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PETER M. KEARL[1] and KIRK ROEMER*,[2]

[1]*Environmental Sciences Division, Oak Ridge National Laboratory, Grand Junction, CO 81503*

[2]*Life Sciences Division, Oak Ridge National Laboratory, Grand Junction, CO 81503*

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EVALUATION OF GROUNDWATER FLOW DIRECTIONS IN A HETEROGENEOUS AQUIFER USING THE COLLOIDAL BORESCOPE

PETER M. KEARL[1] and KIRK ROEMER*,[2]

[1]*Environmental Sciences Division, Oak Ridge National Laboratory, Grand Junction, CO 81503*

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Determining groundwater flow rates and directions in low permeable layered aquifers underlying industrial sites can be a difficult problem due to limited access, multiple flow zones, and multiple potentiometric surfaces. Within the upper-most aquifer, thin permeable zones of limited aerial extent may exhibit different flow directions. A large number of specifically screened observation wells completed in each permeable zone may be necessary to yield sufficient data to construct reliable potentiometric maps for assessing contamination migration patterns. The colloidal borescope, developed by Oak Ridge National Laboratory, offers the potential for measuring groundwater flow directions and rates at specified locations within the aquifer with a limited number of observation wells. By observing the movement of naturally occurring particles in the well screen, it is possible to measure groundwater flow directions and velocities at selected depths within the aquifer. The colloidal borescope was used at a large industrial site in Western Kentucky to characterize flow patterns in a clayey-silt aquifer containing numerous sand lenses. Results of the colloidal borescope measurements were compared with existing contaminant plumes and surface hydrologic features to assess the reliability of the measurements. Test results indicate that similar flow directions were observed in the same sand lenses and flow directions were consistent with expected flow directions in areas where surface hydrologic features or industrial features such as water lines and waste water discharges affect the movement of groundwater. Different sand lenses within the aquifer, however, exhibited different flow directions. Based on the results of this investigation, the colloidal borescope offers a low-cost, reliable screening method for groundwater characterization studies.

Key words: colloidal borescope, groundwater, flow rates, flow directions

INTRODUCTION

An important regulatory requirement for hazardous waste site investigations is the characterization of the upper-most aquifer. Commonly this involves the characterization of a geologic unit that is not typically an aquifer in the water supply sense. Instead, the investigation involves a heterogeneous unit of varying lithologies that yields only minor quantities of water. Determining fundamental properties such as groundwater flow directions and rates, the hydraulic connection with adjacent geologic units, and the location and extent of subsurface contamination in these heterogeneous aquifers can be difficult.

Several factors complicate the use of conventional hydrogeologic techniques to characterize heterogeneous aquifers. For example, the aquifer may be comprised of sand and gravel lenses surrounded by fine grain silts and clays. These sand and gravel units may only be a few feet in thickness with a limited aerial

*Corresponding author. Fax: (970) 248-6207; Email: e81@ornl.gov.

extent. Observation wells, commonly used to determine water levels and other aquifer properties, may be screened across several of these sand and gravel zones or be limited to a few wells in each of the individual zones. With only a limited number of wells in individual sand and gravel units or numerous wells in several sand and gravel units, there is limited control for developing potentiometric maps representative of the overall aquifer.

Another important factor that can impact the hydrogeologic characterization is the location of the site. Commonly, hazardous waste sites are located in active industrial areas. Large areas at the industrial site may be paved thereby restricting groundwater recharge or there may be leaking underground utilities that are impacting groundwater flow. In addition, access for a sufficient number of monitoring wells may be limited.

A tool that is useful in hydrologic characterizations is the colloidal borescope. This instrument is capable of measuring groundwater flow directions and rates in at selected intervals in individual wells.

This paper presents the results of a site investigation at a large industrial facility in Western Kentucky. The colloidal borescope was used to determine groundwater flow directions and rates in existing monitor wells completed in a heterogenous aquifer. Results of the investigation are compared with existing site information to develop a conceptual model of groundwater flow in the upper-most aquifer at the site.

INSTRUMENT DESCRIPTION

The colloidal borescope consists of two CCD (charged-couple device) cameras, a ball compass, an optical magnification lens, an illumination source and a stainless steel housing. The device is approximately 60 cm long and has a diameter of 44 mm, thus facilitating insertion into a 5-cm-diameter monitoring well (Figures 1a and 1b). Upon insertion into a well, an electronic image magnified 140X is transmitted to the surface, where it is viewed and analyzed. The compass is viewed by one of the CCD cameras in order to align the borescope in the well. As particles pass beneath the lens, the back lighting source illuminates the particles similar to a conventional microscope with a lighted stage. A video frame grabber digitizes individual video frames at intervals selected by the operator. A software package developed by Oak Ridge National Laboratory compares the two digitized video frames, matches particles from the two images, and assigns pixel addresses to the particles. Only particles that remain in focus across the field of view indicating horizontal flow are analyzed. Using this information, the software program computes and records the average particle size, number of particles, speed and direction. The system is capable of analyzing flow measurements every four seconds resulting in a large data base after only a few minutes of observations. Since standard VHS video uses 30 frames per second, a particle that moves 1 mm across the field of view could be captured in subsequent frames 1/30 of a second apart. This would result in an upper velocity measurement of 3 cm/s. For low flow conditions, the delay between frames can be set for large time periods resulting in a lower velocity measurement range that includes practically stagnant flow conditions.

Work based on borescope observations has been used to support micropurge sampling as an effective way to obtain groundwater samples representative of the total mobile pollutant load [Kearl *et al*., 1994].

The most significant difference in colloidal borescope observations versus conventional hydraulic testing methods is the magnitude of groundwater velocity. Observed seepage velocities in the well bore based on particles observed by the colloidal borescope are generally higher than seepage velocities calculated using conventional hydraulic tests, hydraulic gradients, porosities and Darcy's law. This has been shown to be the case at several sites across the United States where the borescope has been tested (Kearl, 1997).

Several factors must be considered when interpreting velocities based on colloidal borescope measurements. First, the colloidal borescope provides a microscopic view of ambient flow in a well bore. Conventional hydraulic test methods provide a macroscopic measurement under stressed conditions. While the borescope measures flow velocities at distinct points in the well bore, conventional methods provide an estimate of the average flow over a selected interval. It should be noted that the borescope can measure small pressure changes in ambient flow conditions. For example, the colloidal borescope has observed significant flow changes from a pressure wave milliseconds after a slug was released into a well 40 ft away. Similarly, when a nearby pumping well is turned on, the response of the colloidal borescope to the directional changes is almost instantaneous, and occurs before any discernable water level change is detected. Varying water levels in ditches or drainages invoke the same instantaneous directional changes.

Aquifer heterogeneity, well construction and well skins influence flow in a well bore. For the colloidal borescope to be an effective tool in characterizing groundwater flow velocity, it is necessary to differentiate and quantify these effects. This is a difficult task because the hydraulic conductivity of the filter pack and surrounding formation may be unknown and/or the skin effects may not be easily quantified. However, following some basic assumptions and general guidelines, it is possible to select reliable data and estimate a range of groundwater velocities.

First, the presence of a well bore in an aquifer affects the flow velocity. Directly assessing groundwater seepage velocities from flow velocities in a well is feasible based on theoretical and experimental evidence. Potential flow theory solutions and laboratory experiments describing flow through a cylinder of infinite permeability surrounded by a porous medium of finite permeability have been studied by Ogilvi (1958), Carslaw and Jaeger (1959), Drost *et al*. (1968), Wheatcraft and Winterberg (1985) and Bidaux and Tsang (1991). These studies indicate that it is necessary to determine a factor for converting well bore velocity measurements to groundwater seepage velocities in the adjacent aquifer.

Oak Ridge National Laboratory/Grand Junction, Colorado (ORNL/GJ) conducted a series of laboratory experiments to assess the reliability of the colloidal borescope and to determine the conversion factor. The results of the laboratory measurements were in good agreement with predicted results from theoretical models presented in the literature (Kearl, 1997). Laboratory measurements showed a minimum seepage velocity conversion factor ($\overline{\alpha}$) of 1 and a maximum value of 4. In other words, colloidal borescope velocity measurements should be reduced by this range of conversion factors. Therefore, using an $\overline{\alpha}$ conversion factor of 1 to 4 provides an acceptable range for calculating seepage velocity in the adjacent porous medium from velocity measurements in most monitoring wells.

Velocity measurements presented in this paper are actual borehole flow velocities and should be reduced by a factor of 1 to 4 to provide a range for seepage velocity in the surrounding porous medium. It should be noted that each velocity data point represents the average velocity of up to 256 particles. Depending on

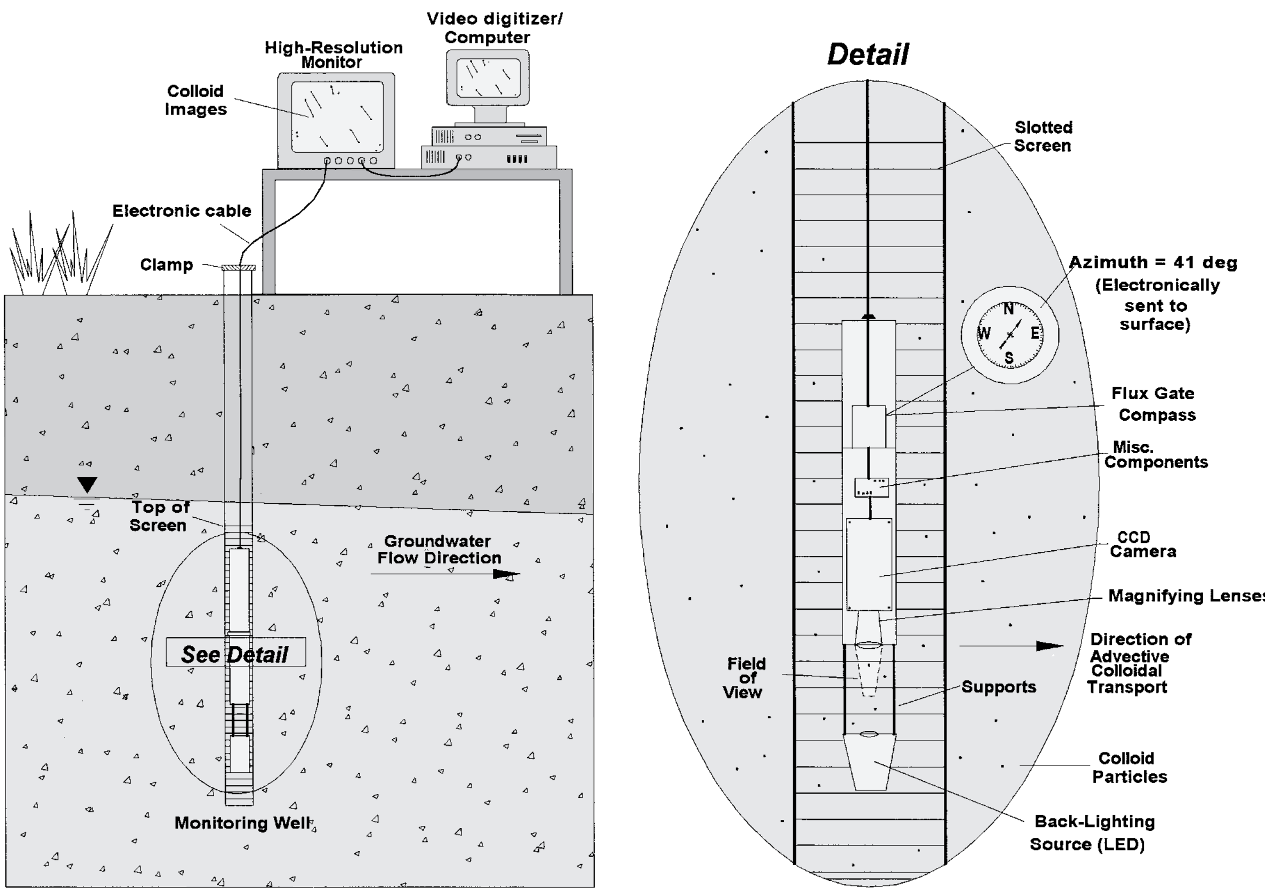

Figure 1. Conceptual diagram of the colloidal borescope.

the time period for the measurement, thousands of data points are averaged to yield a mean velocity and standard deviation that are presented on the velocity and direction figures.

The next factor that should be considered is the flow behavior in a well bore and the impact on estimating groundwater velocity. Both horizontal laminar flow and swirling nondirectional flow are commonly observed in wells. Based on laboratory work, the horizontal laminar flow zones in the well are adjacent to permeable or preferential flow zones (Kearl, 1997). In the absence of effects from underground utilities, swirling flow zones are the result of low-permeability sediments, positive skin effects, vertical flow gradients, or nearby preferential flow zones that dominate flow in the observed zone. For the flow in the divergent channel, a vortex results in the region adjacent to the main flow channel. This vortex is similar to the swirling flow observed by the colloidal borescope in low-permeability zones, both in the laboratory and in the field.

Because only those zones that display consistent horizontal laminar flow in a steady direction over a substantial time period (several hours) are considered, groundwater flow velocities measured by the colloidal borescope in heterogeneous aquifers will be biased toward the maximum velocity values present in the aquifer. Low flow zones exhibit swirling nondirectional flow that does not permit a linear velocity measurement. Consequently, measurements in swirling flow zones are disregarded. These low-flow zones are averaged into macroscopic flow velocity estimates which explains the upward bias in velocity estimates yielded by the colloidal borescope.

Finally, it is important to note that the borescope velocities for the preferential flow zones do not represent contaminant transport velocities. Sudicky *et al*. (1985) conducted a laboratory tracer test in a layered porous medium (Figure 2). The velocity in the sand layer was set at 0.1 m/d. As shown in the graph, if

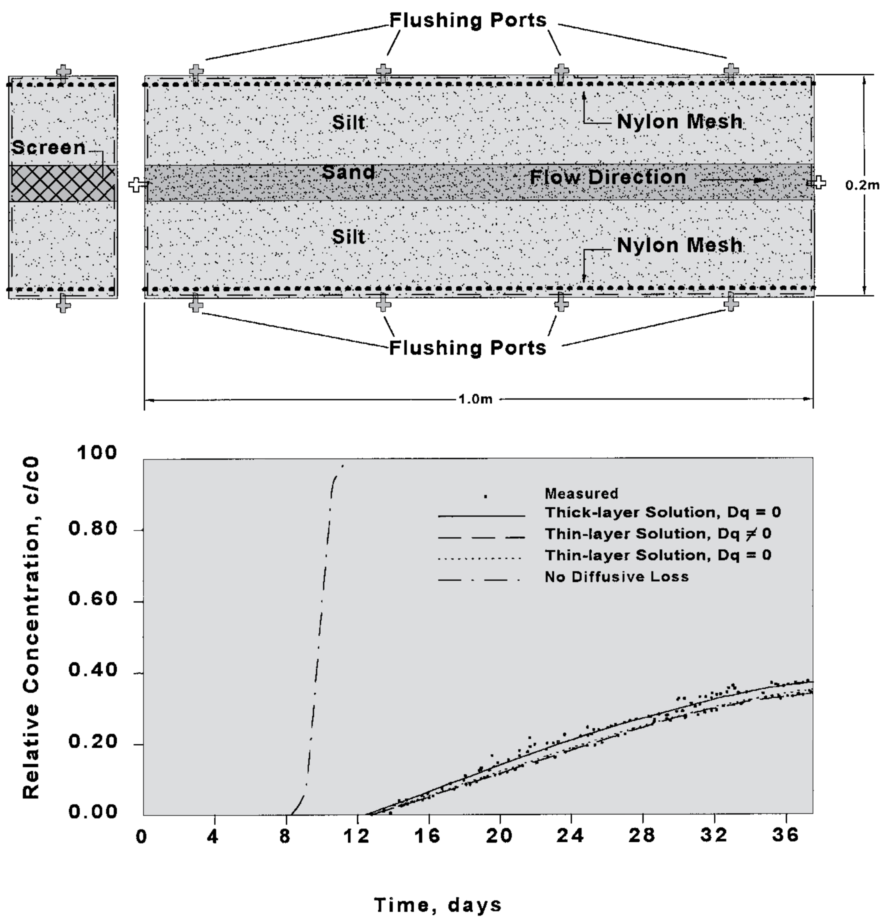

Figure 2. Laboratory tracer test results using sodium chloride with an average linear porewater velocity in the sand equal to 0.10 m/d. (Sudicky *et al.,* 1985).

the velocity interpretation is based on the tracer test ($C/C_0 = 0.5$), a velocity value of approximately 0.02 m/d would result. This lower tracer velocity is due to diffusion of tracer from the preferential flow zone to the surrounding low permeability material which has the net effect of retarding the transport rates. If a well was placed in the tank, the colloidal borescope would measure a velocity ranging from 0.1 to 0.4 m/d adjacent to the sand layer and swirling flow in the intervals adjacent to the silt units. When the velocities measured by the tracer and the borescope are compared, the borescope yields a value that is approximately 1 order of magnitude higher than the tracer tests. This is consistent with several comparison studies conducted at field test sites.

SITE HYDROGEOLOGY

Researchers within this large industrial facility have divided the ancestral Tennessee River deposits into hydrologic units (HUs) to facilitate study of the area hydrogeology. From surface to base, these HUs are:

HU1: loess and shallow lacustrine sediments interval,
HU2: shallow sands and gravels and sandy silt/clay interval,
HU3: lacustrine sediment interval underlying HU2,
HU4: fine to medium sand interval overlying sand and gravel bar deposits, and
HU5: sand and gravel bar deposits interval at base of valley fill sequence.

Within the valley fill sequence, the HU1, HU2 and HU3 intervals comprise the upper continental recharge system (UCRS). HU4 and HU5 comprise the lower continental deposits and are termed the Regional Gravel Aquifer (RGA). Groundwater flow in the UCRS is primarily downward while flow in the RGA intervals are generally northward discharging into the Ohio River.

The HU1 interval occurs at the surface across this industrial site, with a thickness typically ranging from 15 to 20 ft. The HU2 unit ranges up to 45 ft thick while the HU3 unit ranges from 10 to 30 ft thick. The HU4 unit, which averages approximately 30 feet thick, is described as a thin sandy layer overlying the HU5 unit.

Analysis of soil cores taken from within the industrial site were used to determine the percentage (by weight) of grain sizes in the HU1 sediments. Silt comprises between 60 and 80 percent of the sediment with clay accounting for 10 to 30 percent. HU2 sediments are highly variable, ranging from winnowed gravels to sandy silts, with the greatest percentage of sand and gravels occurring in the channels defined as the base of the HU2. The HU3 interval is recognized by its finer-grained texture relative to the overlying HU2 and underlying HU4 intervals. The HU4 and HU5 intervals are coarse-grained deposits of the ancestral Tennessee River System. HU4 sands are generally finer-grained than those of the HU5 intervals.

Groundwater in the UCRS originates as infiltrating rainfall, infiltration from surface water, flow from the Terrace Gravels (underflow), and leakage from utilities and other plant structures (point and line source recharge). Flow from the UCRS recharges the RGA.

Detailed discussion of the site geology, hydrology, boring loggs and cross-sections are presented in the Phase III Groundwater Investigation (Clausen *et al*. 1992). This report describes the UCRS as sand and gravel dominated lithofacies found at different elevations throughout a predominantly clayey-silt matrix. This report further states that the sand and gravel lithofacies appear relatively discontinuous in cross section but may be more connected in three dimensions.

To address the issue of three dimensional continuity of the UCRS, a fence diagram of the UCRS and RGA was constructed using existing monitoring well logs (Figure 3). Correlation between the control points was based on the following assumptions:

- Coarse grain sediments such as sands and gravels at the same horizontal position were assumed to be the same lithofacies.
- Sand and gravel zones 1 to 2 ft in thickness were only correlated over a few hundred feet.
- If a sand and gravel zone greater than 3 ft in thickness was not present in a surrounding well, it was correlated over approximately one-half the distance to this control point.
- The sand unit (HU4) directly overlying the RGA is combined with the RGA as a single unit.

Sand and gravel units are assumed to be the primary water transport zones in the UCRS and are shown as separate hydrogeologic units from the surrounding fine grain silts and clays.

The most striking feature of the UCRS stratigraphy, based on the fence diagram, is the lenticular nature of the deposits. This diagram is consistent with the depositional environment (braided stream) from which the UCRS is derived. Assuming lateral continuity between control points, sand and gravel zones can be correlated over distances of only a few thousand feet or less in any direction. Even these distances

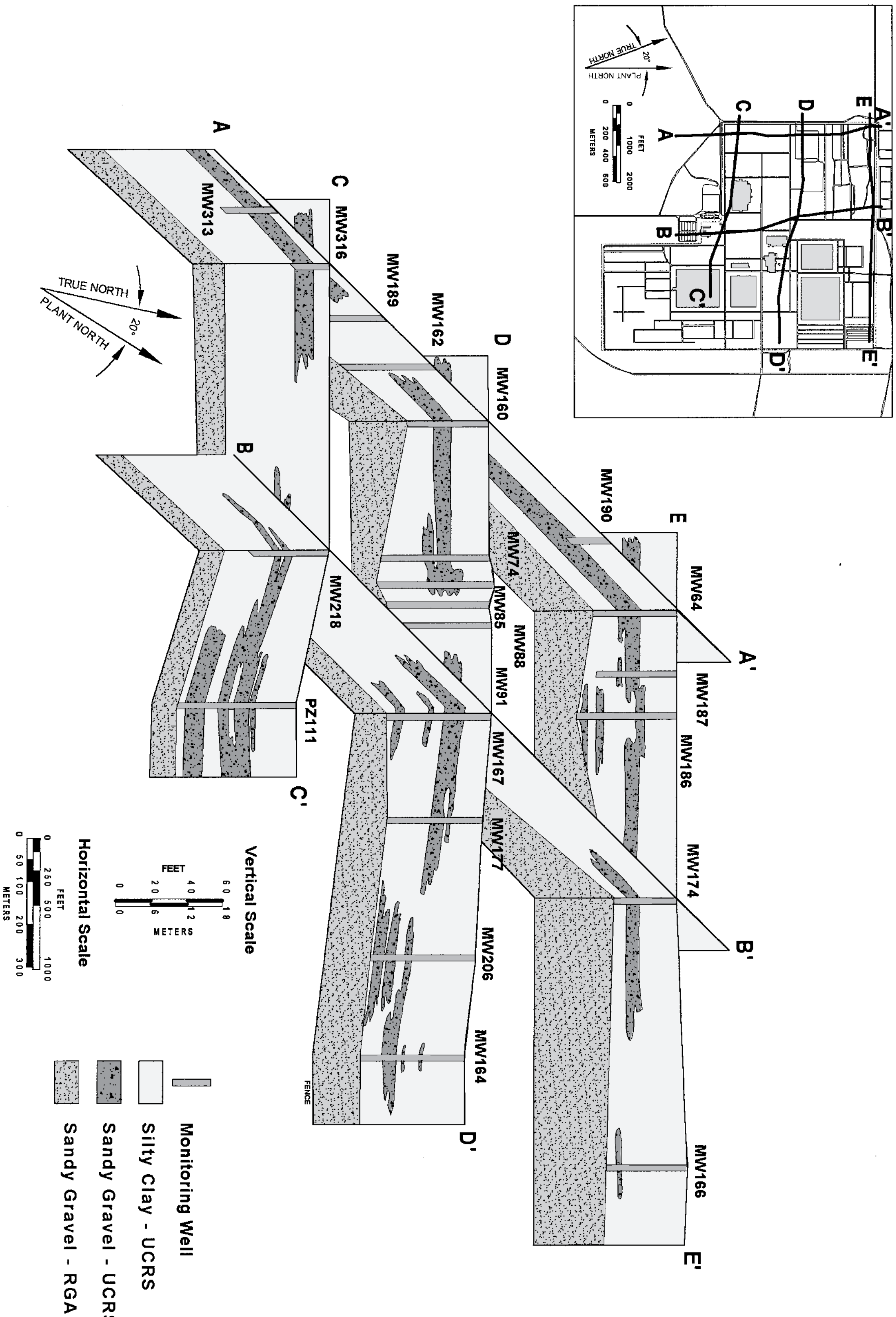

Figure 3. UCRS and RGA fence diagram.

may be too great considering the abrupt termination of units in areas with control. For example, a sand and gravel zone that is more than 12 ft thick is correlated between wells MW74 and MW85, and perhaps MW160, but is absent from nearby wells MW88 and MW91.

Figure 3 shows a sand and gravel zone at an average depth of 20 to 30 ft below land surface that can be correlated over a large region in the northwest area of the site. This unit appears to be continuous from MW174 westward to MW64 and southward to MW160. The northern and western extents are unknown because there is no control in these areas. However, the southern and eastern extents are reasonably well-defined. The aerial extent of the remaining sand and gravel zones underlying the site is significantly smaller. As noted above, where control is present, no sand or gravel zones extend more than a few thousand feet. This observation supports the work of Clausen *et al*. (1992), who reported that measured hydraulic gradients within the UCRS are strongly downward (on the order of 1) suggesting hydraulic isolation between the individual UCRS sand and gravel units.

The HU3 confining unit appears to be continuous across the site. Because of this separation of the UCRS from the RGA and the lenticular nature of the permeable UCRS units, flow in the RGA has little impact on flow directions in the sand and gravel zones in the UCRS. Thus, it is misleading to assume that the UCRS has a northerly flow direction similar to the RGA.

Groundwater flow and subsequent contaminant transport in the isolated sand and gravel zones is dependent on the type and location of recharge and discharge that affect individual units. Previous site investigations have postulated that the terrace gravels are a source of recharge for the UCRS. Such may be the case, however, the lenticular nature of the sand and gravel units suggests that local influences are also important. For example, if the land surface covering the southern portion of a sand and gravel lens is paved and a preferential pathway from the lens to the underlying RGA exists in the same region, then the majority of recharge from precipitation would occur along the northern portion of the lens but groundwater flow would be in a southerly direction. Another possible scenario would be a leaking underground utility that recharges a sand and gravel zone causing divergent groundwater flow from the recharge point. (See Figure 4 for a conceptual illustration of this discussion.)

In summary, the hydrogeology of the UCRS is best described as isolated sand and gravel units that have independent flow directions and rates depending on the type and location of recharge and discharge. Colloidal borescope measurements, discussed subsequently, were used to support or disprove this conceptualization of the groundwater flow system.

FIELD PROGRAM

Prior to initiating the field program, well construction diagrams and lithologic logs were reviewed to identify intervals for colloidal borescope measurements. In general, the targeted intervals corresponded to the more permeable zones, such as sand and gravel, within the screened interval. In the field, for each well, the colloidal borescope was lowered to the target depth interval, and the movement of colloids was observed on the video monitor. If, after some time, typically around 30 min, the flow field appeared stable, defined as when both groundwater direction and flow rate were steady, the data collection system was activated. If the flow field did not stabilize the borescope was moved to a different depth interval and the process was repeated. During data acquisition, the flow field was monitored and if the flow field became unstable, data collection was terminated and the borescope was moved to another depth interval. Long-term data collection, typically greater than 2 hours, was performed on those intervals thought to have active flow.

At the conclusion of data acquisition the colloidal borescope data were re-evaluated to determine the reliability of individual tests. The tests were categorized into three classes: good, intermediate and poor. A good test is defined as a test that was conducted for 2 hours or more during which the groundwater flow rate and direction remained stable (Figure 5). It is also possible for a test to obtain a good rating if groundwater flow rate and direction changes occur, providing the changes are correlated to suspected surface influences such as discharges to nearby outfalls. Intermediate or poor tests showed swirling flow or large variations in the flow direction or velocity. These tests were considered unreliable and representative of low flow zones discussed earlier. Only the good tests were considered reliable and used for the study.

RESULTS AND DISCUSSION

Flow directions measured by the colloidal borescope from selected monitoring wells are illustrated in Figure 6. These measurements were selected based on observations of horizontal flow in a consistent direction over a time period of several hours. Usually the tests were conducted overnight resulting in 12 to 17 hours of data. Note that these graphs contain nearly 5,000 data points. The rose diagrams represent the frequency with which a particular direction occurs at

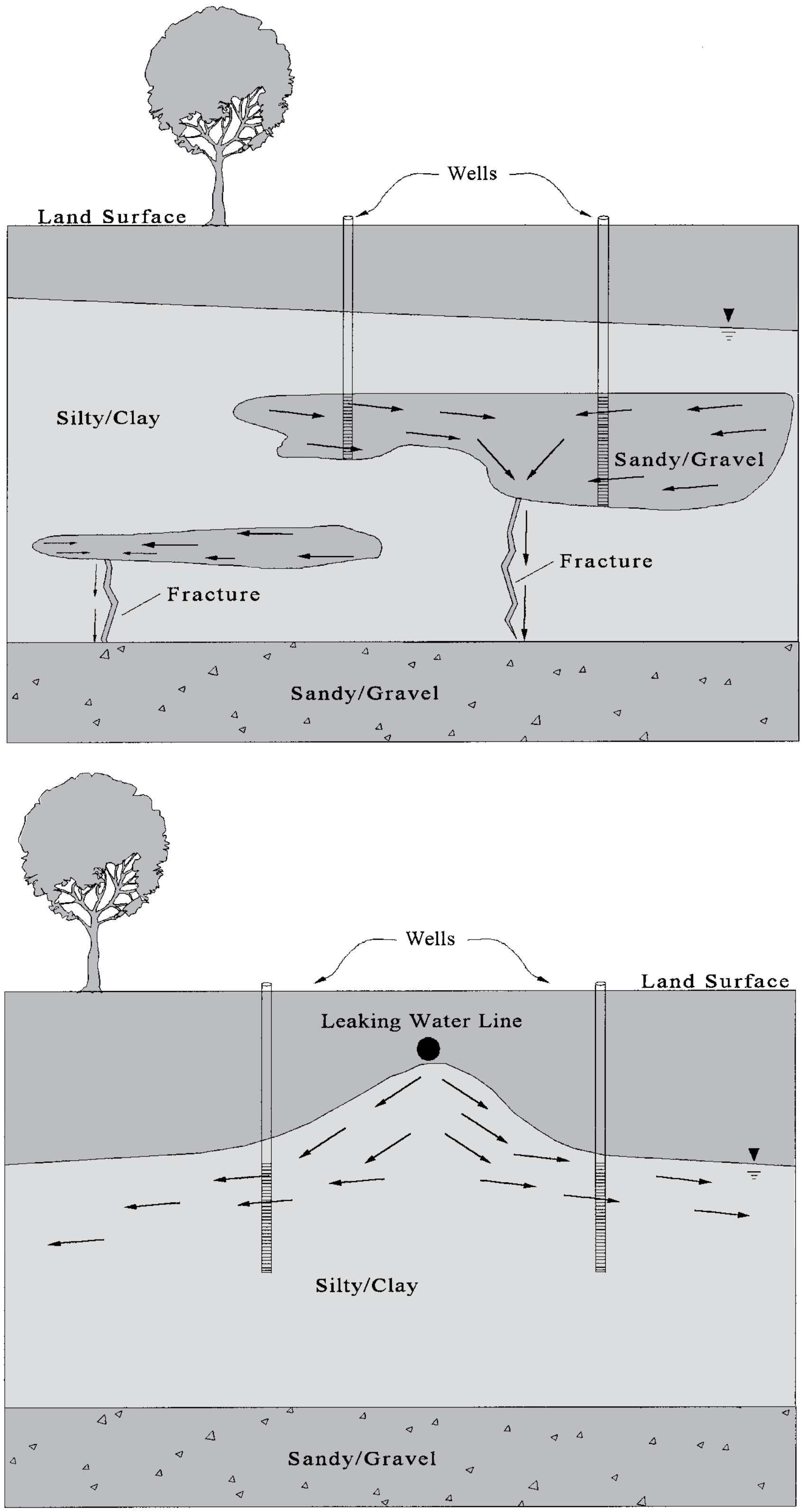

Figure 4. Conceptual illustration of the flow systems.

a selected depth in the well for a continuous measurement period. Based on the interpretation of the authors, the tests discussed in this section were not subject to intermittent influences of plant utilities and activities.

Figure 6 indicates that the UCRS has multiple flow directions that do not appear to form a consistent regional pattern. However, when the measurements are compared to the site geology, as presented in Figure 3, an explanation is evident. By comparing flow directions from wells that are completed in the same sand and gravel zone within the UCRS, similar groundwater flow directions are evident. For example, in the northwest area where the largest sand and gravel zone is present, wells MW174, MW186, MW190 and

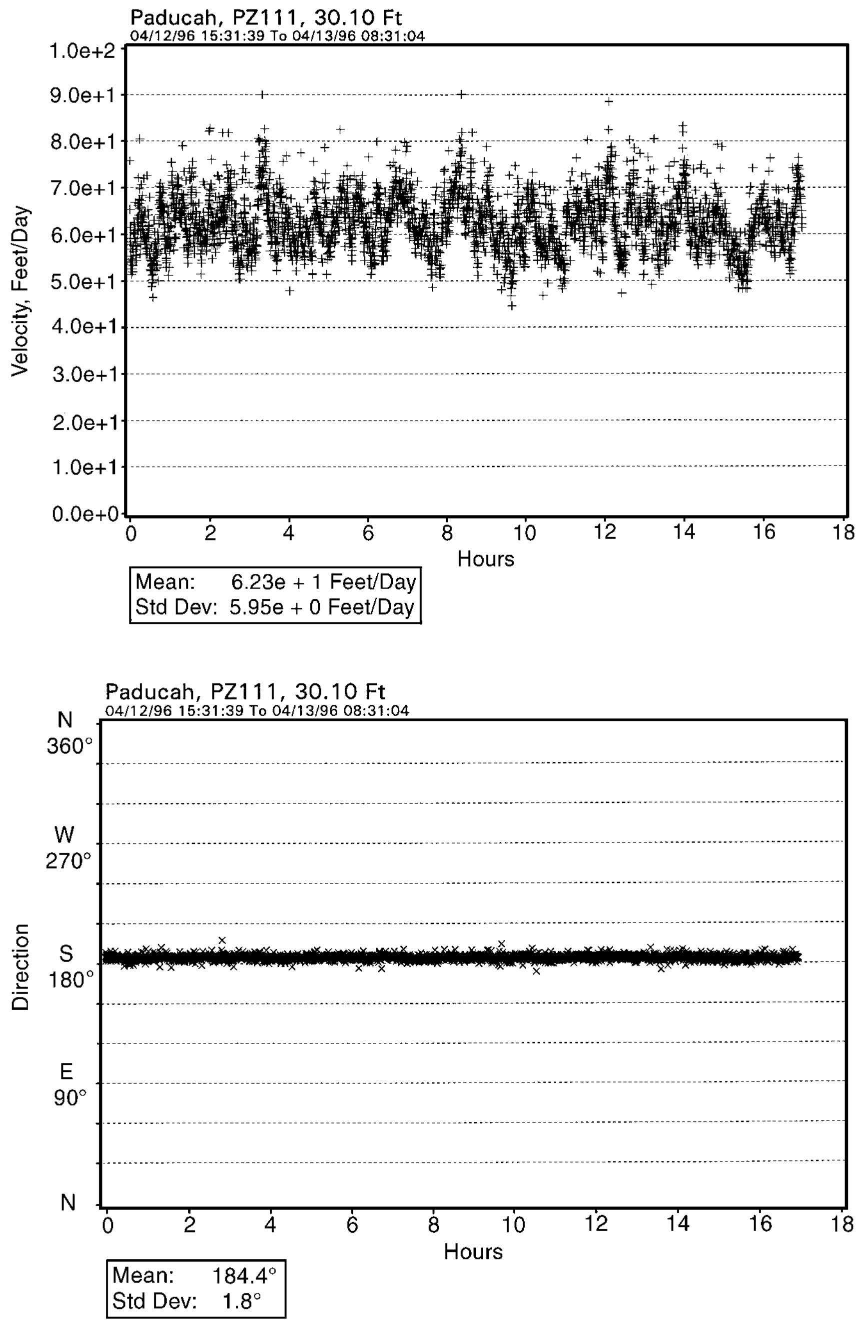

Figure 5. Typical groundwater flow velocity measurements using the Colloidal Borescope.

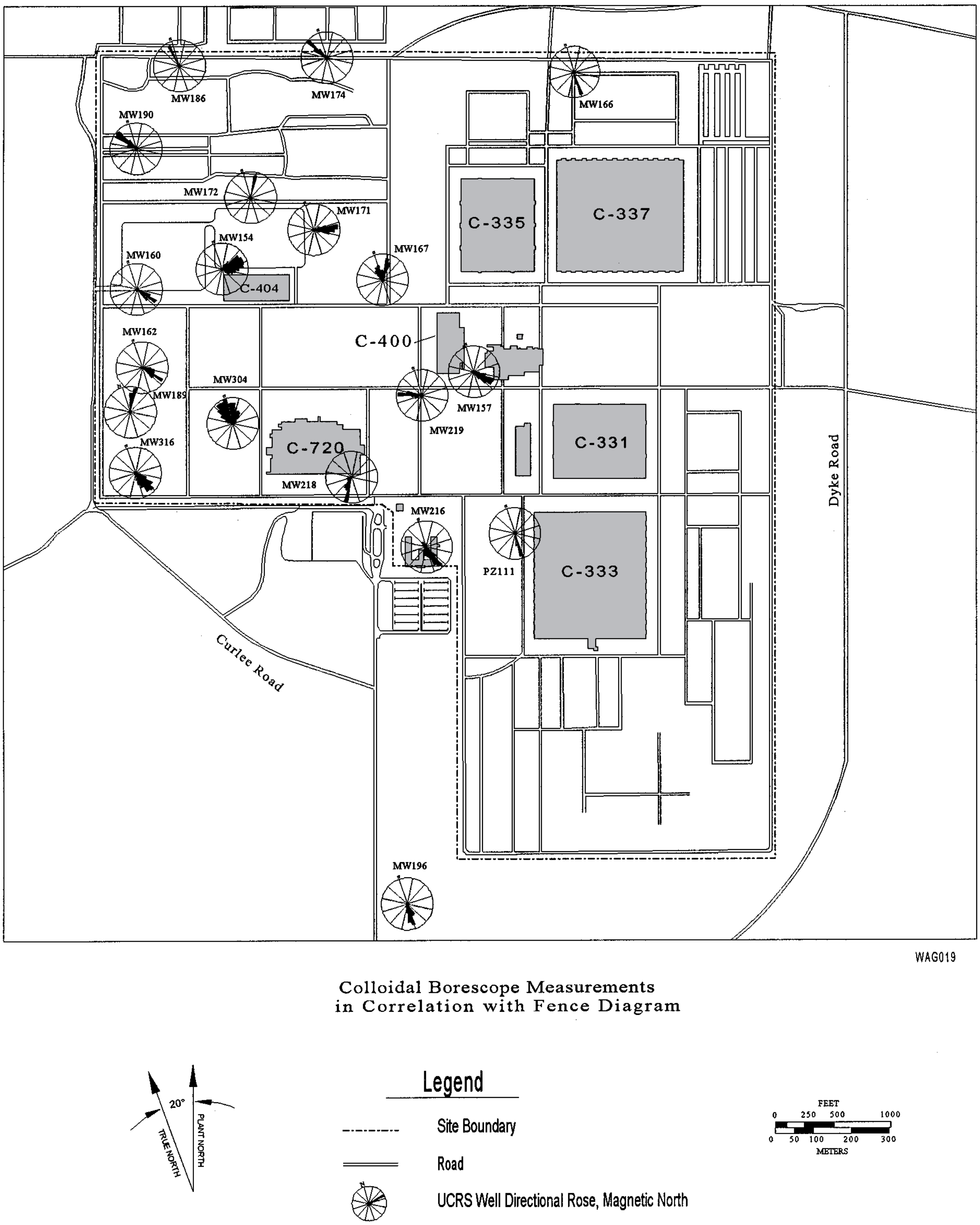

Figure 6. Map showing flow directions based on Colloidal Borescope measurements.

MW172 all show a component of flow toward the north. A drainage ditch running in an east/west direction is located just north of the fence and appears to be a discharge area for this sand and gravel unit. These flow directions are also affected by a lagoon with flucuating water levels which causes directional reversal at certain times. Well MW160 is the only well in this unit that shows a different flow direction. The flow direction toward the south in this well was consistent over several months of measurements. Influences controlling flow in MW160 are not clear but may be related to local lithology (Clausen *et al*., 1996). MW162, located south of MW160, also shows a flow direction toward the south. Nearby wells MW154 and MW171 show northeasterly flow but are not completed in the same sand unit.

Flow directions measured by the colloidal borescope in the C-400 building area provide an interesting comparison to contaminant characterization studies conducted at the site. The C-400 building is believed to be the source of two chlorinated hydrocarbon plumes, one moving in a northwest direction and another moving in a northeast direction. Recent isotope studies of the plumes confirm that they are from the same source. Colloidal borescope direction measurements for wells MW167 and MW219, located west of the building, show a west and north groundwater flow component while well MW157, on the east side of the building, shows an east flow component. The plume configuration and the diverging flow directions on either side of the building suggests that the C-400 building is a local groundwater divide caused by either mounding due to leaking underground water lines or lithologic controls.

Well MW166 is located in the northeast portion of the site directly south of an unlined outfall ditch. This ditch usually contains water that recharges the upper aquifer in this area. Flow directions in MW166 show a southern direction away from the ditch indicating that recharge is sufficient to induce a southern flow gradient in the area.

Wells PZ111 and MW218 are located in a sand and gravel unit near the southern boundary of the site. Both wells show a flow component toward the south. The flow directions are consistent in this unit and are in an opposite direction to the hydraulically isolated sand and gravel zone in the northwest area of the site. These wells are located near large industrial areas with numerous underground water supply lines and wastewater lines north of the wells. Suspected leaks in these lines appear to be influencing groundwater flow in this area.

An interesting series of wells are MW162, MW189 and MW316 located in the southwest portion of the plant. Flow in MW162 and MW316 is to the south while flow in MW189, located between the other two wells, is to the north and east. Once again, when the measurements are compared to the site geology, presented in Figure 3, an explanation emerges. Well MW316 is located in a shallow sand and gravel zone approximately 10 to 20 ft below land surface. This sand and gravel zone is not present in MW189. Borescope measurements in MW189 were taken in a sandy-clay zone. The lithologic record is unclear for well MW162; however, this well may be completed in the large sand and gravel unit correlated in the northeast portion of the site and shows a flow direction toward the south.

CONCLUSIONS

The colloidal borescope directional measurements support the hydrogeologic conceptual model that the UCRS consists of isolated sand and gravel units that have independent flow directions and velocities depending on the type and location of recharge and discharge. Borescope measurements generally show consistent flow directions in the same sand and gravel units, but flow directions vary widely between individual sand and gravel units. The directional data further support the conceptual model that localized flow and not regional flow dominates groundwater movement in the UCRS. Again, these results are consistent with the contaminant distributions, areas with suspected leaky underground utilities, and groundwater flow directions affected by surface features such as drainage ditches and outfalls.

Results of this investigation indicate that the colloidal borescope is a useful tool for describing the flow hydraulics of a complex subsurface flow system. This instrument can have a wide application at other industrial sites for assessing groundwater flow velocities and influences of man-made features, assessing the area of influence for pump and treat systems, and determining the degree of interconnection for subsurface flow zones. Cost compared with conventional pumping tests can be significantly lower without the problems of contaminated water disposal.

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