2002 SUPERFUND TECHNOLOGY EVALUATION: HYDROTECHNICS IN SITU FLOW SENSOR

During 2001, the U.S. Environmental Protection Agency (EPA) Superfund Innovative Technology Evaluation (SITE) Program evaluated performance of HydroTechnics, Inc. flow sensors in measuring the three-dimensional flow pattern created by operation of the Wasatch Environmental, Inc. (WEI) groundwater circulation well (GCW). The GCW is a dual-screened, inwell air-stripping system designed to remove volatile organic compounds (VOC) from groundwater. Operation of the GCW creates a groundwater flow pattern that forms a three-dimensional regime known as a "circulation cell." EPA's evaluation of the GCW circulation cell involved the use of in situ ground water velocity flow sensors that were developed at Sandia National Laboratories and manufactured by HydroTechnics, Inc. This Technology Evaluation Report (TER) documents and summarizes the findings of EPA's evaluation of HydroTechnics' flow sensors. The flow sensors are in situ instruments that use a thermal perturbation technique to directly measure the velocity of groundwater flow in unconsolidated, saturated, porous media.

The primary conclusions of EPA's technology evaluation of the HydroTechnics flow sensors during the GCW evaluation include:

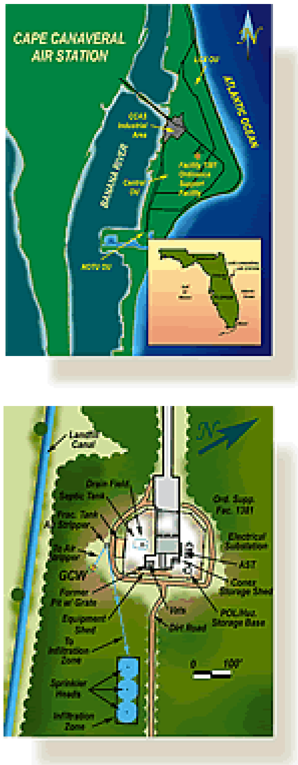
- ***During GCW operation, the groundwater velocities measured by all seven sensors increased by more than 0.1 ft/day, indicating that (1) the sensors were within the circulation cell established by the GCW, and (2) the horizontal extent of groundwater circulation was greater than 15 feet. Flow direction data further support the establishment of a circulation cell and that all the flow sensors are within the horizontal extent of groundwater circulation cell.***

- ***The demonstration data suggest that the flow sensors are responsive to changes in groundwater flow conditions and can be used to help define and evaluate the three-dimensional flow pattern.***

PROJECT BACKGROUND

As part of ongoing efforts to address impacts to groundwater from chlorinated solvents, CCAS is conducting a series of pilot-scale treatability studies to obtain site-specific data on perfor-mance and cost for potentially applicable reme-diation technologies. AFCEE identified the WEI GCW as a possible solution for remediation of nonaqueous-phase liquids (NAPL) source areas such as Facility 1381. Facility 1381 was selected as the demonstration site because it was thought to have a favorable site hydro- geologic condition (relatively high hydraulic conductivity) and the presence of a NAPL source.

GCW technologies have been proposed as a cost-effective alternative to traditional pump-and-treat technologies for remediation of ground water contaminated with volatile organic compounds (VOC). AFCEE developed a comprehensive test plan to evaluate the GCW, which included installation of a 6-inch GCW and 99 microwells that radiate from the GCW; collection of samples from the soil core, groundwater, and air for subsequent geotechnical and chemical analysis; completion of a dye tracer test; and development of a site groundwater flow model. AFCEE alternated operation of the GCW between pump-and-treat mode and circulation mode to obtain reliable data on the relative capabilities of the GCW technology. Samples of groundwater and air were collected during both modes of operation to obtain performance data under various operating scenarios and to allow comparisons of results. AFCEE invited EPA to participate in an evaluation of a GCW at CCAS Facility 1381. To evaluate the circulation cell, EPA installed in situ groundwater flow sensors to measure the magnitude and direction of groundwater flow near the GCW, and conducted a series of aquifer hydraulic tests. Data from the groundwater flow sensors were collected during (1) long-term pump-and-treat operation, (2) long-term GCW operation, (3) final pump-and-treat operation, (4) aquifer hydraulic tests, and (5) post-GCW operation.



CCAS is on Canaveral Peninsula, which is on the Atlantic coast of Florida. The site consists of facilities for missiles and space vehicles and occupies 25 square miles.

Long-Term Pump-and-Treat Operation. The GCW was installed at the site in November 1999. After a tidal influence study, tracer test, and a series of short-term aquifer hydraulic tests, the system began operation in pump-and-treat mode in February 2000. The system remained in pump-and-treat mode through April 2000. AFCEE monitored the system to calculate mass removal rates for comparison to rates achieved during other modes of operation by the GCW.

Long-Term GCW Operation. Long-term operation of the GCW was initiated in April and continued until July 2000. The in situ groundwater flow sensors were installed in June 2000. Continuous collection of data on groundwater flow from the sensors was initiated in July 2000.

Final Pump-and-Treat Operation. Final pump-and-treat operation of the GCW was conducted during August 2000. Eight transducers were installed to evaluate changes in hydraulic head in the aquifer during August 2000.

Aquifer Hydraulic Test Operation. A series of aquifer hydraulic tests were conducted in September 2000. Hydraulic head data were collected from the aquifer using eight pressure transducers, and data on direction and magnitude of groundwater flow were collected from the seven in situ groundwater flow sensors.

Post-GCW Operation. The GCW has not operated after aquifer hydraulic testing was completed in September 2001. EPA collected data from the in situ groundwater flow sensors from September 2000 through September 2001 to document groundwater flow during non-operation of the GCW.

THE SUPERFUND INNOVATIVE TECHNOLOGY EVALUATION (SITE) PROGRAM

EPA's Office of Solid Waste and Emergency Response (OSWER) and Office of Research and Development (ORD) created the SITE Program in response to the Superfund Amendments and Reauthorization Act of 1986 (SARA). The SITE Program promotes the development, evaluation, and use of new or innovative technologies to clean up Superfund sites across the country. The primary purpose of the SITE Program is to maximize the use of alternatives in cleaning up hazardous waste sites by encouraging development and evaluation of innovative treatment and monitoring technologies. It consists of three major elements:

- The Technology Evaluation Program
- The Monitoring and Measurement Technologies Program
- The Technology Transfer Program

The objective of the Technology Evaluation Program is to develop reliable data on performance and cost for innovative technologies so that potential users may assess the technology's site-specific applicability. Technologies evaluated are either currently available or are close to being available for remediation of Superfund sites. SITE evaluations are conducted on hazardous waste sites under circumstances that closely simulate full-scale remediation conditions, thus ensuring the usefulness and reliability of the information collected. Existing technologies that improve field monitoring and site characterizations are identified in the Monitoring and Measurement Technologies Program. This program supports new technologies that provide faster, more cost-effective contamination and site assessment data. The Monitoring and Measurement Technologies Program also formulates protocols and standard operating procedures for evaluation methods and equipment. The Technology Transfer Program disseminates technical information on innovative technologies in the Evaluation and Monitoring and Measurements Technologies Programs through various activities. These activities increase the awareness and promote the use of innovative technologies for assessment and remediation at Superfund sites. The goal of the technology transfer is to develop communication among individuals who require up-to-date technical information.

Site History

Since it was established in 1950, CCAS has been a proving ground for research, development, and testingof the country's military missile programs. Seventy-three miles of paved roads at CCAS connect the various launch and support facilities with the centralized industrial area. The primary industrial activities at CCAS support missile launches from CCAS and spacecraft launches from KSC. CCAS also provides support for submarine port activities. Facility 1381 has been used for several operations since it was built in 1958. For the 10 years after construction, Facility 1381 was used as the Guidance Azimuth Transfer Building. Aerial photographs from that time indicate numerous drums and tanker trucks at the facility. Verbal reports indicate that the tanker trucks were used for dumping waste solvents in the forest that surrounds the facility. In 1968, the site became the In-Place Precision Cleaning Laboratory. Specific activities included cleaning metal components in acid and solvent dip tanks, resulting in the generation of approximately 3,300 gallons of waste trichloroethene (TCE) per year. In 1977, the facility became known as the Ordnance Support Facility, and its name has remained un-changed to the present time.

Site Geology

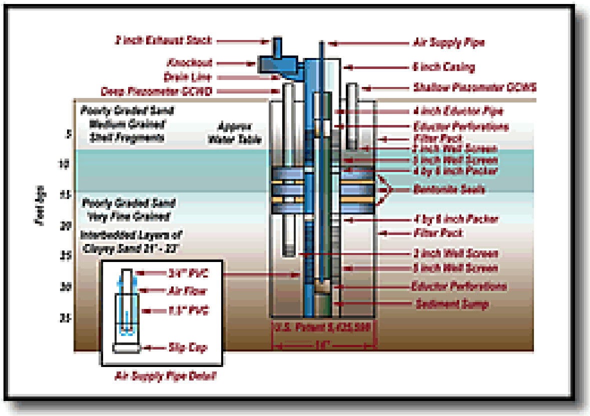
CCAS is situated on Canaveral Peninsula, which is on the east side of Merritt Island, a barrier island in Brevard County on the Atlantic coast of Florida. Facility 1381 is located in the central portion of CCAS. The topography at Facility 1381 is relatively flat, with ground elevations ranging from approximately 5 to 10 feet above mean sea level (msl). The topography consists of long, northeast-southwest trending, low rises that are most likely depositional features associated with accretion of the barrier island. Vertical relief in the area is limited to shoulders of drainage canals that slope from the ground surface to the canal bed. Drainage canals are located 200 feet southwest (Landfill Canal) and 2,500 feet north (Northern Drainage Canal) of the GCW; both flow westward toward the Banana River. Based on previous work at the site conducted by Parsons (2000), the geology at Facility 1381 consists of unconso-lidated sediments to a depth of at least 60 feet bgs. The upper 15 feet consists of poorly sorted, dominantly coarse shell material and coarse to medium sand. The average grain size of the sand fraction decreases and the silt and clay content increases from depths of 35 feet to approximately 50 feet below ground surface (bgs). A 5-foot-thick unit of fine to very fine-grained sand and silt occurs from 35 to 40 feet bgs. Shell frag-ments and coarse sand occur with varying amounts of clay from approximately 40 to 50 feet bgs. A layer of firm clay, which may be continuous across the site, has been encountered at a depth of 50 feet bgs.

Surficial Aquifer

The uppermost water-bearing unit near the site is the surficial aquifer, which is unconfined and consists primarily of unconsolidated materials. The surficial aquifer system is a shallow, nonartesian aquifer, which occurs over much of eastern Florida but is not an important source of ground water because better supplies are generally available from other aquifers. The surficial aquifer system extends to a depth of approximately 50 to 60 feet bgs near CCAS. The surficial aquifer is described as consisting of fine to medium quartz sand that contains varying amounts of silt, clay, and loose shells that are post-Miocene in age. In coastal areas, such as at CCAS, the surficial aquifer may also consist of partially cemented shell beds or coquina. The depth of the water table in the surficial aquifer ranges from at or near the land surface in low-lying areas to tens of feet below the land surface in areas of higher elevations. The most important function of the surficial aquifer is to store water, some of which recharges the underlying Floridan aquifer. The surficial aquifer is little used as a source of drinking water since its permeability is low, resulting in relatively limited yield to wells, when compared with the Floridan aquifer system. The surficial aquifer is used to supply potable drinking water only in coastal areas where the underlying Floridan aquifer may be brackish (Miller 1986). The sands of the surficial aquifer generally grade into less permeable clayey or silty sands or low-permeability carbonate rocks at depths of usually less than 75 feet below the land surface. These rocks act as a confining unit for limestones that compose the underlying Floridan aquifer system. This upper confining unit of the Floridan aquifer system, as it is known, is generally composed of the middle Miocene-aged Hawthorn Formation, low-permeability rocks that in most places separate the Floridan aquifer from the surficial aquifer.

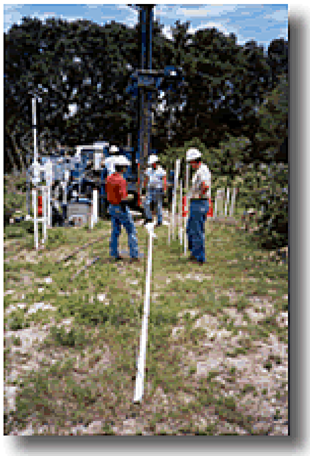
The shallow aquifer zone at Facility 1381 is part of the surficial aquifer, which, as described previously, is a regionally unconfined water table aquifer. The water table at CCAS generally occurs at depths ranging from 3 to 15 feet bgs. The water table occurred at approximately 8 feet bgs near the area where the groundwater circulation well was installed. Flow of shallow groundwater at CCAS is controlled by an engineered drainage system consisting of a series of man-made canals, which were installed to reclaim land by lowering the water table. Surface water at the site drains through the canals and discharges into the Banana River, which is located west of CCAS. Closest to Facility 1381 is Landfill Canal, which is located 200 feet southwest; the Northern Drainage Canal is located about 2,500 feet due north of Facility 1381.

The canals strongly influence flow of shallow groundwater at the site. A groundwater divide is indicated in the vicinity of the GCW, as evidenced by groundwater flow to the southwest toward Landfill Canal, as well as to the northeast in the direction of the Northern Drainage Canal. Surface water elevations measured in the canals are lower than adjacent shallow groundwater elevations, suggesting groundwater discharge to the canals (Parsons 2000). The upper part of the surficial aquifer at Facility 1381 has been delineated into shallow and deep aquifer zones for this evaluation. The shallow aquifer zone is defined as the upper saturated portion of the aquifer, from the water table to the contact of the coarse-grained shell and coarse to medium grained sand unit that occurs approximately 15 feet bgs. The shallow aquifer zone is approximately 8 feet thick. The deep aquifer zone is made up of medium to fine sand units, which occur at depths of 15 to 30 feet bgs. The hydraulic conductivity of the surficial aquifer at Facility 1381 was previously measured using rising head slug tests at a monitoring well pair, 1381MWS09 (screened 7.5 to 12.5 feet bgs) and 1381MWI09 (screened 30 to 35 feet bgs), located 55 feet southeast of the GCW. The calculated hydraulic conductivity values are 11.6 ft/day for the shallow well and 0.4 ft/day for the deep well. Slug testing in piezometers near the GCW yielded hydraulic conductivity values of 17.8 to 24.2 ft/day in piezometer 4PZS (screened 6.5 to 9.5 feet bgs) in the shallow aquifer zone and 0.1 to 0.2 ft/day in piezometers 2PZD (screened 21.3 to 24.6 feet bgs) and 6PZD (screened 22.7 to 26 feet bgs) in the deep aquifer zone. The groundwater velocity in the shallow aquifer zone under natural flow conditions is estimated at 0.21 ft/day (Parsons 2000). Values for hydraulic conductivity obtained from aquifer testing conducted in September 2000 are presented in Appendix A of the full report, the Hydrogeological Investigation Report. Based on the pumping test data, the hydraulic conductivity of the estimated saturated upper portion of the aquifer (42 feet thick) ranges from 43 to 53 ft/day.



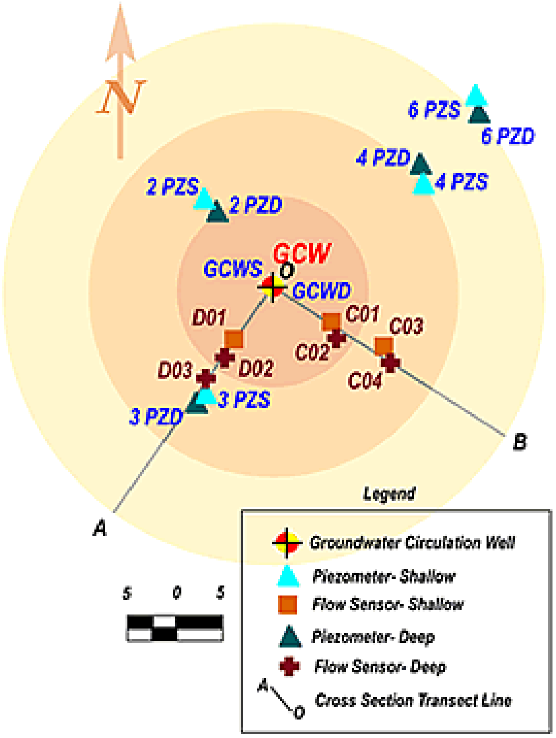
Site Contamination

Contamination in soil and groundwater at Facility 1381 has been attributed to historical waste disposal practices. A plume of contaminants in groundwater, consisting primarily of TCE and associated degradation products including cis-1,2-dichloroethene and vinyl chloride, has been detected at the site. The plume is 110 acres in areal extent and is 2,500 feet long. The axis of the plume is elongated to the north-northeast. The maximum concentration of TCE detected to date in the suspected source area is 342,000 micrograms per liter (µg/L) (Parsons 1999b). Concentrations of TCE measured in samples from the source area have been lower during more recent sampling rounds.



Placement of Sensors and Data Evaluation

Seven groundwater flow sensors manufactured by HydroTechnics were installed in two separate clusters southeast of and in two separate clusters southwest of the GCW. Data collected from the flow sensors were used to evaluate both the horizontal extent of recirculation and the overall three-dimensional groundwater flow pattern that surrounds the GCW.



Modeling of the circulation cell performed by the Oregon Graduate Research Institute was used to predict the horizontal extent of the circulation cell and to select the locations of the flow sensors. The modeling predicted that groundwater in the upper portion of the treatment zone would flow radially away from the GCW, and that groundwater in the lower portion of the treatment zone would flow radially toward the GCW. The results of modeling were also used to show that flow velocities surrounding the GCW would decrease with distance from the GCW. The modeling results indicated that the extent of circulation at velocities that exceeded 0.05 ft/day appeared to be limited to a radial distance of 10 feet from the GCW. In addition, induced groundwater flow velocities near the GCW were predicted to exceed 2.0 ft/day at a distance of 5 feet from the GCW. Based on the modeling results, the most appropriate zone for installation of flow sensors is between 5 feet and 10 feet from the GCW. The velocity range of groundwater flow that can be accurately measured by the groundwater flow sensors is between 0.01 and 2.0 ft/day, based on the manufacturer's specifications. Based on this criterion and the results of modeling for the GCW, two of the flow sensor clusters were installed 7.5 feet from the GCW, and two of the flow sensor clusters were installed 13 to 15 feet from the GCW. This strategy for placement of the sensors took into account the measurement range of the sensors of 0.01 to 2.0 ft/day to ensure that changes in the velocity of groundwater flow can be accurately measured.

The sensors were installed in relation to the assumed hydraulic gradient, which was determined to be to the southwest. Three flow sensors were placed to the southwest (assumed downgradient) of the GCW. Another four flow sensors were placed to the southeast (assumed cross gradient) of the GCW. The sensors were installed using a hollow-stem auger drilling rig equipped with 4.25-inch-inner-diameter augers. The sensor was then lowered through the inner annulus of the drill pipe by attaching it to a 2-inch- diameter schedule 40 PVC well casing. The well casing was used to house the sensor cables in addition to providing a platform that enabled the field crew to lower the sensors into the borehole. After the sensor was seated at the bottom of the boring, the auger flights were retracted, allowing the saturated unconsolidated aquifer matrix to collapse around the flow sensor.

Evaluation of the flow sensors consists of using the data collected to assess the presence of a three-dimensional groundwater flow regime or circulation cell. The circulation cell is induced when the GCW is in recirculation mode. For this evaluation, evidence for the existence and the extent of the circulation cell was as follows:

- Increases in horizontal groundwater Darcy velocities (hydraulic conductivity times hydraulic gradient) in excess of 0.1 ft/day.
- Changes in vertical groundwater Darcy velocities and the vertical hydraulic gradient.
- Changes in direction of groundwater flow such that flow is away from the upper screen of theGCW in the shallow aquifer zone and toward the lower screen of the GCW in the deep aquifer zone.

The evaluation was designed to assess changes in the velocity of groundwater flow (magnitude and direction) measured by the flow sensors. Data from the flow sensors were presented in hydrographs as horizontal and vertical velocity versus time, plotted in map view to show the horizontal component of velocity and direction, and plotted in cross-section view showing resulting groundwater velocities and directions of groundwater flow. In addition, the data on groundwater velocity that represent each operational period were tabulated.

The groundwater flow sensors were installed in linear arrays at varying distances and depths from the GCW in order to achieve the primary objectives defined in Section 2.2. Velocities and directions of ground water flow within the circulation cell of the GCW were measured using seven in situ groundwater flow sensors in each cluster. The horizontal change in velocity was calculated by subtracting the measured flow velocity. The changes in velocity of flow were calculated for each operational mode using the data set that began when steady-state flow conditions had been established. Locations where changes in the velocity of flow were equal to or greater than 0.1 ft/day were considered to be within the extent of the circulation cell created by the GCW. The three-dimensional groundwater flow that surrounds the GCW was evaluated to identify overall changes in direction of ground water flow and velocity attributed to the GCW. The three-dimensional groundwater flow pattern was depicted qualitatively using hydrographs, horizontal flow vector maps, and resulting flow velocity projected onto cross-sections. The three-dimensional groundwater flow was depicted separately for each operating condition.

Hydrogeologic data collected during previous investigations at Facility 1381 were reviewed to develop a site hydrogeologic conceptual model. A series of aquifer tests were also conducted to evaluate the hydraulic parameters in the shallow aquifer zone such as hydraulic conductivity (K), transmissivity (T), storativity (S), and specific yield (Sy). These data were used in combination with data from the flow sensors to assess groundwater flow patterns within the treatment zones.

MODIFICATIONS TO THE TECHNOLOGY EVALUATION PLAN

The TEP (Tetra Tech 2000) specified that the flow sensors would be installed near the GCW and in relation to the natural flow gradient. Two groups of flow sensors, consisting of deep and shallow clusters, were to be installed downgradient of the GCW, and two clusters were to be installed cross-gradient from the GCW. The sensors were installed assuming a natural flow gradient to the southwest. Groundwater elevation data collected in 2000, however, suggest that the horizontal hydraulic gradient is very low and that the direction of groundwater flow near the GCW varies. Evidence also indicates that a groundwater flow divide is present near the GCW. Because a constant hydraulic gradient is absent, the relationship of the locations of the flow sensors to the natural direction of groundwater flow cannot be established. The flow sensors were installed at depths that varied from the plan. The deep sensors were installed 1 to 2 feet shallower than was planned because of subsurface conditions encountered during their installation. Soil samples collected from the deeper portion of the aquifer showed an increase in fine-grained materials. The sensors were installed in the shallower, more permeable portion of the aquifer to ensure flow around the sensor would be measurable. To evaluate the flow in the upper screened interval, it was therefore decided in the field to install the shallow sensors at a depth of approximately 1 foot (0.3 meters) below the existing groundwater surface. The shallow sensors were installed at a lower depth because the groundwater level at the site was lower than was anticipated. Florida was experiencing a drought and static water levels were several feet lower than had been reported in previous site investigations. The shallow flow sensors were installed with less than manufacturer recommended submergence because initial modeling results indicated that there would not be measurable flow deeper than 6.6 feet (2 meters) into the aquifer 6.6 feet (2 meters) radial distance from GCW. With effort the manufacturer was able to interpret shallow sensor data. In most cases, the radial distances of the flow sensors from the GCW were within 0.25 feet of those specified in the plan. The clusters of flow sensors were installed along a line such that the deep flow sensors were farther away from the GCW than were the shallow flow sensors. As a result, the following exceptions were noted with respect to installation distances of the flow sensors. Deep flow sensor C02 was installed 1.5 feet farther away from the GCW than was specified in the plan. Deep flow sensor D02 was installed approximately 1.75 feet farther from the GCW than was specified in the plan. Shallow flow sensor C03 was installed 0.5 feet closer to the GCW than was specified in the plan.

While the technical data collection performed during the demonstration was generally consistent with the requirements of the TEP, except as noted above, the wording of the primary objective and first secondary objective were slightly revised for the purposes of clarity in reporting the results of the demonstration. The TEP reports the primary objective as to evaluate the horizontal extent of the groundwater circulation cell. This TER reports the primary objective more accurately as to evaluate the flow sensor’s ability to detect the horizontal extent of the groundwater circulation cell. The first secondary objective was reworded to more accurately reflect the objective to evaluate the reproducibility of the groundwater velocity data obtained from the flow sensors; rather than the original wording, which was to evaluate the precision of the sensors.

Placement of Flow Sensors in Relation to Direction of Groundwater Flow

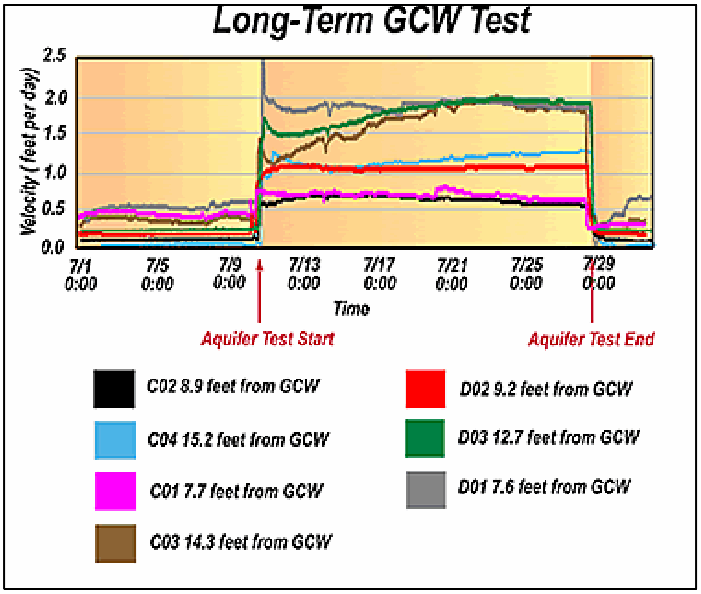
The flow sensors were installed based on distance from the GCW and relative to the expected natural direction of groundwater flow toward the southwest. Based on this assumption, cross gradient (southeast) and downgradient (southwest) clusters of flow sensors were installed. However, because of the probable presence of a groundwater flow divide near the GCW, direction of groundwater flow is more variable. As a result, the relationship of the flow sensors to the horizontal hydraulic gradient is most likely transient. Therefore, the flow sensors and clusters are referred to as “southeast” and “southwest,” rather than “cross gradient” and “downgradient” for this evaluation.

Depth of Shallow Flow Sensors with Respect to Water Table

The manufacturer’s recommended installation depth requires a minimum of 5 feet of saturated aquifer material between the top of the flow sensor and the water table. If the flow sensor is too near the unsaturated zone, which tends to be higher in temperature than the underlying groundwater, then the existing temperature gradient will incorrectly be interpreted by the sensor as upward flow. These superposed vectors can be accounted for and corrected using the programs’ vector subtraction feature. To evaluate the flow in the upper screened interval, it was decided in the field to install the shallow sensors at a depth of approximately 1 foot below the existing groundwater surface (approximately 8 feet below ground surface) to allow the sensor to be placed at a depth similar to the upper screened interval of the GCW. However, it was suspected that deeper placement of the flow sensors would compromise the ability to evaluate GCW performance in the shallow aquifer zone.

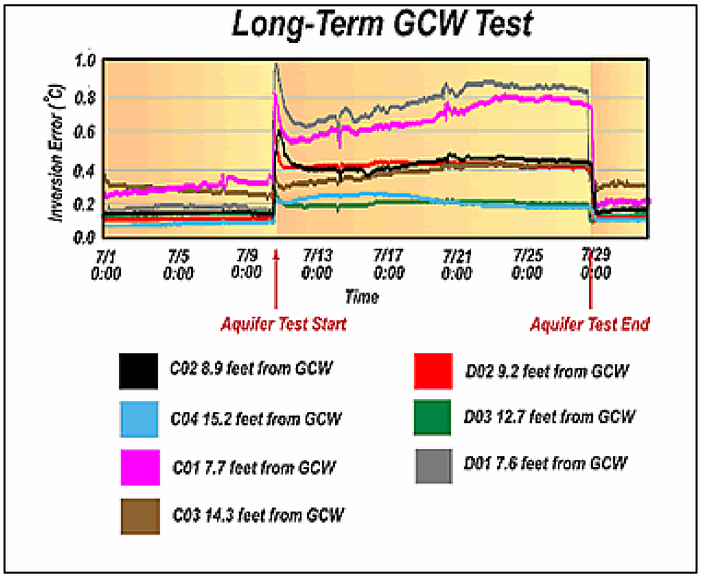
Accuracy and Precision of Flow Sensor Data

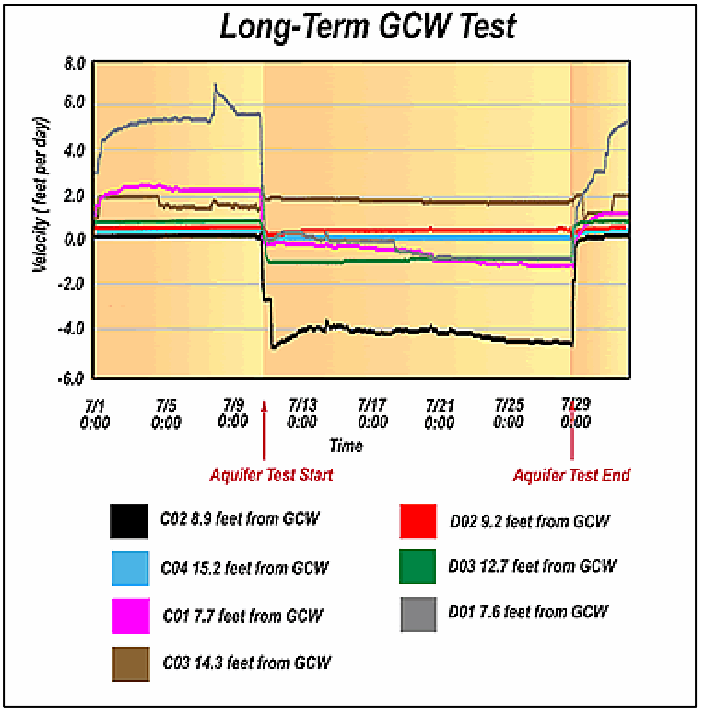
Past studies conducted by independent parties have shown that the flow sensors accurately record precise flow velocity data when directly compared to piezometric analysis in fluctuating flow environments such as occur in natural ground water/surface water interactions as well as pump test of many varieties. Though the probes routinely and accurately record fluctuations in flow velocities, flow velocities higher than 2 ft/day have higher interpretation errors. This upper limit is dictated by the sensor geometry and the heat flow equation central to the algorithm. The algorithm used by the sensor to calculate a flow vector requires the last collected data point; if that last data point is outside the upper specified limit, it will calculate the next data point but yield an incorrect velocity. In addition, rapid oscillations in flow velocities, as might be experienced by turning a nearby pump on and off very quickly, may yield ambiguous data. Some measure of equilibrium must be attained between changes in velocities for any one velocity to be calculated faithfully.



Horizontal Groundwater Darcy Velocities

Horizontal and vertical groundwater Darcy velocities are presented and discussed in this section. The flow sensor data indicate that the GCW was not operational until July 11, when the four flow sensors in the deep aquifer zone recorded sharp increases in horizontal velocities. The increases in flow velocity recorded on July 11 are caused by initiation of the long-term GCW circulation mode test; that is, simultaneously pumping from the lower screen and injecting into the upper screen. The responses of the flow sensors indicate that all of the deep sensors were in an area of the aquifer zone that was affected by operation of the GCW. Southwest flow sensor D03, fartherfrom the GCW, exhibited a greater response to operation of the GCW than did flow sensor D02, which is closer to the well. Southeast flow sensor C02, whichis closer to the GCW, exhibited a greater response to operation of the GCW than did flow sensor C04, farther from the pumping well. Different responses in south west flow sensors D02 and D03 possibly indicate aquifer heterogeneity and anisotropy in this direction. According to the flow sensor data, the long-term GCW test ended late on July 28, 2000, resulting in a test period of about 17 days. The velocity data from the flow sensors suggest that the GCW circulation flow was generally constant over the testing period. As with the deep aquifer zone, the data collected before July 11 shows the natural flow velocities, which in the shallow aquifer zone are approximately 0.3 to 0.5 ft/day. On July 11, 2000, similar to the deep flow sensors, the shallow flow sensors recorded a sharp change in horizontal Darcy groundwater velocity. South east flow sensor C01, which is closer to the GCW, showed lower horizontal velocities than were measured at southeast flow sensor C03, which is farther from the GCW. Horizontal velocities recorded at shallow south east flow sensor C03 were simila r to southwest flow sensor D01, on the order of 1.5 to 2 ft/day.

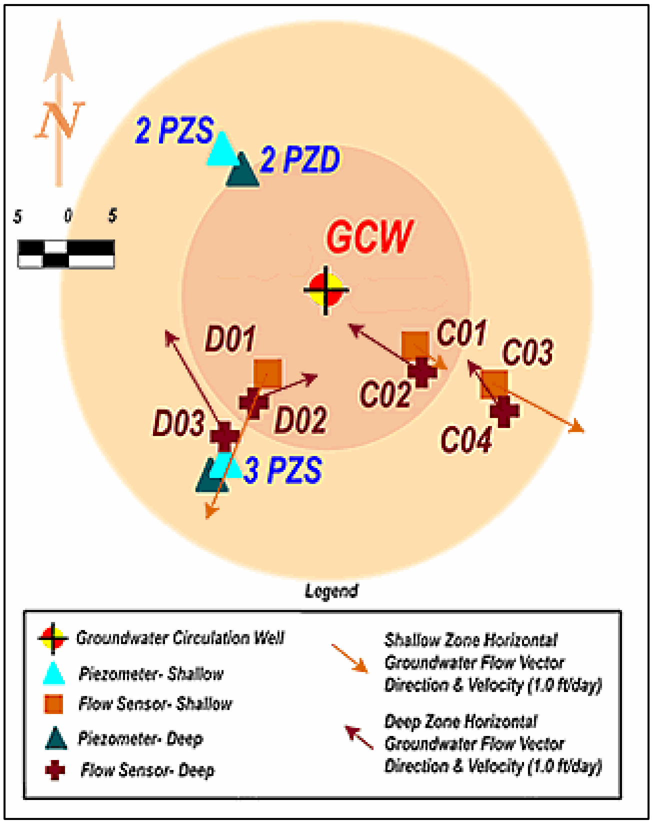




Flow sensor inversion error is a built-in, internal measure of how well the calculated probe surface temperature distribution matches the observed temperature distribution. Error versus time indicate that inversion errors increased by up to about 0.6 °C during the GCW testing period. The 0.6 °C inversion error is gene-rally considered the upper limit of the errors for reasonably reliable velocity simulations. Thermistor temperatures versus time indicate that more variation in temperature at flow sensor C01 occurred during the GCW testing period. The net flow velocities for the deep flow sensors ranged from 0.5 to 1.5 ft/day during the GCW testing period. The net flow velocities for the shallow flow sensors ranged from 0.5 to 2.0 ft/day during the GCW testing period.

Vertical Groundwater Darcy Velocities

The measured vertical Darcy groundwater velocities versus time in the shallow and deep aquifer zones are shown in the adjacent figure. As with the horizontal velocities, a change in the vertical velocities occurred on July 11. This change is the start of pumping associated with the long-term GCW test. The most significant change in the vertical velocity occurred in flow sensor C02, 8.9 feet southeast of the GCW, where the vertical velocity reversed from upward to down-ward, to approximately minus 5.0 feet per day. The change in vertical velocity was much less pronounced in the other deep southeast flow sensor, C04. At southwest flow sensors D02 and D03, the more significant change in vertical velocity occurred at D03, farther from the GCW than is flow sensor D02, which exhibited a much less pronounced response that was similar to flow sensor C04. Vertical groundwater velocities in each of the deep flow sensors appear to have stabilized quickly after the GCW test began and remained consistent until the apparent end of the test on July 28, 2000.

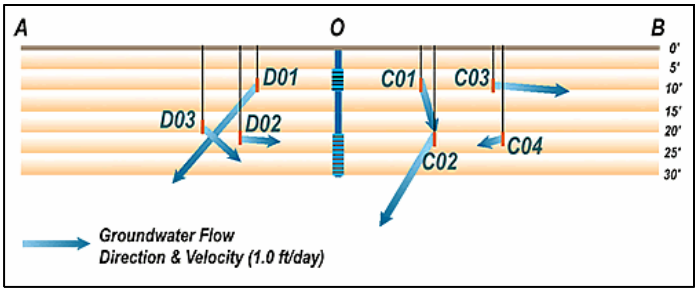


Horizontal Groundwater Flow Directions

Horizontal directions of groundwater flow under GCW circulation mode measured in the deep aquifer zone are shown in the adjacent figure. The data shown were collected at 4 p.m. on July 28, 2000, near the end of the pumping period associated with the GCW testing period. It is assumed that groundwater circulation reached a steady state condition at the end of the GCW testing period. The length of the arrows shown represents the magnitude of horizontal flow velocity. It appears that velocities of groundwater flow in three out of the four sensors are on the order of 1 foot per day. Assuming natural flow velocities in the deep aquifer flow zone on the order of 0.01 ft/day, the arrows that represent vectors of velocity and direction indicate that all of the flow sensors are in areas that were affected by pumping of the GCW. In gene-ral, except for flow sensor D03, the directions of groundwater flow shown are toward the lower screen of the GCW. The flow velocities at sensors C03 and D01 are an order of magnitude higher than the estimated natural rate of flow in the shallow aquifer zone of about 0.3 ft/day, with little change recorded at flow sensor C01. The directions of flow are away from the GCW, indicating that the sensors in the shallow aquifer zone were recording the effects of water recharged to the upper screen of the GCW.

Resultant Groundwater Flow Velocities Projected in CrossSection

Resulting groundwater flow velocities and directions, measured by the flow sensors on July 28, 2000, were projected onto cross-section AOB, as shown here. (The location of cross-section AOB is shown above). Under pumping and reinjection conditions, as represented at the end of the GCW circulation test, velocities and directions of groundwater flow in the deep and shallow aquifer zone were clearly altered by operation of the GCW. The highest velocities were recorded in sensors closest to the GCW, C01, C02, and D01. The flow regime near the GCW, as defined by those sensors, appears to contain a more pronounced component of vertical flow than of horizontal flow. This phenomenon is consistent with the Oregon Graduate Institute's model predictions and observations during aquifer testing. The magnitude of flow velocity reflected may be less reliable than the directions of the recorded flow because (1) flow velocities at sensors C01, C02, and D01 are out of the range that can measured, according to specifications for the flow



sensors, and (2) the shallow flow sensors may be significantly affected by ambient temperatures in the vadose zone. Nevertheless, flow at each of the shallow flow sensors is directed away from the GCW, while flow recorded at each of the deep flow sensors is toward the GCW, consistent with the direction expected in a circulation cell produced by operation of the GCW.

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