

# Fractured Bedrock Aquifer Hydrogeologic Characterization for a Bioaugmentation Pilot Study

Paul Jeffers and Veryl Wittig, GeoSyntec Consultants

## Abstract

A hydrogeologic characterization was performed to evaluate the nature of groundwater flow in an alluvial and underlying fractured bedrock aquifer in the area between an unlined, inactive landfill and a river in southern California. The hydrogeologic characterization was used to enhance the site conceptual model for the site, and to design a bioaugmentation pilot test to evaluate the use of enhanced in-situ bioremediation (EISB) to treat chlorinated VOCs, primarily PCE, TCE, 1,1-DCA, cis-1,2-DCE, and VC in the fractured rock aquifer beneath the site.

The pilot test area (PTA) is characterized by a thin veneer of alluvium overlying fractured tonalite (bedrock). Groundwater beneath the site is unconfined within the alluvium and fractured bedrock and flows from the landfill and through the PTA toward the river. Chlorinated VOCs have been detected in shallow, intermediate and deep monitor wells installed in the PTA at depths of up to 300 feet below ground surface (bgs). To date, VOCs have not been detected in surface water or shallow groundwater samples along the northern river margin.

Using lineament analyses and geophysical surveys, subsurface bedrock fracture zones and potential zones of higher groundwater flow rates were identified. Three multi-level monitoring well clusters were installed in the PTA in areas believed to be within significant fracture zones. The upgradient and intermediate monitoring clusters consist of a shallow well screened in the alluvium, an intermediate well screened in the upper highly fractured bedrock aquifer, and a deep well screened in the lower fresh, slightly fractured bedrock aquifer. The downgradient monitoring cluster includes an additional deep bedrock well. Downhole geophysical logging conducted in select boreholes prior to well construction included caliper, electrical logging, acoustic televiewer (ATV), and borehole image processing system (BIPS) logging. Additional testing performed on selected borings included thermal flow meter testing and hydrophysics.

A 48-hour continuous rate pumping test and a 72-hour recovery test were performed to evaluate the hydraulic connection between well clusters and different screened intervals within the PTA. Aquifer test analyses indicated that hydraulic conductivities (K) ranged from 25 to 40 feet per day (ft/day) in the fractured rock aquifer, and 13 to 17 ft/day in the alluvium. However, due to the low effective porosity of the fractured rock aquifer, groundwater velocities as high as 40 ft/day per day were estimated, compared to velocities of less than 2 ft/day for the alluvium.

A qualitative dye tracer study using three distinct dyes was performed in the PTA to evaluate hydraulic communication between the three clusters and intervals under passive, non-pumping conditions. Results of the tracer study confirmed that groundwater within the fractured rock aquifer was moving rapidly under passive conditions, and confirmed communication between the upgradient and downgradient wells within the pilot test area. The hydrogeologic characterization demonstrated that sufficient hydraulic communication is present within the PTA and that plans for a passive EISB pilot test should proceed.

## Background

The site consists of a Class III landfill that was operated between 1960 and 1978. The landfill was constructed without a liner, leachate collection and removal system, or leak detection system. A landfill gas extraction system was installed in 1996. Groundwater monitoring initiated at the site in 1990 identified volatile organic compounds (VOCs) and elevated concentrations of chloride and total dissolved solids. The landfill is located in a southerly trending canyon that drains to an ephemeral river. The river drains into a drinking water reservoir approximately 2 ½ miles southwest of the landfill. The potential for discharge of landfill-related constituents to the river is of paramount importance and therefore the focus of the hydrogeologic characterization. The

hydrogeologic characterization will be used to design a bioaugmentation pilot test to evaluate the use of enhanced in-situ bioremediation (EISB) to treat chlorinated VOCs in the fractured rock aquifer beneath the site.

## Geologic and Hydrogeologic Setting

The landfill is located within the Peninsular Range geomorphic province of southern California near the western margin of the southern California batholith. The southern California batholith is comprised primarily of Jurassic- to Cretaceous-age igneous rocks, ranging in composition from gabbro to granite, which were intruded into Jurassic-age metavolcanic and metasedimentary rocks (IT, 1999). Compositionally, bedrock beneath the site consists of tonalite with isolated exposures of Jurassic-age metamorphic rocks. The upper 30 to 60 feet of the site consist of grus, *in situ*, highly weathered bedrock. Recent alluvial deposits consisting of silty sands and gravels form a thin veneer over the underlying bedrock in the southern portion of the site along the northern margin of the river.

Surface features and lineaments mapped in the vicinity of the site generally trend N45°E and N50°W and are typically composed of high angle fractures (IT, 1999). Fractures observed at the surface appear to be randomly oriented and horizontally discontinuous.

Groundwater at the site is unconfined and occurs within the porous media of the alluvium/grus and in the fractures of the competent granitic bedrock. Groundwater flow within the alluvium/grus is controlled by the river system and mimics the direction of flow of the river (southwest). Groundwater within the fractured bedrock flows through fractures at depth and follows the preferential orientation of these fractures towards the river (Figure 1). Once the groundwater reaches the fracture set that defines the river valley, the groundwater at depth follows the direction of the river. Groundwater in the PTA between the landfill and the river is impacted with tetrachloroethene (PCE), trichloroethene (TCE), 1,1-dichloroethane (1,1-DCA), cis-1,2-dichloroethene (cis-1,2-DCE), and vinyl chloride in shallow, intermediate and deep monitor wells at depths of up to 300 feet bgs. The main pathway for landfill-related constituent migration from the site is through the fractured bedrock. To date, VOCs have not been detected in surface water or shallow groundwater samples along the northern river margin.

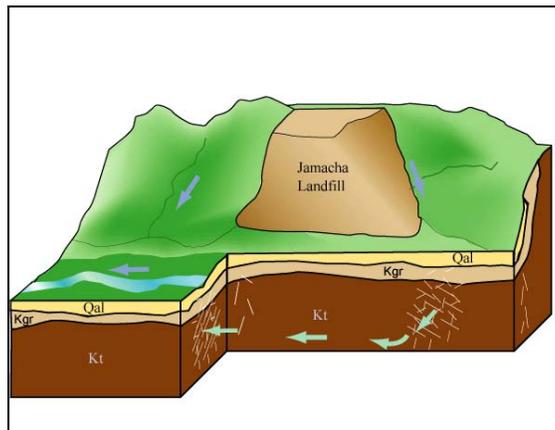


Figure 1 - The landfill is situated in a northwest/southeast trending fracture canyon. The primary pathway for offsite migration of landfill constituents is through the fractured bedrock.

## Surface Geophysical Surveys

Lineament analyses and geophysical surveys were performed to identify subsurface bedrock fracture zones and potential zones of higher groundwater flow rates. Geophysical surveys conducted include very low frequency (VLF), electromagnetic induction (EMI), and STING Resistivity Surveys (Figure 2).

Two VLF and EMI geophysical profiles were performed to identify the primary fracture trends and to assist in the siting of downgradient monitor wells for the pilot test area (PTA). Optimum coupling with a VLF transmitting station was achieved by orienting the survey perpendicular to a subsurface structure and using a transmitter station located perpendicular to the survey line. Attempts were made to align the survey lines at right angles to the northwest- and northeast-striking structures identified during geologic field mapping. The actual survey line orientations were adjusted in the field based on accessibility and to avoid interference from cultural features such as overhead power lines, fences, and underground utilities. The EMI anomalies correlated well with each other, indicating fractures striking approximately N85°W. The VLF survey was influenced by one cultural feature, a power line that produced significant noise. The results indicated the presence of two geophysical anomalies, distinguished by total field peaks and in-phase signal crossovers. At the time the survey was conducted, one of these anomalies appeared to coincide with one of the site paleodrainages; however, following corrections to the survey line locations on the site base map, neither anomaly coincided with the paleodrainages underlying the landfill.

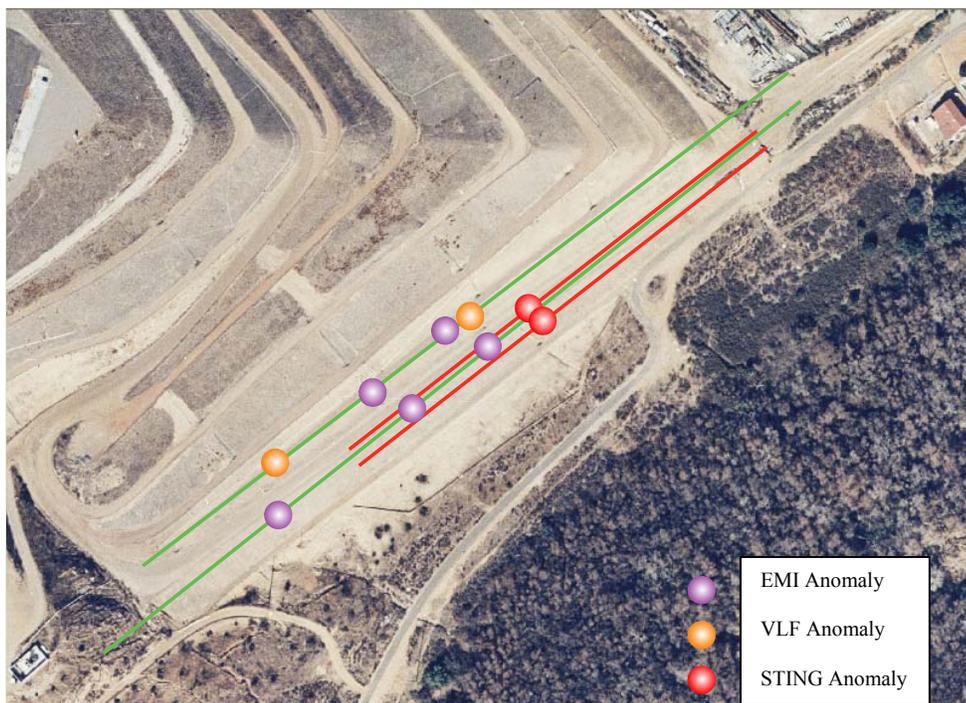


Figure 2 - EMI surveys identified anomalies oriented N85°W which correlate to high-angle joints in outcrops west of the site. VLF surveys identified several anomalies with apparent orientations of N55°E.

A STING resistivity survey was conducted to further characterize the fracture network along the toe of the landfill (Figure 3). The STING resistivity survey uses regularly spaced electrodes to measure the resistance of subsurface materials to identify areas of high and low resistivity which can be used to interpret the locations of fracture zones. For instance, a water-filled fracture or fracture zone surrounded by unfractured rock shows up as a low-resistivity or conductive anomaly. The resistivity survey was performed over a length of 900 feet and penetrated to a depth of 200 feet. The results of the resistivity survey are somewhat masked by local cultural interference effects, however, the survey indicated a significant conductive anomaly that correlates to the main fracture canyon.

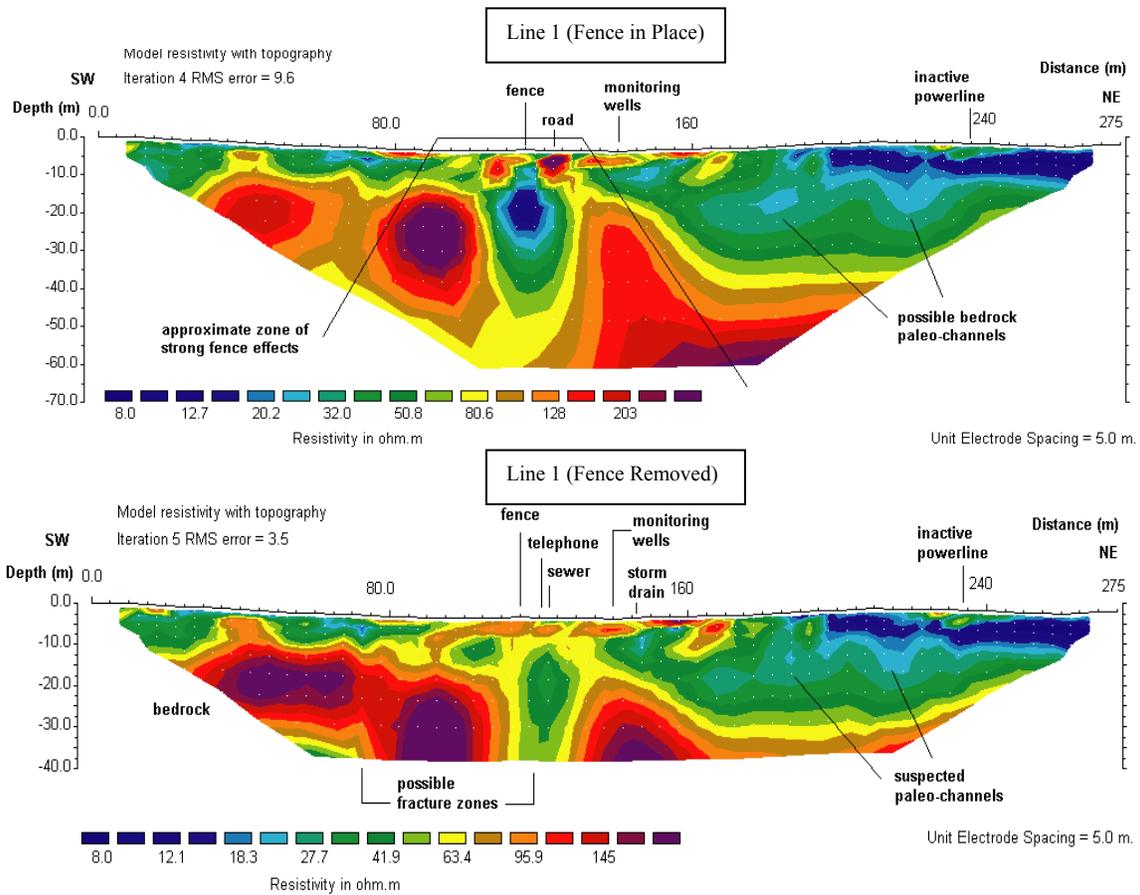


Figure 3 - The STING Resistivity survey identified a significant anomaly which appears to correlate with the main fracture set which forms the canyon containing the landfill.

## Borehole Geophysics

Downhole geophysical logging conducted in select boreholes prior to well construction included caliper, electrical logging, acoustic televiewer (ATV), and borehole image processing system (BIPS) logging (Figure 4). Additional testing performed on selected borings included thermal flow meter testing and hydrophysics. Based on data collected from the geophysical logs, the contact between the grus and competent granite appeared to be gradational, occurring from 76 to 78 feet bgs in JAGW-10A, from approximately 82 to 84 feet in JAGW-10D, and at approximately 69 feet in JAGW-10E. The boreholes appeared moderately fractured from 80 to 100 feet bgs and from 115 to 125 feet bgs. JAGW-10D is also moderately fractured from 133 to 143 feet bgs. JAGW-10E is highly fractured from 130 to 260 feet bgs and again from 270 to the bottom of the borehole. Fracture data from the geophysical logs suggested shallow, intermediate, and deep fracture zones that appeared to be hydraulically connected. When plotted on a rose diagram, the fracture orientation data collected from the three borings listed indicate three distinct fracture orientations including N75°E, N30°W, and N45°E with dips ranging from 35 to 75 degrees. The dominant strike and dip of fractures identified using BIPS logging is N30°W, with a dip of 55 degrees to the southwest.

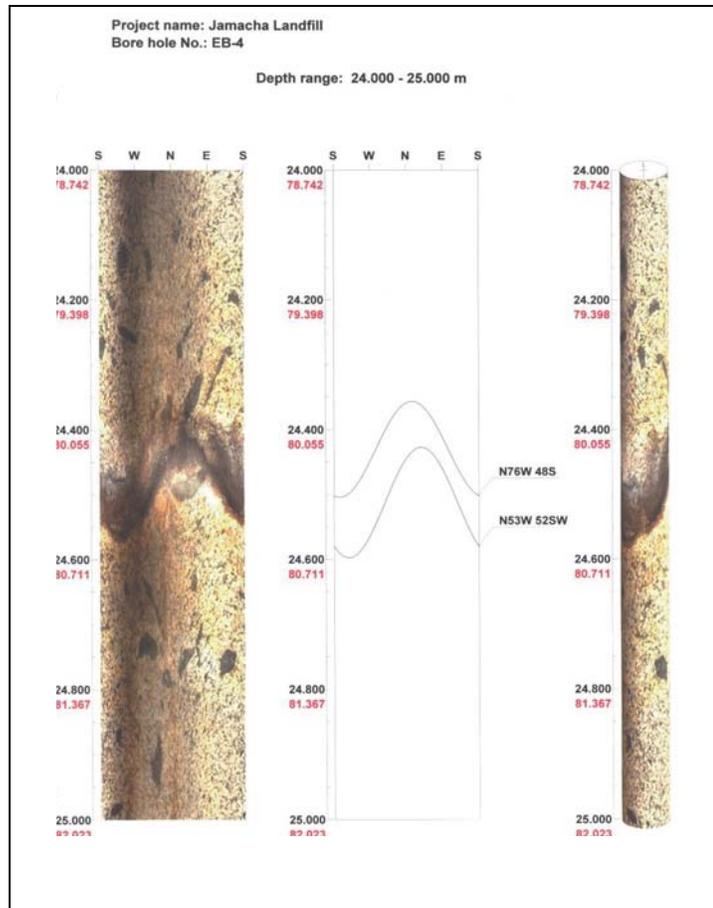


Figure 4 - BIPS logs were performed for several bedrock borings advanced in the study area to identify orientation and continuity between boreholes.

## Pilot Test Area (PTA)

The PTA is located in the downgradient direction of the landfill in an area between the landfill and the river. The PTA consists of shallow, intermediate and deep groundwater monitor wells arranged in three separate clusters located 100 feet apart (Figure 5). The upgradient (JAEB-4, JAEB-5, and JAEB-6) and intermediate (JAPW-1, JAPW-1A, and JAPW-1B) monitoring clusters consist of a shallow well screened in the alluvium, an intermediate well screened in the upper highly fractured bedrock aquifer, and a deep well screened in the lower, slightly fractured bedrock aquifer. The downgradient (JAGW-10, JAGW-10A, JAGW-10D, and JAGW-10E) monitoring cluster includes an additional deep bedrock monitor well. The JAGW-10 well cluster is located within the main fracture canyon. The well cluster was designed to be utilized as the downgradient monitoring point within the PTA. Monitor wells JAGW-10, JAGW-10A, JAGW-10D, and JAGW-10E were installed to depths of 85, 94, 150, and 300 feet bgs, respectively. Three upgradient injection wells (JAEB-4, JAEB-5, and JAEB-6) were installed in the primary fracture canyon 100 feet upgradient of the JAGW-10 well cluster. The major fracture set was identified through lineament analysis, surface geophysics, and the examination of downhole geophysics from monitor wells in the JAGW-10 cluster. The location of these borings was selected to assist in discerning the hydrogeologic properties of this potential pathway of fluid migration during aquifer tests. The depths of the wells (34, 100, and 150 feet bgs) were selected to approximate the depths of three of the wells in the JAGW-10 cluster (10, 10A, and 10D). The JAPW-1 well cluster is located 25 feet downgradient from the injection well cluster and is utilized as an intermediate monitoring point within the PTA. The depths of the wells (30, 100, and 150 feet bgs) were selected to approximate the depths of the three upgradient injection wells (JAEB well cluster).

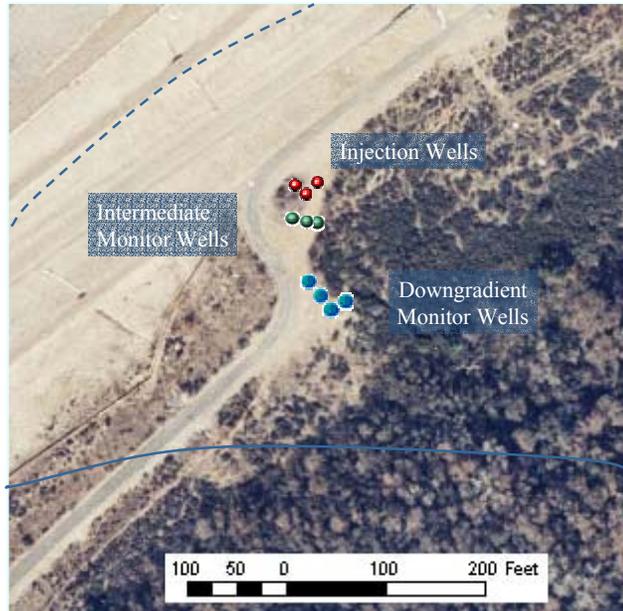


Figure 5 - The PTA is situated at the toe of the landfill, in what is believed to be the primary fracture pathway. JAEB-4, -5, -6 are upgradient injection wells, JAPW-1, -1A, -1B are intermediate monitor wells, JAGW-10, -10A, -10D, and -10E are downgradient monitor wells.

## Aquifer Tests

Aquifer tests were performed to evaluate the hydraulic connection between well clusters and different screened intervals within the PTA. A 48-hour aquifer pump test and a 72-hour recovery test were performed in the PTA to evaluate the hydraulic connection between the alluvium, grus and unweathered granitic bedrock. The data collected during these tests were analyzed using the AQTESOLV™ program. The results of these tests were used to determine the hydraulic properties of the water bearing units in the vicinity of the PTA.

Prior to beginning the aquifer test, an abbreviated step-drawdown test was performed to determine a pumping rate that could be maintained by the pumping well for the duration of the test. Monitor well JAGW-10A was pumped at a rate of 10, 20, and 30 gallons per minute (gpm) for one hour per step with one hour of recovery in between each step. Water levels were measured by hand in the pumping well and two observation wells (JAGW-10 and JAGW-10D). Evaluation of the results of the step-drawdown test suggested that a pumping rate of 30 gpm could be maintained for the duration of the 48-hour test without drawing water below the level of the pump.

A 48-hour pump test was performed to determine the hydraulic properties in the vicinity of the fractured zone within the PTA. This fracture zone corresponds to the drainage on the northern portion of the landfill. Monitor well JAGW-10A served as the pumping well for the aquifer test and was pumped at a constant rate of 30 gpm for 48 hours. Immediately following the pumping phase, recovery was monitored for 72 hours. The JAEB well cluster, located approximately 100 feet from the pumping well, JAGW-10A, were monitored during the aquifer test. The results of the pump test and recovery were recorded through the use of pressure transducers and a datalogger. Pressure transducers were placed in the pumping well and eight observation wells, six of which are located within the same fracture set within 150 feet of the pumping well.

Monitor wells JAGW-10, JAGW-10D, and JAGW-10E, located in the immediate vicinity of the pumping well (JAGW-10A) were monitored during the pump test and recovery. Each observation well is located less than 30 feet from the pumping well, and are screened at various depths. Three upgradient injection wells, located approximately 100 feet from the pumping well JAGW-10A, were also monitored during the aquifer test. The

depths and screens of the wells were constructed to be similar to JAGW-10, JAGW-10A, and JAGW-10D. The pumping and recovery data were analyzed by the Theis solution and the Cooper-Jacob approximation for unconfined aquifers using the program AQTESOLV™. Table 1 summarizes the aquifer tests analysis and the following subsections detail the results from each of the observation wells and the pumping well.

**Table 1**

	JAGW-10A	JAGW-10	JAGW-10D	JAGW-10E	JAEB-4	JAEB-5	JAEB-6
Transmissivity <sup>1</sup> (ft <sup>2</sup> /day)	202	212	273	430	-	247	360
Hydraulic conductivity <sup>1</sup> (ft/day)	20	14	27	22	-	17	36
Storativity <sup>1</sup> (dimensionless)	-	0.14	0.01	0.04	-	0.003	0.001
Transmissivity <sup>2</sup> (ft <sup>2</sup> /day)	-	187	418	547	-	338	403
Hydraulic conductivity <sup>2</sup> (ft/day)	-	13	42	27	-	27	40
Storativity <sup>2</sup> (dimensionless)	-	0.15	0.04	0.02	-	0.001	0.001

1 - Theis solution for unconfined aquifers using the program AQTESOLV™.

2 - Cooper-Jacob approximation for unconfined aquifers using the program AQTESOLV™.

- Not analyzed

### *JAGW-10A*

JAGW-10A, the pumping well, is screened between 80.5 and 90.5 feet bgs. Monitor well JAGW-10A was pumped at a constant rate of 30 gallons per minute (gpm) for 48 hours, at which time the pump was turned off. The recovery of the water levels within the pumping well in addition to the observation wells were monitored for 72 hours. At the end of 48-hours of pumping, JAGW-10A had approximately 59 feet of drawdown. The effect of pumping was evident in the observation wells located within 150 feet of the pumping well. The Theis method provided the best curve fit for the data. The semi-logarithmic plot of time versus drawdown from the pumping well showed no significant changes in slope, which indicates that no hydraulic boundaries were encountered within the radius of influence of the test. Analysis of the drawdown data from the pumping well was performed to obtain an estimated transmissivity. In order to analyze the data using the Theis method, the distance to the observation well was assumed to be the radius of the well casing. The length of the well screen was taken as the saturated thickness of the aquifer, 10 feet. The calculated transmissivity from the Theis solution for unconfined aquifers was 202 feet<sup>2</sup>/day, with a hydraulic conductivity of 20 ft/day. The recovery data were also analyzed using the Theis recovery solution. This solution yielded a transmissivity value of 317 feet<sup>2</sup>/day.

### *JAGW-10*

Monitor well JAGW-10 is completed within the alluvium/grus and is located approximately ten feet from the pumping well, JAGW-10A. The well is constructed with a total depth of 26.5 feet with a screened interval from 11.5 to 26.5 feet bgs. The saturated thickness of the aquifer is assumed to be the length of the well screen, 15 feet. Ten feet of drawdown was recorded in this monitor well during the test. The Theis solution produced a transmissivity of approximately 212 feet<sup>2</sup>/day and a storativity of 0.14. These data indicate that for a saturated thickness of 15 feet, the hydraulic conductivity of the alluvium/grus is approximately 14 feet/day. The Cooper-Jacob approximation solution yielded values for transmissivity of 187 feet<sup>2</sup>/day and a storativity of 0.15. Similarly, for a saturated thickness of 15 feet, the hydraulic conductivity of the alluvium/grus is approximately 13 feet/day. Based on the data from the aquifer test, JAGW-10 and JAGW-10A are hydraulically connected.

### *JAGW-10D*

Monitor well JAGW-10D is screened exclusively in the fractured bedrock and is approximately 14 feet from the pumping well. This well is 148 feet deep and screened between 137 to 147 feet bgs. Eight feet of drawdown was recorded during the test. The transmissivity from the Theis solution is 273 feet<sup>2</sup>/day and the storativity is 0.01. Based on these data for a saturated thickness of 10 feet, the hydraulic conductivity of the fractured bedrock at this depth and location is approximately 27 feet/day. The Cooper-Jacob approximation solution yielded values for transmissivity of 418 feet<sup>2</sup>/day and a storativity of 0.04. Similarly, for a saturated thickness of 10 feet, the hydraulic conductivity of fractured bedrock at this depth and location is approximately 42 feet/day. The results from the aquifer tests indicate that monitor wells JAGW-10A and JAGW-10D are hydraulically connected.

#### *JAGW-10E*

Monitor well JAGW-10E is screened from 275 to 295 feet bgs in fractured bedrock. During the development of this well, a pumping rate of 30 gpm was easily sustained. Four feet of drawdown was recorded in this monitor well during the pump test. The Theis solution produced a transmissivity of approximately 430 feet<sup>2</sup>/day and a storativity of 0.04. Based on these data and for a saturated thickness of 20 feet the hydraulic conductivity of the fractured bedrock at this depth and location is approximately 22 feet/day. The Cooper-Jacob approximation solution yielded values for transmissivity of approximately 547 feet<sup>2</sup>/day and a storativity of 0.02, and a hydraulic conductivity of 27 feet/day. The results from the test indicate that monitor wells JAGW-10A and JAGW-10E are hydraulically connected.

#### *JAEB-4*

Well JAEB-4 is screened from 140 to 150 feet bgs. The construction of this well is analogous to JAGW-10D. The well is approximately 100 feet from the pumping well. At the time of the aquifer test, JAEB-4 had not fully recovered from development. The decision was made to proceed with the test and monitor the well response during the aquifer test. The water level in the well continued to recover throughout the constant rate test at a steady rate. Based on the aquifer test results and the fact that JAEB-4 was still recovering from well development and continued to recover throughout the constant rate test suggest this well is not hydraulically connected to the main fracture set or the pumping well.

#### *JAEB-5*

JAEB-5 is a shallow well that is screened in the alluvium/grus similar to JAGW-10. This well is located approximately 100 feet from the pumping well and is screened from 13 to 28 feet bgs. Almost 7 feet of drawdown was recorded during the test. The saturated thickness of the aquifer was taken as the length of the well screen, 15 feet. The results from JAEB-5 were plotted and matched to the Theis curve. The transmissivity from the Theis solution is 247 feet<sup>2</sup>/day, the storativity is 0.003, and the hydraulic conductivity of the alluvium/grus at this depth and location is 17 feet/day. Using the Copper-Jacob approximation, the transmissivity calculated for this solution is approximately 338 feet<sup>2</sup>/day, the storativity is 0.001, and the hydraulic conductivity of the alluvium/grus at this depth and location is 22 feet/day. The results from the aquifer test indicate that there is a hydraulic connection between the pumping well and well JAEB-5.

#### *JAEB-6*

Well JAEB-6 was constructed similarly to the pumping well, JAGW-10A. The well is located approximately 105 feet from the pumping well and is screened from 90 to 100 feet bgs. The maximum drawdown observed in JAEB-6 was 6.5 feet. The saturated thickness of the aquifer for calculation of the hydraulic conductivity was taken as the length of the well screen, 10 feet. The results from JAEB-6 were plotted and matched to the Theis curve. The transmissivity from the Theis solution is approximately 360 feet<sup>2</sup>/day, the storativity is 0.001, and the hydraulic conductivity of the fractured bedrock at this depth and location is approximately 36 feet/day. The transmissivity from the Cooper-Jacob approximation yielded values of approximately 403 feet<sup>2</sup>/day, a storativity of 0.001, and a hydraulic conductivity of the fractured bedrock at this depth and location is approximately 40 feet/day. The results from the aquifer test indicate that there is a connection between the pumping well and this well.

The aquifer test yielded estimated horizontal hydraulic conductivity values of 25 to 40 feet/day for the fractured bedrock and from 13 to 17 feet/day for the alluvium/grus. The groundwater velocity within the alluvium/grus is approximately 180 feet/year. The groundwater velocity of the fractured bedrock within the main fracture canyon is approximately 6,600 to 16,000 feet/year. These data demonstrate that zones of the fractured bedrock within the fracture canyon can be more permeable than the overlying alluvium/grus. These data and analyses suggest that the fractured bedrock in the major fracture canyons is the predominant pathway for the migration of landfill related constituents in groundwater.

### **Tracer Study**

A fluorescent dye-tracer study was conducted under ambient conditions within the PTA to further analyze hydraulic connectivity in the PTA. A unique dye was placed into JAEB-4, JAEB-5, and JAEB-6, respectively (Figure 6). The downgradient wells were monitored with carbon dye receptors, which were exchanged every two weeks and analyzed with a spectrofluorophotometer for the presence of dyes potentially adsorbed onto the carbon packs.

Positive detections of the dye placed into the intermediate upgradient well (JAEB-6) were observed in JAPW-1A and JAPW-1B after two weeks and JAGW-10 after four weeks. Tentative detections (less than ten times background results) were recorded in JAGW-10A and JAGW-10D after two weeks, however, these concentrations were too low to be considered true positives. The dyes injected into the shallow and deep upgradient wells have not been detected in any downgradient wells. The dyes injected into the shallow and deep upgradient wells have not been detected in any downgradient wells. The dye placed into the alluvium may be migrating slowly, or dispersing too much to be detected in downgradient wells, and based on the results of the aquifer test, the deep upgradient well does not appear to be in fracture communication with the downgradient monitor wells, and the dye placed in JAEB-4 was not detected.

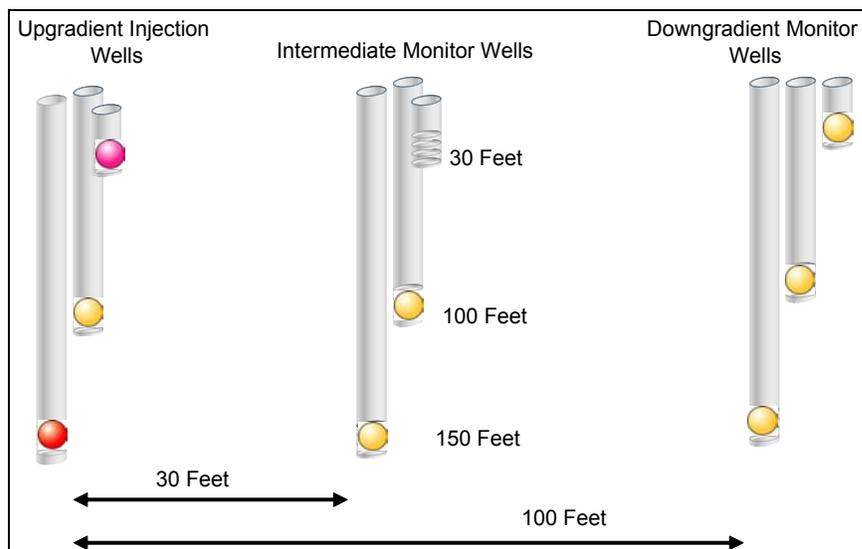


Figure 6 - Three distinct dyes were injected into the upgradient wells, one into each interval. Carbon receptors were placed into downgradient wells and were analyzed for dye every two weeks.

## Summary

The results of the hydrogeologic characterization suggest the PTA is located near the primary fracture set that forms the canyon containing the landfill. Aquifer testing results suggested hydraulic communication exists between all wells and intervals in the PTA. Tracer study confirmed that groundwater within the fractured rock aquifer was moving rapidly under passive conditions, and confirmed communication between the upgradient and downgradient wells within the PTA. The hydrogeologic characterization demonstrated that sufficient hydraulic communication is present within the PTA and that plans for a passive EISB pilot test should proceed.

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## **Biographical Sketches**

Paul Jeffers

GeoSyntec Consultants

11305 Rancho Bernardo Road, Suite 101

San Diego, CA 92127

Phone: (858) 674-6559

Fax: (858) 674-6586

E-mail: [pjeffers@geosyntec.com](mailto:pjeffers@geosyntec.com)

Mr. Jeffers is a geologist with more than five years of experience in hydrogeologic and contaminant assessment investigations, including numerous assessments of sites underlain by fractured rock. Mr. Jeffers has performed geophysical surveys and aquifer tests at several sites throughout southern California.

Veryl Wittig, R.G.,C.Hg.

GeoSyntec Consultants

11305 Rancho Bernardo Road, Suite 101

San Diego, CA 92127

Phone: (858) 674-6559

Fax: (858) 674-6586

E-mail: [vwittig@geosyntec.com](mailto:vwittig@geosyntec.com)

Mr. Wittig is a Senior Hydrogeologist with more than twelve years of planning, conducting and managing contaminant assessment hydrogeologic investigations, many of which have been conducted in fractured bedrock settings. Mr. Wittig constantly seeks to apply new and innovative technologies in the characterization of groundwater at fractured bedrock sites.