	0.052	1	0.000	57	0.034	57	0.796
1.75	0.073	1.58	0.003	67	0.038	67	0.808
2	0.082	1.5	0.006	77	0.043	77	0.814
2.5	0.104	1.67	0.012	87	0.043	87	0.820
3	0.125	1.75	0.015	100	0.046	100	0.826
4	0.165	1.8	0.027	200	0.058	200	0.863
5.5	0.207	2.17	0.021	300	0.061	300	0.875
6	0.216	2.33	0.024	400	0.067	400	0.893
7	0.235	2.5	0.027	500	0.073	500	0.905
8	0.253	3	0.037	600	0.079	600	0.917
9	0.268	3.5	0.052	700	0.085	700	0.939
10	0.280	3.75	0.055	800	0.085	800	0.948
20	0.360	4	0.058	900	0.088	900	0.960
30	0.393	4.58	0.072	1440	0.094	1440	0.963
40	0.411	5	0.076	1627	0.098	1627	0.966
50	0.436	6	0.091	1807	0.101	1807	0.988
60	0.448	7	0.108	2843	0.113	2843	1.030
70	0.457	8	0.119	2880	0.113	2880	1.033
80	0.466	9	0.128				
90	0.472	10	0.139				
100	0.479	11	0.148				
200	0.521	12	0.155				
300	0.533	16	0.183				
400	0.552	20	0.201				
500	0.564	30	0.232				
600	0.579	40	0.251				
700	0.600	50	0.262				
800	0.613	60	0.276				
900	0.622	70	0.288				
1440	0.637	80	0.296				
1627	0.643	90	0.302				
1807	0.649	100	0.307				
2843	0.692	200	0.344				
2880	0.693	300	0.363				
		400	0.375				
		500	0.387				
		600	0.402				
		700	0.421				
		800	0.433				
		900	0.445				
		1440	0.460				
		1627	0.465				
		1807	0.466				
		2843	0.512				
		2880	0.514				

PW-2 Time Drawdown **Q=5307 L/min (1402 gal/min)** **Date 2/11/04**

PW-1		MW-1		MW-2		MW-3	
Min	**s (m)**	**Time**	**s (m)**	**Min**	**s (m)**	**Min**	**s(m)**
0	0.000	0	-0.015	0	0.006	0	0.116
0.75	0.229	0.33	-0.046	0.25	0.015	0.1	0.000
1	0.305	0.5	-0.061	0.42	0.027	0.3	0.134
1.33	0.405	0.67	-0.067	0.62	0.052	0.5	0.146
1.5	0.457	0.87	-0.091	0.8	0.067	0.8	0.162
1.72	0.524	1.08	-0.098	1	0.082	1	0.177
1.8	0.549	1.33	-0.107	1.17	0.098	2	0.204
2.05	0.625	1.67	-0.122	1.5	0.119	3	0.244
2.33	0.710	1.83	-0.122	2.5	0.171	4	0.265
3	0.914	2.17	-0.122	3.5	0.204	5	0.290
4	1.219	3	-0.122	4.5	0.233	6	0.311
5.17	1.576	4	-0.137	5.5	0.256	7	0.326
6	1.829	5	-0.128	6.5	0.275	8	0.344
7	2.134	6	-0.122	7.5	0.291	9	0.354
8	2.438	7	-0.116	8.5	0.308	10	0.369
9	2.743	8	-0.107	9.5	0.320	20	0.436
10	3.048	9	-0.098	10.5	0.354	30	0.469
11	3.353	10	-0.098	11.5	0.338	40	0.488
12	3.658	11	-0.073	12.5	0.346	50	0.506
21	6.401	21	0.290	13.5	0.354	60	0.512
30	9.144	22	0.244	23.5	0.407	70	0.523
40.5	12.344	23	0.213	33.5	0.436	80	0.527
51	15.545	24	0.198	43.5	0.453	90	0.533
60	18.288	25	0.168	53.5	0.463	100	0.539
71	21.641	27	0.165	63.5	0.472	210	0.579
81	24.689	31	0.165	73.5	0.480	310	0.619
90	27.432	41	0.198	83.5	0.485	410	0.597
100	30.480	42	0.232	93.5	0.489	510	0.604
110	33.528	61	0.262	103.5	0.494	610	0.613
210	64.008	71	0.296	113.5	0.500	710	0.616
310	94.488	81	0.320	210	0.524	810	0.616
410	124.968	91	0.341	310	0.539	910	0.619
510	155.448	101	0.381	410	0.552	1010	0.640
610	185.928	111	0.384	510	0.555	1110	0.640
710	216.408	210	0.533	610	0.564	1210	0.640
810	246.888	310	0.610	710	0.567	1310	0.643
910	277.368	410	0.655	810	0.570	1410	0.643
1010	307.848	510	0.716	910	0.604	1510	0.649
1110	338.328	610	0.686	1010	0.604	1610	0.658
1210	368.808	710	0.686	1110	0.591	1710	0.658
1310	399.288	810	0.698	1210	0.602	1840	0.658
1410	429.768	910	0.792	1310	0.607	2470	0.658
1510	460.248	1010	0.808	1410	0.607	2570	0.664
1610	490.728	1110	0.808	1510	0.610	2670	0.674
1710	521.208	1210	0.808	1610	0.614		
1840	560.832	1310	0.838	1710	0.610		
2470	752.856	1410	0.838	1840	0.607		
2570	783.336	1510	0.853	2470	0.613		
2670	813.816	1610	0.869	2570	0.619		
2740	835.152	1710	0.884	2670	0.625		
		1840	0.838	2740	0.622		
		2470	0.893				
		2570	0.930				
		2670	0.945				
		2740	0.914				

PW-3 Time Drawdown **Q=7195 L/min (1901 gal/min)** **Date 8/30/04**

PW-1		PW-2		MW-1		MW-2	
Min	**s (m)**	**Time**	**s (m)**	**Min**	**s (m)**	**Min**	**s(m)**
0	0.000	0.13	0.000	0.2	0.000	0	0.000
0.08	0.000	0.25	0.002	0.4	0.000	0.17	0.000
0.42	0.003	0.38	0.003	0.6	0.000	0.33	0.000
0.75	0.003	0.50	0.008	0.8	0.001	0.5	0.000
1	0.006	0.63	0.009	1	0.001	0.67	0.002
2	0.012	0.75	0.011	2	0.005	1	0.005
3	0.018	0.88	0.014	3	0.005	2	0.021
4	0.027	1	0.050	4	0.005	3	0.040
5	0.034	2	0.084	5	0.005	4	0.056
6	0.043	3	0.104	6	0.005	5	0.072
7	0.049	4	0.120	7	0.005	6	0.084
8	0.055	5	0.134	8	0.006	7	0.096
9	0.061	6	0.149	9	0.006	8	0.107
10	0.064	7	0.163	10	0.007	9	0.116
20	0.189	8	0.174	20	0.019	10	0.125
30	0.201	9	0.183	30	0.029	20	0.191
40	0.210	10	0.191	40	0.037	30	0.226
50	0.226	20	0.244	50	0.043	40	0.247
60	0.238	30	0.291	60	0.049	50	0.265
70	0.247	40	0.312	70	0.052	60	0.276
80	0.253	50	0.328	80	0.055	70	0.283
90	0.262	60	0.338	90	0.058	80	0.293
100	0.268	70	0.347	100	0.060	90	0.300
200	0.329	80	0.357	200	0.075	100	0.308
300	0.351	90	0.367	300	0.082	200	0.347
400	0.357	100	0.375	400	0.088	300	0.364
500	0.354	200	0.416	500	0.094	400	0.376
600	0.360	300	0.437	600	0.099	500	0.392
700	0.354	400	0.450	700	0.104	600	0.399
800	0.352	500	0.462	800	0.109	700	0.413
900	0.357	600	0.472	900	0.113	800	0.431
1000	0.360	700	0.491	1000	0.113	900	0.439
1218	0.364	800	0.507	1218	0.122	1000	0.451
1368	0.369	900	0.517	1368	0.125	1218	0.469
1518	0.448	1000	0.526	1518	0.128	1368	0.479
1668	0.459	1218	0.547	1668	0.130	1518	0.485
		1368	0.554			1668	0.488
		1518	0.559				
		1668	0.561				

Continued

PW-3 Time Drawdown **Q=7195 L/min (1901 gal/min)** **Date 8/30/04**

MW-3	
Min	**s (m)**
0	0.003
1.7	0.003
0.33	0.003
0.5	0.004
0.67	0.005
0.83	0.005
1	0.006
1.17	0.008
2	0.017
3	0.031
4	0.046
5	0.059
6	0.070
7	0.081
8	0.091
9	0.101
10	0.110
20	0.175
30	0.213
40	0.237
43.67	0.246
66.8	0.291
90	0.291
100	0.298
107.33	0.306
110	0.306
200	0.337
300	0.358
400	0.370
500	0.381
600	0.387
700	0.404
800	0.422
900	0.432
1000	0.445
1218	0.459
1368	0.462
1518	0.477
1668	0.477

PW-1 Free Flowing Time Drawdown Pump Test

Date 4/20/04

PW-2		MW-2		MW-3	
Min	**s (m)**	**Min**	**s (m)**	**Min**	**s (m)**
0.5	0.030	0.17	0.003	0.25	0.003
0.67	0.046	0.33	0.006	0.47	0.007
1	0.061	0.5	0.006	0.57	0.005
2	0.091	0.67	0.006	0.73	0.006
3	0.122	0.83	0.009	0.85	0.008
4	0.137	1	0.009	1.02	0.009
5	0.168	1.25	0.009	1.18	0.009
6	0.183	1.5	0.009	1.37	0.011
7	0.198	1.75	0.010	1.48	0.011
8	0.213	2	0.012	2.48	0.014
9	0.229	2.5	0.014	3.48	0.015
10	0.244	2.75	0.015	4.48	0.015
20	0.290	3	0.015	5.48	0.020
30	0.320	3.5	0.017	6.48	0.021
40	0.335	4	0.018	7.48	0.024
50	0.351	4.5	0.020	8.48	0.025
60	0.351	5	0.020	9.5	0.025
70	0.366	6	0.021	10.5	0.026
80	0.381	6.5	0.049	11.5	0.027
90	0.396	7	0.023	21.5	0.029
100	0.396	7.5	0.024	31.5	0.033
200	0.408	8	0.024	41.5	0.035
300	0.408	8.5	0.024	51.5	0.036
400	0.408	9	0.025	61.5	0.038
500	0.399	9.5	0.025	71.5	0.041
600	0.396	10	0.027	81.5	0.038
700	0.395	11	0.027	91.5	0.044
800	0.399	12	0.028	101.5	0.040
900	0.404	13	0.029	200	0.048
1000	0.404	14	0.030	300	0.051
1440	0.399	15	0.030	400	0.051
1740	0.053	20	0.033	500	0.044
2000	0.045	30	0.035	600	0.043
2850	0.046	40	0.037	700	0.043
3000	0.049	50	0.039	800	0.043
3300	0.061	60	0.040	900	0.043
4000	0.064	70	0.041	1000	0.043
4320	0.069	80	0.042	1440	0.043
5000	0.059	90	0.043	1740	0.055
6000	0.059	100	0.043	2000	0.050
7000	0.073	200	0.048	2850	0.052
8000	0.076	300	0.050	3000	0.055
8610	0.082	400	0.050	3300	0.064
8850	0.069	500	0.043	4000	0.067
9000	0.059	600	0.043	4320	0.072
9120	0.053	700	0.040	5000	0.063
10000	0.046	800	0.043	6000	0.066
10320	0.011	900	0.046	7000	0.066
11460	-0.006	1000	0.046	8000	0.075
11760	-0.011	1440	0.044	8610	0.090
12900	-0.009	1740	0.055	8850	0.079
14340	-0.009	2000	0.047	9000	0.073
14640	-0.008	2850	0.051	9120	0.067

PW-1 Free Flowing Time Drawdown Pump Test Continued **Date 4/20/04**

PW-2		MW-2		MW-3	
Min	**s (m)**	**Min**	**s (m)**	**Time**	**s (m)**
14850	-0.009	3000	0.055	10000	0.049
17610	-0.003	3300	0.067	10320	0.028
18660	0.002	4000	0.061	11460	0.002
19140	-0.012	4320	0.066	11760	-0.012
20100	0.005	5000	0.058	12900	0.018
20430	-0.006	6000	0.059	14340	0.008
20760	-0.009	7000	0.055	14640	0.008
21660	0.000	8000	0.000	14850	0.002
21960	-0.003	8610	0.085	17610	-0.035
22185	-0.012	8850	0.073	18660	-0.030
23140	-0.015	9000	0.064	19140	-0.037
		9120	0.060	20100	-0.024
		10000	0.047	20430	-0.018
		10320	0.023	20760	-0.026
		11460	-0.002	21660	-0.008
		11760	-0.011	21969	0.005
		12900	0.009	22185	0.005
		14340	0.000	23140	0.005
		14640	-0.006	23445	0.005
		14850	-0.008	23730	0.035
		17610	-0.040	24660	0.059
		18660	-0.040		
		19140	-0.049		
		20100	-0.034		
		20430	-0.034		
		20760	-0.040		
		21660	-0.024		
		21960	-0.009		
		22185	-0.015		
		23140	-0.009		
		23445	0.009		
		23730	0.015		

STEP TEST

PW-2 2/13/04

Min	Q (gal/min)	L/min	s (m)
0	1154	4368	6.53
1.38	1154	4368	6.58
1.77	1154	4368	5.74
3.68	1154	4368	5.74
8	1154	4368	5.74
13	1154	4368	5.74
18	1154	4368	5.74
23	1154	4368	5.74
28	1154	4368	5.74
29.5	1308	4951	5.79
30	1308	4951	6.55
30.33	1308	4951	6.65
30.67	1308	4951	6.73
30.83	1308	4951	6.78
31.08	1308	4951	6.81
31.67	1308	4951	6.86
31.83	1308	4951	6.88
32.35	1308	4951	6.88
37	1308	4951	6.91
42	1308	4951	6.93
47	1308	4951	6.91
52	1308	4951	6.91
57	1308	4951	6.91
61.17	1446	5473	7.47
61.5	1446	5473	7.82
61.83	1446	5473	8.08
62	1446	5473	8.23
62.17	1446	5473	8.23
62.33	1446	5473	8.25
62.5	1446	5473	8.28
62.75	1446	5473	8.31
63	1446	5473	8.33
63.33	1446	5473	8.28
63.92	1446	5473	8.38
64.43	1446	5473	8.38
65	1446	5473	8.38
67	1446	5473	8.38
75	1446	5473	8.38
80	1446	5473	8.37
85	1446	5473	8.38
90	1446	5473	8.39
91.33	1592	6026	8.53
91.52	1592	6026	8.79
91.67	1592	6026	8.99
91.83	1592	6026	9.14
92	1592	6026	9.32
92.33	1592	6026	9.47
92.5	1592	6026	9.65
92.6	1592	6026	9.68
92.78	1592	6026	9.70
92.87	1592	6026	9.73
93.08	1592	6026	9.75
93.35	1592	6026	9.78
93.75	1592	6026	9.80
94.4	1592	6026	9.83

Continued

PW-2 2/13/04

Min	Q (gal/min)	L/min	s (m)
94.87	1592	6026	9.83
95.3	1592	6026	9.86
96	1592	6026	9.88
101	1592	6026	9.93
106	1592	6026	9.93
111	1592	6026	9.96
116	1592	6026	9.98
121	1592	6026	9.79
126	1592	6026	10.07
129.5	1592	6026	10.06
131	1592	6026	10.07

STEP TEST

PW-3 8/27/04

Min	Q (gal/min)	L/min	s (m)
0.00	1126	4262	0.00
2.00	1126	4262	1.98
2.75	1126	4262	2.03
3.33	1126	4262	2.03
6.12	1126	4262	2.03
9.67	1126	4262	2.03
19.33	1126	4262	2.03
27.13	1126	4262	2.03
30.50	1490	5640	2.74
31.00	1490	5640	3.05
31.25	1490	5640	3.35
31.50	1490	5640	3.73
31.58	1490	5640	3.96
31.78	1490	5640	4.04
32.17	1490	5640	4.04
33.18	1490	5640	4.11
35.00	1490	5640	4.14
40.00	1490	5640	4.14
44.50	1490	5640	4.14
50.00	1490	5640	4.14
53.62	1490	5640	4.14
61.40	1490	5640	4.14
62.00	1833	6938	4.88
62.25	1833	6938	5.33
62.35	1833	6938	5.64
62.42	1833	6938	5.79
62.62	1833	6938	6.10
62.78	1833	6938	6.15
62.90	1833	6938	6.32
63.12	1833	6938	6.38
63.25	1833	6938	6.40
63.33	1833	6938	6.45
63.52	1833	6938	6.48
63.67	1833	6938	6.50
63.77	1833	6938	6.53
63.97	1833	6938	6.55
64.00	1833	6938	6.58
64.17	1833	6938	6.60
64.18	1833	6938	6.63
64.48	1833	6938	6.63
64.68	1833	6938	6.65
64.83	1833	6938	6.68
65.00	1833	6938	6.68
65.50	1833	6938	9.22
65.92	1833	6938	6.68
68.00	1833	6938	6.71
83.12	1833	6938	6.73
88.05	1833	6938	6.73
91.00	2209	8361	7.01
91.07	2209	8361	7.32
91.17	2209	8361	7.92
91.30	2209	8361	8.08
91.33	2209	8361	8.38
91.68	2209	8361	8.84
91.83	2209	8361	8.89
91.98	2209	8361	8.99
92.25	2209	8361	9.14
92.48	2209	8361	9.30
92.63	2209	8361	9.45
92.80	2209	8361	9.53
93.00	2209	8361	9.55
93.17	2209	8361	9.55
93.35	2209	8361	9.55
93.50	2209	8361	9.58
94.40	2209	8361	9.60
94.72	2209	8361	9.63
95.00	2209	8361	9.65
95.25	2209	8361	9.68
95.50	2209	8361	9.70
95.75	2209	8361	9.68
97.30	2209	8361	9.75
97.62	2209	8361	9.75
101.63	2209	8361	9.86
103.75	2209	8361	9.91
106.83	2209	8361	9.93
110.25	2209	8361	9.96
113.58	2209	8361	9.98
116.13	2209	8361	10.01
119.82	2209	8361	10.03
119.92	2209	8361	10.06

APPENDIX B

Water Sample Chemistry

		Date	Cond	pH	temp.	mg/L											
Lab #	Sample	Collected	µS/cm		°C	Ca	Mg	Na	K	Fe	Sr	HCO3	F	Cl	NO3	Br	HPO4	SO4
Unconfined																		
519	Headspring	9/28/1999	705	7.00	14.7	129.00	28.86	37.80	9.68			360.00	0.94	37.17	0.71	0.17		222.73
2117	MW-4	4/20/1997	1080	7.17	10.7	140.30	41.54	61.87	10.19	0.06	1.78	397.00	1.50	42.78	0.52	0.17	0.68	256.93
2118	MW-5	4/20/1997	1061	7.07	12.4	146.60	31.10	48.52	9.35	0.05	1.32	370.00	1.07	42.44	0.65	0.14	0.58	243.58
2119	MW-6	4/20/1997	1024	6.99	13.1	149.40	30.00	42.08	7.85	0.06	1.35	357.00	0.92	43.06	0.70	0.14	0.60	242.50
Upper Confined																		
3298	MW-1	6/26/2003	921	7.28	14.2	79.60	25.63	30.52	6.98			213.60	2.35	24.25				140.31
2114	MW-1	4/20/1997	619	7.25	12.7	82.07	19.41	24.21	6.45	0.02	0.79	275.00	0.86	16.71	0.89	0.07	0.11	88.14
1899	MW-1	1/9/1997	481	7.34	12.7	76.15	18.06	23.34	6.27	0.13	0.74	270.00	0.80	14.73	0.88	0.10	0.13	83.37
Lower Confined																		
2115	MW-2	4/20/1997	451.5	7.54	12.6	57.58	15.08	17.17	4.59	0.01	0.54	222.00	0.75	12.17	0.75	0.05	0.11	44.62
2116	MW-3	4/20/1997	497	7.39	12.6	64.25	16.66	19.31	5.21	0.03	0.60	231.00	0.82	14.89	0.57	0.06	0.11	61.11
1900	MW-2	1/9/1997	287.1	7.65	12.1	41.72	12.38	14.15	2.59	0.12	0.36	204.00	0.15	6.86	1.02	0.00	0.00	17.39
3879	PW-3	9/1/2004				47.87	13.77	18.76	2.55	0.00		213.10	3.23	11.19	0.96			16.89
1Streams	n=15	Mean	234.15	8.18	12.27	37.45	9.84	6.29	1.84		153.59	0.37	0.07	8.26	0.31	0.00	0.04	17.52
		n=	15															
1Thermal	n=6	Mean	3200	6.22	40.1	333.55	72.79	129.25	28.81			699.50		110.29	0.23	0.44		723.67
		n=6	6															

1 From Carreón et al (2003)
All others from water database

	Sample	Date Collected	δ18O	δD	TU	eTU
Unconfined						
519	Headspring	9/28/1999	-16.69	-124.598549	8	3
2117	MW-4	4/20/1997	-16.5135554	-124.55	5	2
2118	MW-5	4/20/1997	-17.1479653	-125.07	7	2
2119	MW-6	4/20/1997	-16.3601146	-123.9	4	3
3300	Headspring	6/26/2003	-16.65	-123.66	2.3	6520
[1]MFH-1			-16.50	-125.50		
[1]MFH-2			-16.50	-126.30		
[1]MFH-3			-16.80	-126.50		
[1]MFH-1			-16.50	-125.30		
[1]MFH-2			-16.60	-125.70		
[1]MFH-3			-16.40	-126.80		
Upper Confined						
1899	MW-1	1/9/1997	-17.4776712	-132.454979		
2114	MW-1	4/20/1997	-16.85	-128.76	6.39	0.21
3298	MW-1	6/26/2003	-17.66	-129.47		
		Mean	-17.3292237	-130.228326	6.39	0.21
Lower Confined						
1900	MW-2	1/9/2001	-17.42	-132.16		
1901	MW-2 Post test	1/16/2001	-17.15	-129.79		
1902	MW-2 Pre-test	1/16/2001	-17.18	-128.79		
2029	MW-3	2/19/2001	-17.61	-133.94		
2115	MW-2	4/20/1997	-16.93	-129.15		
2116	MW-3	4/20/1997	-17.42	-130.17	8	2
2840	PW #1	5/29/2002	-17.54	-130.32		
2841	PW #1	4/8/2002	-17.37	-129.45		
2844	PW #1 Post Test	6/7/2002	-17.49	-129.56		
2845	PW #1 Pre Test	6/6/2002	-17.26	-130.02		
3299	PW-1	6/26/2003	-17.66	-129.50		
3879	PW-3	9/1/2004	-17.16	-128.35		

[1] From Carreón et al (2003)

All others from water database