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WHAT HAPPENS WHEN THE CONFINED CAMBRIAN-ORDOVICIAN AQUIFER IN SOUTHEASTERN WISCONSIN BEGINS TO BE "DEWATERED"?

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PROJECT SUMMARY

Background/Need: The Cambrian-Ordovician aquifer has long been an important source of municipal water supply in Wisconsin, and recent trends are of some concern for future supply. Pumping has drawn down the potentiometric surface (hydrostatic pressure) of this deep aquifer system by over 400 ft during the 20th century. Wisconsin state observation wells show that head in the deep aquifer system continues to decline at a rate of 7 ft/yr and will eventually dip into the top of the St. Peter sandstone, causing dewatering as air enters the pore space. Computer simulations cannot account for reduction in hydraulic conductivity caused by progressively developing unsaturated conditions near the well bore, which forms the principal avenue for air to reach the aquifer. It is not clear exactly what happens under these conditions in the real world because few observations have been made of this phenomenon in deep aquifers where field data are rarely available.

Objectives: The goal of the research reported here was to investigate possible dewatering phenomena in the Cambrian-Ordovician aquifer system in southeastern Wisconsin. The specific objectives were **1)** to investigate how unsaturated conditions might develop in a physical sand-tank model, **2)** to attempt to verify the development of such hydrogeologic conditions in the field, and **3)** to predict the long-term impact on water supply and quality by observing the evolution of head in the vicinity of model pumping wells.

Methods: The sand-tank model was based on a design developed by Dr. James O. Peterson and Ronald Hennings, now in widespread use across the United States. It consists of vertical Plexiglas plates mounted one inch apart containing saturated sands and clays arranged to represent generic subsurface formations in profile. Sediments used were carefully analyzed for grain size and uniformity to be able to estimate resulting hydraulic conductivity when packed. The model was customized with double-curved manometer tubes and scaled graduations on either face of the model, that enabled head to be measured as the colored water levels fell below the elevation of the piezometer openings in the model aquifer. In response to pumping of wells centered in the sediment, head data over time was recorded on video camcorders. Model runs were made with a laboratory pump connected to both well discharge tubes, with wellhead valves in closed and open positions. Head in the pumping wells was drawn down below the top of the confined aquifer, drawdown was observed in the manometer water levels around each pumping well, and resulting cones of depression quickly merged. Data were compiled by viewing the resulting videotape and transcribing the head values, read as the water levels in each manometer passed the graduated lines on the model faces. These data were plotted in the form of graphs of head change over time. They were also plotted as contour maps of the head field in the plane of the model at successive times. A field component of this project consisted of converting and instrumenting an open borehole at a site west of Milwaukee to a monitoring well with a short screen in the Sinnipee Group dolomite below the Maquoketa Formation.

Results and Discussion: Basic drawdown data shows that heads at the monitoring points responded rapidly to the pumping well drawdown, and that there are significant variations in head with depth. Head data at the monitoring points after pumping water level stabilization indicates fluctuations over time. Close examination of these fluctuations show that they are out of sequence with changes in pumping water level, a complexity in the head field in a near-uniform model aquifer, that is rarely if ever observed in actual monitoring wells. The effective pumping rate was uncontrolled, but monitored. As the pumping water level dropped, the instantaneous pumping rate peaked and then was reduced to stabilize at about 66% of maximum capacity. The coincidence of maximum pumping rate with drawdown stabilization suggests that the pumping reached some equilibrium where it was balanced by steady-state flow from the lateral constant-head boundaries. In the confined model aquifer, the hydraulic head was used to infer less than saturated conditions when the measured head fell below the elevation of the monitoring points. Resulting hydraulic pressure at the monitoring points decreases below atmospheric, at which time air enters the pore space, and pore water drains out forming a seepage face. The data show that this desaturation phenomenon occurs relatively rapidly. Head decreased to the elevation of the top of the aquifer first near one well then the other, followed by a merging of the desaturating fronts, which advanced quickly to approximately halfway down the thickness of the aquifer. Water level measurements at the field site indicate that hydraulic head in the Sinnipee Group dolomite is just above the elevation of the monitoring screen at that location.

Conclusions/Implications/Recommendations: After onset, the spread of desaturating conditions is relatively rapid at first, but then slows. Simulated lateral spread from wells is also rapid, leading to a merging of zones of desaturation near the top of the aquifer, before spreading to greater depths, in contrast to expected vertical development near well bores. As pumping well head decreases level off when flow from the boundaries equals the rate of well pumpage, head at monitoring points at elevations near the pumping water level continue to fluctuate over timeframes that are difficult to explain solely by pumping water level fluctuations. Pumping rates decrease as pumping water levels fall below the top of the aquifer and saturated thickness diminishes. Without airflow down the wellbore, pumping rates are much lower and head drawdown much less rapid. Measurement of hydraulic head at the field site suggests that regional drawdown in the underlying Cambrian-Ordovician aquifer is now sufficient to cause development of desaturated zones in the Sinnipee Group dolomite around open wells.

Desaturation of pore-space causes decreases in hydraulic conductivity that affect flow through the desaturating zone to the well, shown by the asynchronous fluctuations in head. Such dynamics would be more complex in a fully three-dimensional system, and flow to an overpumped well may be the integration of sequential flows from different sectors around the well depending on the relative saturation of the surrounding pore space. The practical consequences could be increased oxidation reactions and deterioration of water quality depending on the mineralogy of the aquifer material. These dynamics of desaturation may also seriously reduce municipal well yields for given rates of drawdown. Once such desaturation is widespread, it may be impossible for well yields to recover, even with cessation of pumping, because air becomes indefinitely trapped in the pore-space.

Related Publications: Eaton, T.T., 2004. Desaturation and flow dynamics beneath an aquitard near excessively pumped wells. Geological Society of America *Abstracts with Programs*, Vol 36 No.5

Key Words: confined aquifer, aquitard, desaturation, flow dynamics

INTRODUCTION AND BACKGROUND

The Cambrian-Ordovician aquifer has long been an important source of municipal water supply in Wisconsin, and recent trends show significant drawdown due to pumpage. In inland counties in southeastern Wisconsin, where diversion of water from Lake Michigan is limited by international treaty (the Great Lakes Charter; International Joint Commission, 2000), pumping for municipal water supply has drawn down the potentiometric surface (hydrostatic pressure) of the deep Cambrian-Ordovician aquifer system by over 400 ft during the 20th century (SEWRPC/WGNHS, 2002). Although recent results of a regional groundwater flow model (Feinstein et al., 2004) show that the potentiometric surface has been drawn down locally below the base of the Maquoketa Formation, which forms the regional aquitard, little field evidence exists to substantiate this. Construction records from the late 1980s and 1990s for some wells open to the upper part of the underlying aquifer system suggest that static water levels are in the Sinnipee Group dolomite, below the base of the Maquoketa Formation. Wisconsin state observation wells show that head in the deep aquifer system continues to decline at a rate of 7 ft/yr and will eventually dip into the top of the St. Peter sandstone, a major aquifer of the Cambrian-Ordovician system.

Confined aquifers, like the unpumped Cambrian-Ordovician system, have potentiometric heads above the elevation of the base of the aquitard and in some cases, land surface, when wells flow under artesian pressures. Pumping causes water to be released from storage, reducing the potentiometric head. Regional groundwater flow models in the Green Bay area (Krohelski, 1986), the Chicago area (Young, 1992) and southeastern Wisconsin (Feinstein et al., 2004; SEWRPC, 1976) all predicted that pumping would cause potentiometric head to decline below the base of the aquitard, and suggested that locally, the Cambrian-Ordovician aquifer would convert to unconfined, water-table conditions. Conventional flow modeling codes (McDonald and Harbaugh, 1988) simulate this conversion by using a much larger storage coefficient, the specific yield, implying that the formerly confined aquifer will begin to be dewatered as air enters the pore space. However, these simulations cannot account for reduction in hydraulic conductivity caused by progressively developing unsaturated conditions near the well bore, which forms the principal avenue for air to reach the aquifer. It is not clear exactly what happens under these conditions in the real world because few observations have been made of this phenomenon in deep aquifers where field data are rarely available.

The goal of the research reported here was to investigate possible dewatering phenomena in the Cambrian-Ordovician aquifer system in southeastern Wisconsin. The specific objectives were **1)** to investigate how unsaturated conditions might develop in a physical sand-tank model, **2)** to attempt to verify the development of such hydrogeologic conditions in the field, and **3)** to predict the long-term impact on water supply and quality by observing the evolution of head in the vicinity of model pumping wells. A field component of this project (described in the Appendix) consisted of converting and instrumenting an open borehole at a site west of Milwaukee to a monitoring well with a short screen in the Sinnipee Group dolomite below the Maquoketa Formation. This provided a real-world analog to experiments with the sand-tank model. Field instrumentation for long-term monitoring at this observation well will be able to detect the potential spread of unsaturated conditions extending from the nearby municipal pumping wells as head continues to decline in the deep aquifer system as anticipated.

The Maquoketa aquitard has been the subject of recent intensive field investigation (Eaton, 2002) at a site west of Milwaukee within a few miles of several deep municipal wells. Monitoring of hydraulic head in several sealed multi-level wells showed that while there is nearly a 200 ft (>60 m) head drop across the base of the Maquoketa Formation, unsaturated conditions in the underlying Sinnipee Group dolomite had not yet developed. Pumping with in-situ pumps of multi-level intervals for groundwater samples requires a connection to the atmosphere, and brief opening of such a path to the lowest monitoring interval has caused temporary declines in head in the Sinnipee Group dolomite. This suggests that under the extreme conditions of such a vertical head gradient, flow of air down the well bore becomes an important factor in understanding head measurements in wells finished below a deep aquitard.

PROCEDURES AND METHODS

Model construction and testing

The sand-tank model used here (Figure 1a) was based on a design developed by Dr. James O. Peterson (University of Wisconsin Environmental Resources Center) and Ronald Hennings (Wisconsin Geological and Natural History Survey), now in widespread use across the United States. It consists of vertical Plexiglas plates mounted one inch apart containing saturated sands and clays arranged to represent generic subsurface formations in profile. In the model designed for educational outreach, vertical constant-head channels at either end, combined with pumping well tubes attached to the back of the front plate, allow hydrostatic control of the water table near the top of the model. Head changes due to pumping, simulated with the siphon principle, can be measured in piezometer slots etched into the back of the front plate. The model is commonly used with food-grade dyes to illustrate the spread of groundwater contamination through the subsurface.

For the research described here, with the assistance of Dr. Peterson, the design of the model was customized with U-shaped manometers mounted on the piezometer slots on the upper edge of the model (Figure 1b). These double-curved manometer tubes and scaled graduations on either face of the model enabled head (as well as negative matric potential) to be measured as the colored water levels fell below the elevation of the piezometer openings in the model aquifer. This provided head data over time, recorded on video camcorders, at different locations in the model in response to pumping of wells centered in the sediment. Piezometer tips (Figure 1a, gray spots) on either face of the model were offset from each other to provide an equally spaced array of monitoring points. The model horizontal scale is approximately 1:15840, with manometer tubes spaced every 1 inch or 0.25 mile. There is a vertical exaggeration of about 11x for sediment layers to have sufficient thickness.

Sediments used in the research model were carefully analyzed for grain size and uniformity to be able to estimate resulting hydraulic conductivity when packed. Fine natural eolian sand (from Arena, Wisconsin) was collected, but found to be of too broad a grain-size distribution to be useful. Industrial glass beads sieved to between 106 μm (retained by #140 sieve) and 149 μm (retained by #100 sieve), were finally selected for the representation of the Cambrian-Ordovician aquifer system (from the St. Peter sandstone through the Mt. Simon sandstone). This appears in white in Figure 1a, and decreases in thickness to the west (left) as the crystalline Precambrian basement (in black) becomes shallower. The overlying stratigraphic layer representing the Sinnipee Group dolomite (buff), was made up of a 5% by mass mixture of bentonite gel powder and “Engineers sand”, a buff colored material of almost 90% finer than grain size of 250 µm (retained by #60 sieve). Above the Sinnipee Group dolomite layer, the Maquoketa shale, the principal aquitard, is represented by a reddish mixture of 10% bentonite gel powder by mass and the 106-149 µm fraction of Arena sand (80% finer than 250 µm). The Maquoketa shale layer pinches out near the left end of the model, as it does in the subsurface in southeastern Wisconsin. The shallow Silurian dolomite and unlithified aquifer layer above the Maquoketa was represented by pure “Engineers sand”. All sediment layers are scaled so that their relative thicknesses are accurately portrayed, and the major graduated lines visible on the model represent 100 ft of thickness above and below sealevel (0). The sediment in the model is retained in place by a reddish wood seal on top.

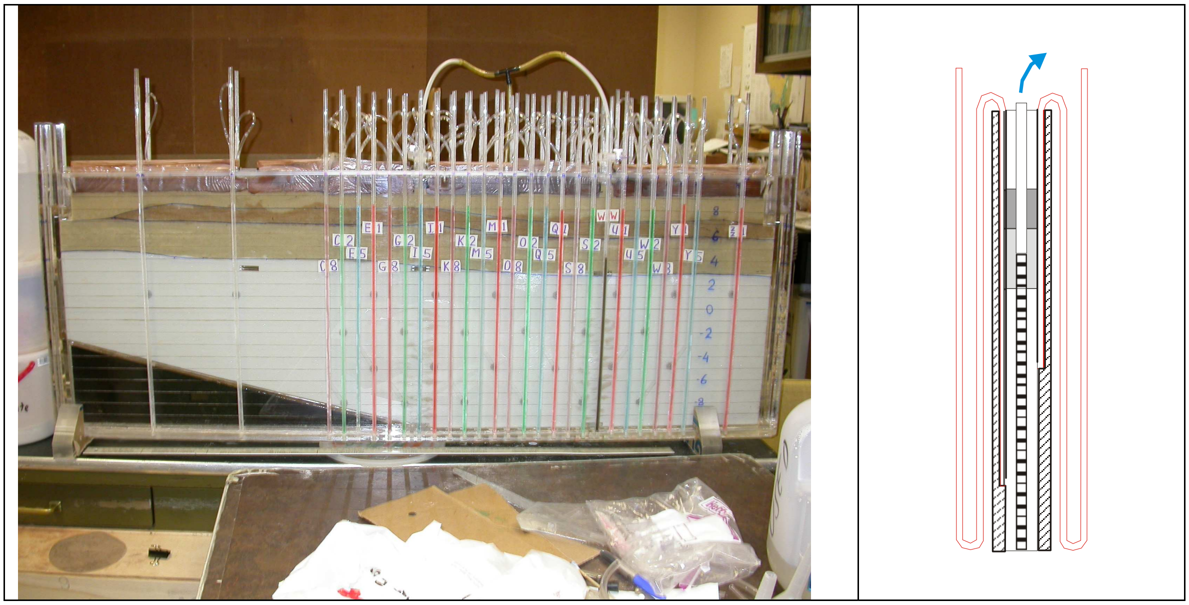

Figure 1: (a) Side view of sand tank model, (b) End view showing manometer design

Table 1: Estimated geometric mean hydraulic conductivity of sand-tank model sediments

Glass beads (106-140 µm) (n=3)	**Pure “Engineers sand” (n=3)**	**90 % “Engineers sand” + 5% bentonite (n=4)**
26.7 ft/d	385 ft/d	0.01 ft/d
31 ft/d (~ 1×10^{-11} m^2)*		
* Estimate of glass bead hydraulic conductivity using formula from Revil and Cathles (1999): **k** (m^2) **=** $d^2\varphi^{3m}/24$ where d: mean grain size diam (assumed 1.25×10^{-4} m) φ: porosity, assumed 0.4 m: cementation exponent (=1.5)		

The glass beads, “Engineers sand” and bentonite mixtures thereof were tested in a falling-head permeameter (Fetter, 2001) to obtain estimates of hydraulic conductivity when packed into the sand-tank model (Table 1). The mixture of Arena sand and 10% by mass bentonite was not tested due to time limitations, but assumed to be of suitably low conductivity to represent the Maquoketa shale. The hydraulic conductivity values estimated for glass beads, "Engineers sand", and the bentonite-sand mixture using the falling-head permeameter (Table 1), are sufficiently different from each other to adequately represent two aquifers and the interlayered aquitard respectively.

The estimated hydraulic conductivity of the glass beads is approximately an order of magnitude higher than the highest hydraulic conductivity of the Cambrian-Ordovician aquifer (Feinstein et al. 2004), but that was the lowest hydraulic conductivity that could be achieved by the selective sieving for this project. It does compare well to the hydraulic conductivity (converted from m^2) calculated with an empirical formula (Table 1) presented by Revil and Cathles (1999), which provides a cross-check on the tightness of glass bead packing (effective porosity) that is achievable in such a model. The hydraulic conductivity for the "Engineer's sand" representing the uppermost aquifer is about four times the largest hydraulic conductivity obtained by model calibration (Feinstein et al. 1999) for the unlithified aquifer. Since the uppermost layer merely represents a constant head boundary for the aquifer system in this model, the value of hydraulic conductivity for that layer is of little importance.

The glass beads were slowly packed into the empty plexiglas model, allowing them to settle underwater, and progressively raising the level of distilled water, used to minimize the possibility of algae growth. Small volumes of "Engineer's sand" (frozen in ice-cubes for installation) were placed immediately adjacent to the two wells in the glass bead aquifer to avoid any possibility of screen (106 μm) clogging. The bentonite-sand mixtures were added dry, but immediately and repeatedly wetted to avoid any trapping of air between the sediment grains. Several times during sand tank filling and at the end, the entire tank was placed on a vibrating sieve shaker to cause the material to settle as tightly as possible and minimize porosity due to poor grain packing. Manometer tubes were then assembled, connected to the model, and air bubbles removed. Food-grade dye was added to the external part of the manometer tubes to label piezometers finished at different elevations. Pumping rates achievable with a laboratory peristaltic pump were tested to determine resulting drawdowns observable in the manometers. The intake tube was placed at the bottom of the pumping wells, which have screens open to the entire Cambrian-Ordovician aquifer (glass beads). Separate manometers were also installed to monitor head levels in the pumping wells.

Model experimentation

Since the role of air penetrating down the pumping well bore is of interest for this investigation, small valves sealing the wellheads were installed after filling the wells. The vertical channels on each end of the model were filled above the level of the top of the model sediment, causing highly confined conditions in the glass-bead aquifer material, as shown by water levels in the manometers. Siphons were placed between the constant-head channels and gallon jugs of distilled water to ensure continuous high heads at the ends of the model. After experiments with an unsatisfactory mirror arrangement, two separate camcorders were placed to film each side of the model and record the head decreases represented by pumping-induced changes in colored water levels in the manometer tubes.

An initial pumping run was made with a laboratory peristaltic pump connected to both well discharge tubes, while keeping the wellhead valves closed. Drawdown was observed in the manometer water levels around each pumping well, and resulting cones of depression quickly merged. Head in the pumping wells was drawn down below the top of the confined aquifer (glass beads) and manometer water levels declined below the elevation of monitoring locations. Pressures of less than atmospheric were inferred for the upper parts of the confined aquifer even though air was not permitted to enter the pore-space. After only a few minutes of pumping however, bubbles appeared in the top of the pumping well manometer tube and the water level in one of the pumping wells slowly began recovering. It is possible that head change caused a pressure decrease below the vapor pressure of the water and degassing occurred. The water level in the other pumping well began a slow fluctuation near the maximum drawdown. Since the impact of degassing or air leaking into the first pumping well was unclear, the experiment was terminated and the water levels allowed to recover completely. In retrospect, the amount of water pumped from both wells (~850 mL), comparable to the amounts pumped for later tests, required almost 34 minutes, 3x longer than for the later test with wellhead valves open. The remainder of this report focuses on pumping with wellhead valves open.

Model operation and data analysis

The principal experiment for this research was conducted with the wellhead valves open, analogous to conditions at unsealed municipal wells in southeastern Wisconsin, where water levels may be drawn down below the elevation of the top of the Cambrian-Ordovician aquifer system. Initial conditions corresponded to prepumping historical conditions with confined aquifer head above land surface, maintained by siphons in the side constant-head channels. Video camcorders were set up to record data and the pump was started. Although no attempt was made to regulate flow, cumulative volumes of water pumped were measured over time in a graduated cylinder. Water levels declined in the pumping wells and surrounding manometer tubes, indicating development of a cone of depression. Maximum drawdown occurred at -350 ft asl in the easternmost well (T, black, at right in Figure 1a), but continued in the other well (H, at center in Figure 1a) down to below -500 ft asl, where it fluctuated before finally reaching -625 ft asl at the end of the test (1000 mL pumped).

Data were analyzed by viewing the resulting videotape and transcribing the head values, read as the water levels in each manometer passed the graduated lines on the model faces. There was some difficulty with video resolution, particularly with the analog camcorder compared with the digital camcorder, and with certain manometers where the dye was not dark enough to obtain unambiguous data. The video data were eventually converted to DVD for viewing using a media player on a computer, which helped in reviewing the data.

These data were processed in a spreadsheet, and then plotted in the form of graphs of head change over time. Using a suitable coordinate system, these data were also plotted as contour maps of the head field in the plane of the model corresponding to successive points in time. As the water levels in the wells dropped, an increasingly long air column is present in the wells, and causes a seepage face on the inside of the wells. This discontinuity in the head field is not handled easily with a contouring package, but was approximated by closely spaced points representing the current head values in the well bore. The data are reported in terms of feet compared to msl. to retain the analogy to possible future conditions in the aquifer system in southeastern Wisconsin, but perfect dynamic similitude was not intended. Additional processing of these data is possible but could not be accomplished within the time-frame of this project. Future analysis could investigate future experiments or corrections needed for dynamic similitude of the results, and three-dimensional vs. two-dimensional flow.

RESULTS AND DISCUSSION

Basic drawdown data (Figure 2) shows that over the 13 minute model run, heads at the monitoring points responded rapidly to the pumping well drawdown, and that there are significant variations in head with depth. For example, compare S1 and S5, or Q2 and Q8, which are heads at the same distances from the pumping well but at different elevations (e.g. S1= +100 ft; S5= -500 ft). In addition, different monitoring points experience changes in head relative to each other. For example, head in monitoring point S1 is at first lower than head in G1, which dips to a lower level between 6 and 8 minutes, after which S1 shows a lower head. Such variations in head represent a complexity in the head field, over time and in space in a near-uniform model aquifer, that is rarely if ever observed in actual monitoring wells.

Furthermore, pumping well drawdown appears to reach a steady-state level near -600 ft asl between 4 and 6 minutes elapsed time. Shortly thereafter, the detail of the drawdown at the monitoring points (Figure 2b, note difference in scale) indicates a fluctuation in the heads over time. Some of the monitoring points are more affected than

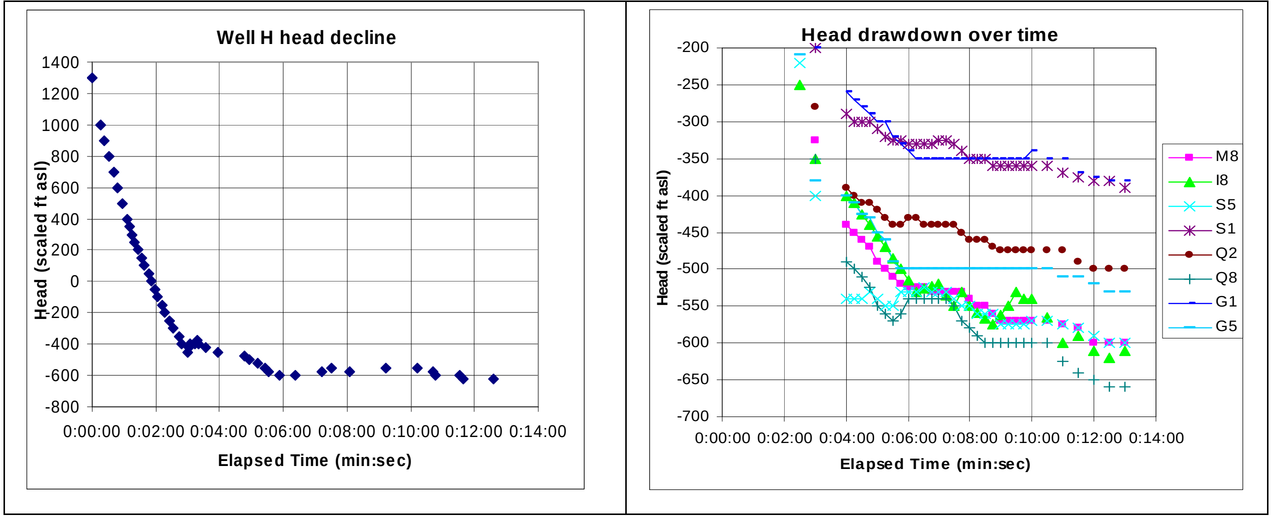

Figure 2: (a) Drawdown in pumping well H; (b) Detail of head decline in selected manometers

others; for example I8, Q8 and S5 in the lower part of the aquifer show up to 50 ft rebounds in head values at different times before continued drawdown. Other monitoring points such as G1, S1 and Q2 near the top of the aquifer show much less fluctuation. Close examination of these fluctuations show that they are out of sequence with changes in pumping water level (Figure 2a). Such fluctuations could occur because of the complex dynamics of desaturation reducing hydraulic conductivity (K) followed by flow diversion, rebound in head, resaturation and increased hydraulic conductivity (Eaton, 2004). As air penetrates down the well bore (Figure 3a), the seepage face migrates from the well, and preferential flow towards the well is likely to be diverted away from areas of lower saturation (low K) and focused in areas of higher saturation (higher K). This would lead to a cyclic pattern in head and flow around a well pumped below the top of the confined aquifer.

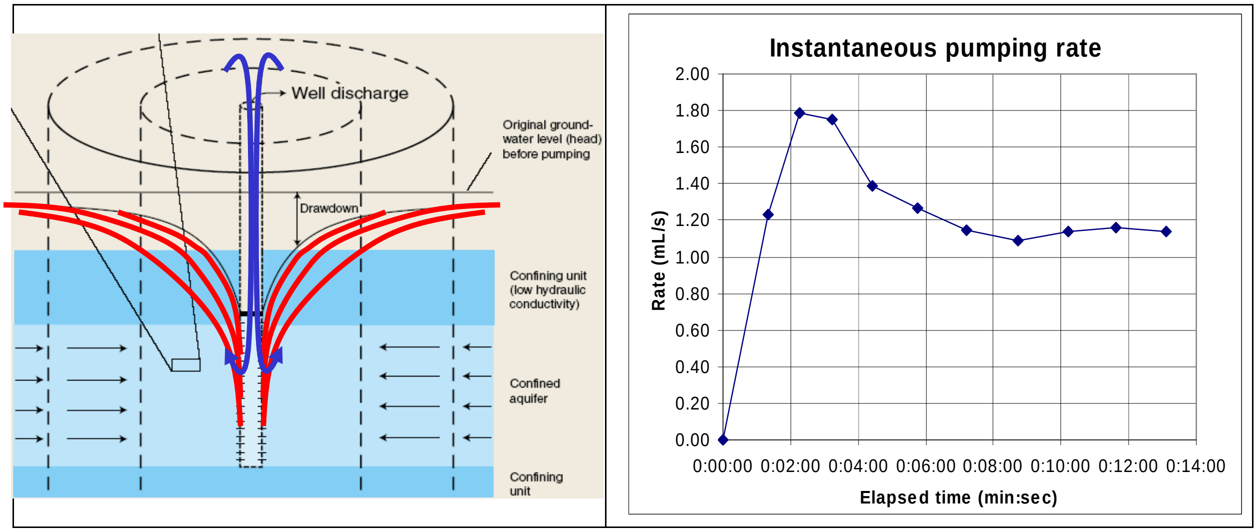

Figure 3: (a) Mechanism of airflow down well bore (adapted from Alley et al. 1999); (b) Calculated pumping rate (combined for both wells)

For this investigation, the effective pumping rate was uncontrolled, but monitored. The peristaltic lab pump was set to a specific rate, but as the pumping water level dropped to below -500 ft asl., the instantaneous pumping rate peaked around 1.7 or 1.8 mL/s and then was reduced to stabilize between 1.1 and 1.2 mL/s or about 66% of maximum capacity (Figure 3b). Despite this reduction in pumping rate, the drawdown also stabilized at near -600 ft asl. This suggests that the pumping reached some equilibrium where it was balanced by steady-state flow from the lateral constant-head boundaries. Had the pumping rate been artificially adjusted to approximate 1.2 mL/s, a Theis-type curve would probably have been obtained for the drawdown. A balance between water pumped and flow from the model boundaries explains why the drawdown ceased at -350 ft asl. in well T (black manometer in Figure 1a), closer to the boundary than well H (center of model), where drawdown continued to -625 ft asl. These model pumping rates would correspond to actual pumping rates greatly in excess of current pumping in municipal wells because of a lack of model dynamic similitude.

It is not possible to directly observe a decrease in saturation as the hydraulic head falls below the elevation of the monitoring points – that would require in-situ specialized instrumentation. However, in a confined aquifer, hydraulic head – the sum of the pressure head (height of the water column) and the elevation head (Figure 4a) – can be used to infer less than saturated conditions when the measured head falls below the elevation of the monitoring point, as is permitted by the manometer design in the sand tank model. Resulting hydraulic pressure at the monitoring point decreases below atmospheric, at which time air enters the pore space or degassing occurs, and pore water drains out forming a seepage face. On a contour plot, the advance of this desaturating

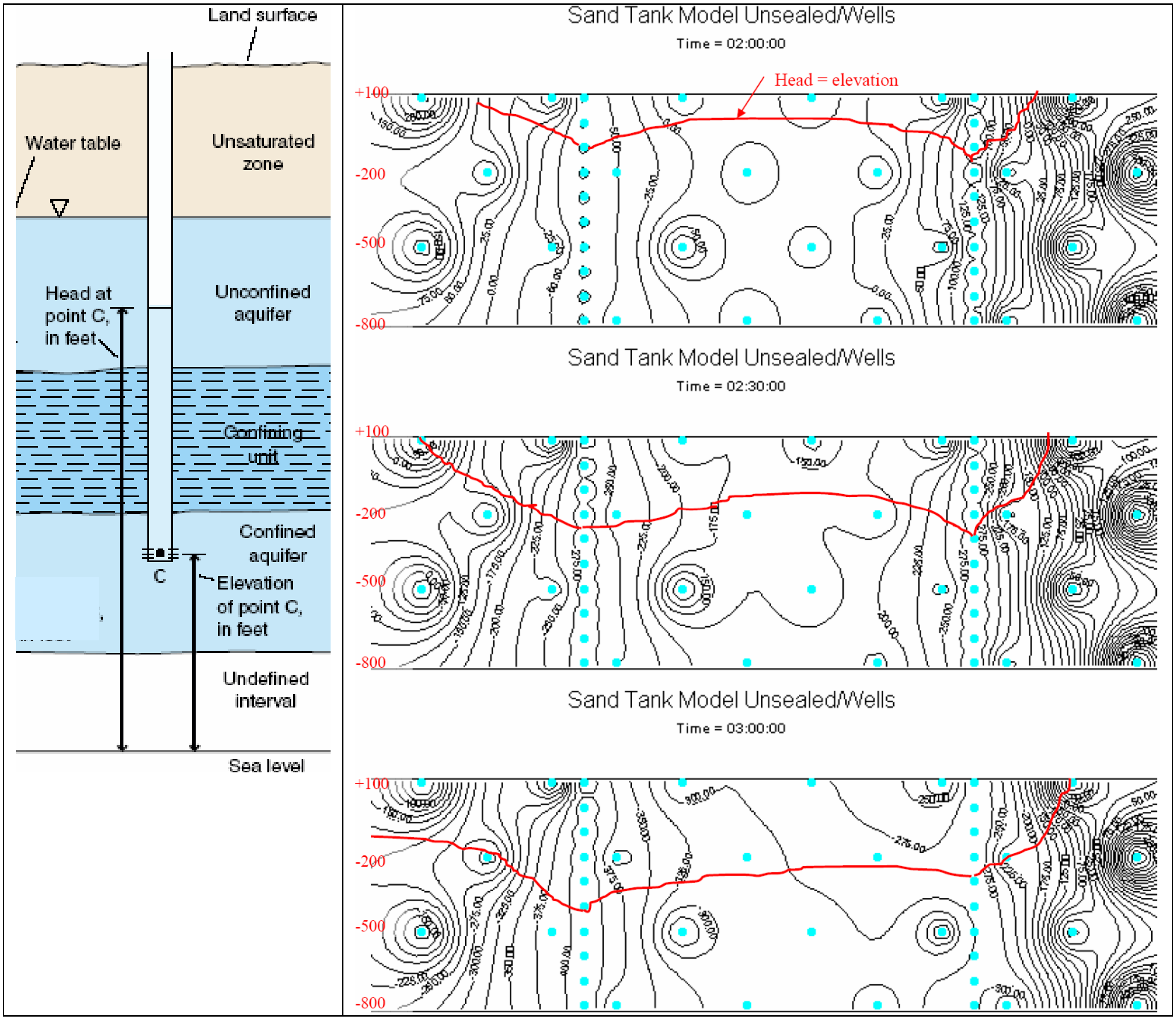

Figure 4: (a) Concept of hydraulic head at a point in an aquifer (adapted from Alley et al. 1999); (b) Hydraulic head distribution in model center, showing unsaturated interface advance over time

front is portrayed using a line connecting the points where hydraulic head is equal to the elevation (Figure 4b). The area of the model above the line is at less than saturated conditions and the area of the model below the line remains fully saturated. The data show that this desaturation phenomenon occurs relatively rapidly. The head decreases to the elevation of the top of the aquifer first near well T at an elapsed time of about 1 minute 30 seconds, and the desaturating front has merged with that from well H and advanced approximately halfway down the thickness of the aquifer by a time of 3 minutes (Figure 4b). The front continued to advance, but more slowly thereafter, reaching an elevation of -625 ft asl at well H by the end of the test at time 13 minutes.

In addition to the laboratory sand tank model experiments, a field component of this research consisted of modifying a borehole used in a study of the Maquoketa aquitard in southeastern Wisconsin (Eaton, 2002) to an open monitoring well with a short screen in the Sinnipee Group dolomite. This was accomplished by technicians of the Wisconsin Geological and Natural History Survey and is more fully described in the Appendix. Resulting water level measurements indicate that hydraulic head in the Sinnipee Group dolomite is just above the elevation of the monitoring port at that location. This may indicate desaturating conditions in the upper Sinnipee at that monitoring well, but its significance for more widespread desaturation is unclear. Other sealed wells about 50 ft away at the same site indicated saturated conditions in the upper Sinnipee dolomite, with heads at an elevation within the overlying Maquoketa Formation (Eaton, 2002).

CONCLUSIONS AND RECOMMENDATIONS

Using a sand tank model, head decline below an aquitard was simulated in a scenario analogous to that of the Cambrian-Ordovician aquifer system in southeastern Wisconsin, where projected heads will ultimately dip into the top of the major aquifer unit, the St. Peter sandstone. Such drawdown in a confined aquifer system below the base of the overlying aquitard is a rarely studied situation, and incompletely represented by common computer flow models (MODFLOW). It was therefore hypothesized that airflow down the wellbore could be an important factor in controlling the development of desaturation and ultimately flow to such an overpumped well. While perfect dynamic similitude could not be maintained in this model, resulting data provide insight into projected conditions in southeastern Wisconsin.

Although conclusions are discussed further below, major findings from this research project consist of the following:

1. The onset and spread of desaturating conditions, as represented indirectly by hydraulic head less than monitoring point elevation, is relatively rapid at first, but then slows. Simulated lateral spread from wells is also rapid, leading to a merging of zones of desaturation near the top of the aquifer, before spreading to greater depths, in contrast to expected vertical development near well bores.
2. As pumping well head decreases level off when flow from the boundaries equals the rate of well pumpage, head at monitoring points at elevations

near the pumping water level continue to fluctuate over timeframes that are difficult to explain solely by pumping water level fluctuations.

3. Pumping rates decrease by 33% as pumping water levels fall below the top of the aquifer and saturated thickness (aquifer transmissivity) diminishes.
4. Free airflow down the pumping wellbore allows high pumping rates and the development of desaturation. Without airflow down the wellbore, pumping rates are much lower and head drawdown much less rapid.
5. Measurement of hydraulic head at an elevation within the Sinnipee Group dolomite at a field site suggests that regional drawdown in the underlying Cambrian-Ordovician aquifer is now sufficient to cause development of desaturated zones in that formation around open wells.

The sand tank model was designed to investigate desaturation processes beginning when hydraulic heads decrease below the top of the major producing units in the Cambrian-Ordovician aquifer system, specifically the St. Peter sandstone. The Sinnipee Group dolomite in southeastern Wisconsin has a very low hydraulic conductivity where it is overlain by the Maquoketa formation (Feinstein et al. 2004). Although one measurement port was finished in the buff layer representing the analogous bottom unit in the model aquitard, no water was observed in that piezometer after construction, and changes in hydraulic head could not be measured in the time-frame of this investigation. Furthermore, the hydraulic conductivity of the glass bead aquifer was one order of magnitude greater than the real Cambrian Ordovician aquifer. Since spreading of the desaturating front or seepage face is likely related to the hydraulic conductivity of the medium, the sand tank model results probably overpredict the rapidity of the desaturation. Full implications of these data would also need to take into account the two-dimensionality of the model vs. a three-dimensional flow field around real wells.

The need for constant-head boundaries in the sand tank model relatively close to pumping wells complicates the analysis. However, the sand tank model construction provides a useful contrast between wells. One well (T) is closer to the right (east) boundary (Figure 1a), where the glass bead aquifer is thick, and the other well (H) in the middle, is closer to the left (west) boundary where the upper unit of the aquitard pinches out and the aquifer thins. Although a single pump was used for both wells, the head decreased faster initially in well T at right, where head stabilized at -350 ft asl (Figure 4b). Later, head continued to decrease to -625 ft asl. in well H at left. It is likely that the proximity of the right (east) boundary limited the drawdown in well T and the thinning of the aquifer to the left (west) enhanced the spreading of the desaturating zone west of well H. Likewise, the geometry of the Cambrian-Ordovician aquifer and the relative placement of municipal wells will probably control the development and lateral extent of the zone of desaturation when heads are drawn down into the St. Peter sandstone.

Desaturation of pore-space causes decreases in hydraulic conductivity, a function of water content, that should then affect flow through the desaturating zone to the well. Evidence of this process is shown by the asynchronous fluctuations in head measured at monitoring points in the sand tank model. Such dynamics are more complex in a fully three-dimensional system in the real world, and flow to an overpumped well may be the integration of sequential flows from different sectors around the well depending on the relative saturation of the surrounding pore space. The practical consequences of such a dynamic flow system are an enhancement of potential oxidation reactions and deterioration of water quality depending on aquifer mineralogy. In addition to the decrease in transmissivity caused by less saturated thickness, these desaturation dynamics may seriously reduce municipal well yields for given rates of drawdown. Once such desaturation is widespread, it may be impossible for well yields to recover, even with cessation of pumping, because air becomes indefinitely trapped in the pore-space.

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APPENDIX: Conversion of well WK4234 to deep piezometer nest

(K. Bradbury, 12/15/04)

The field component of this project involved conversion of an existing deep monitoring well to a nest of piezometers, with the objective of obtaining reliable hydraulic head measurements deep in the Sinnipee Formation. The well chosen for conversion was WGNHS well Wk-4234, located in the Village of Pewaukee in Waukesha County (see Figure A1 for location map). This well was originally installed during a WGNHS investigation of the Maquoketa Formation, and is described by Eaton and others (2000) where it is referred to as well W-0 (see *Eaton, T.T. K.R. Bradbury, and H.F. Wang, 2000. Verification and characterization of a fracture network within the Maquoketa shale confining unit, southeastern Wisconsin. Open-file Report 2001-04, Wisconsin Geological and Natural History Survey, 35 p.*).

The existing 6-inch diameter well was 450 feet deep, cased to 157 feet, and open to the formation below the casing. It was open to nearly the entire Maquoketa shale interval and to nearly 220 feet of the underlying Sinnipee Formation. This well had previously been used for pumping tests and packer tests. Eaton and others (2000) collected significant hydraulic, geochemical, and geophysical data from this hole, including downhole geophysical logs.

This well was chosen for piezometer conversion because it is located near the center of the regional bedrock cone of depression in Waukesha County, it provided the only local access to the Sinnipee dolomite, and it was no longer needed for its original purpose. The regional groundwater flow model of Feinstein and others (2003) suggested that the Sinnipee Formation in this area might be dewatered or at least have very low heads, and this location provided an excellent point for model verification.

The piezometer conversion was accomplished by WGNHS technicians during November, 2004. During the conversion, two 2-inch diameter standpipe piezometers were installed in the original 6-inch borehole. Each piezometer had a 10-ft screen. The hole was filled sequentially from the bottom using sand packs around the piezometer screens and bentonite chips between and above the screens. The final design located the lower screen at a depth of 450.8 feet and the upper screen at a depth of 339 feet. Figure A2 shows the construction details.

The initial measurement of water levels in the piezometers was made on 11/16/04. At this time the water level in the deep piezometer was 440.8 ft below the top of the casing, apparently just above the screened interval. The water level in the upper piezometer stood at 19 feet below the top of the casing.

The data clearly indicate a very low head in the Sinnipee Formation. Figure A3 is a composite log of the well showing the hydraulic head profile at the site using data from Eaton and others (2000). The very steep decline in total head with depth below the

Sinnipee/Maquoketa contact suggests that the Sinnipee might be dewatered below this point. Alternatively, the low head could result from a steep hydraulic gradient through the saturated Sinnipee. The WGNHS intends to conduct additional data collection and analyses from this piezometer nest in order to explain the observed hydraulic-head profile.

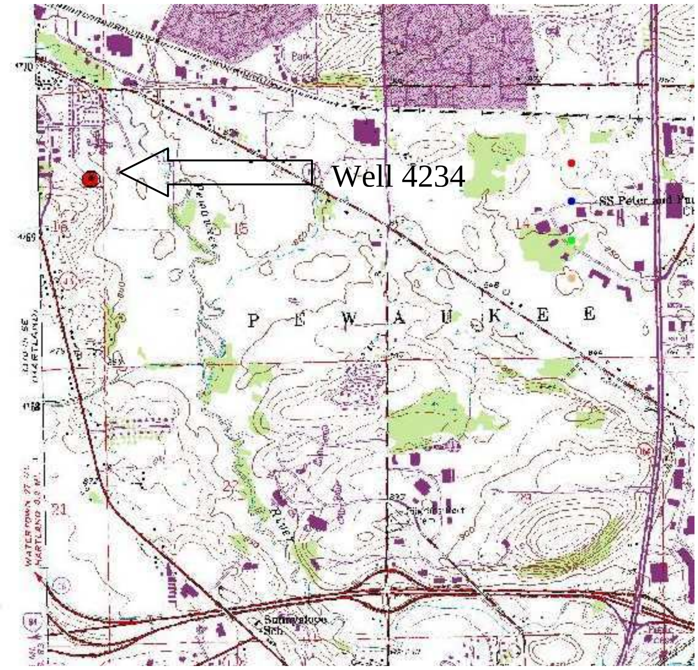

Figure A1. Location of piezometer nest in well Wk-4234, at Pewaukee, WI.

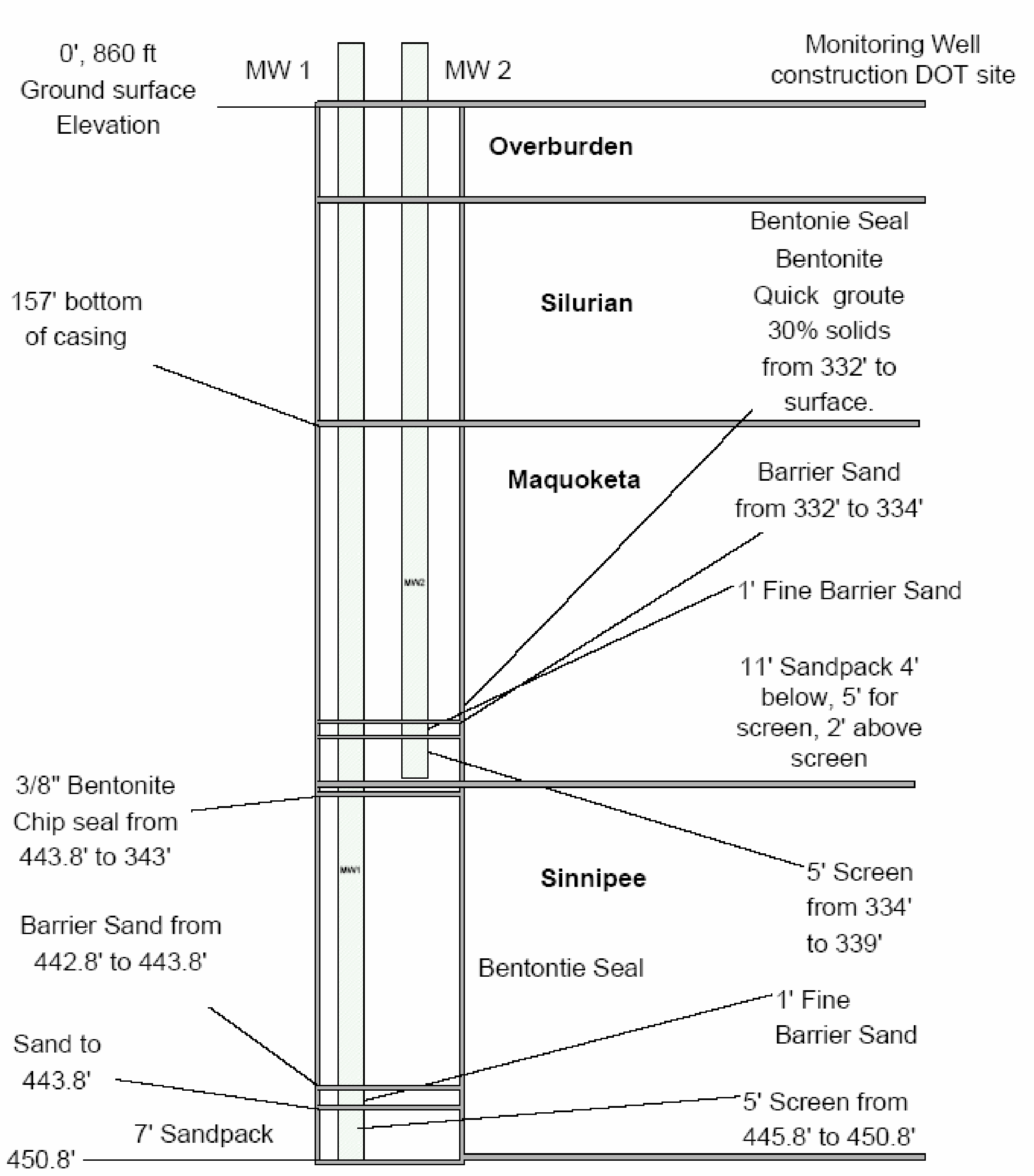

Figure A2. Construction diagram of piezometer nest at well Wk-4234

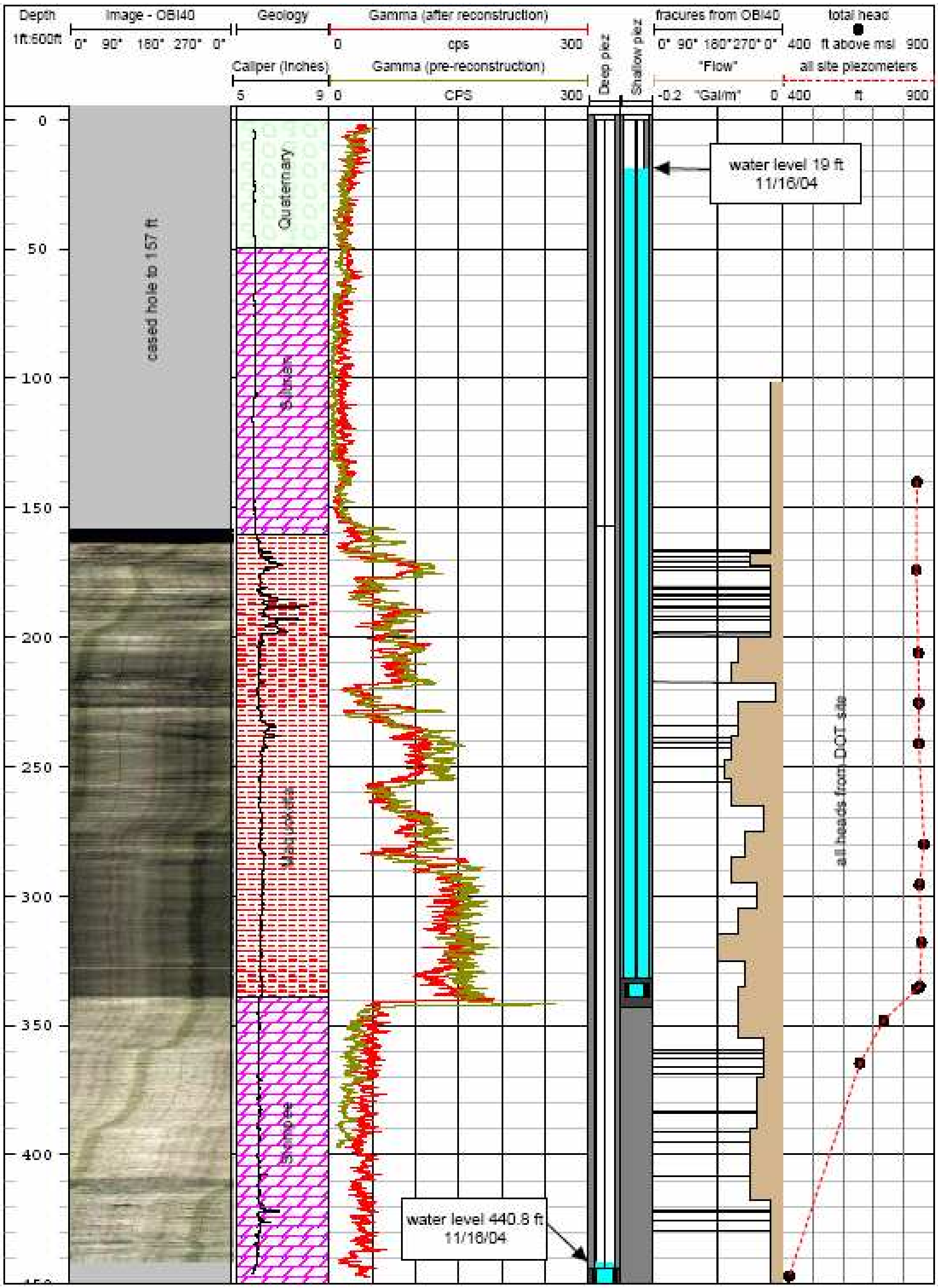

Figure A3. Geophysical logs, piezometer construction, and head profile from Wk-4234.