Blast-Fractured Enhanced Permeability Remediation System at Modern Landfill, York, Pennsylvania: A Five-Year Update

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Abstract

Modern Landfill in York, Pennsylvania installed the Enhanced Western Groundwater Control System (EWGCS) in 1999 to control groundwater impacted by leachate constituents between two non-contiguous landfills. The EWGCS replaced a conventional extraction well network while accommodating a landfill expansion. The EWGCS is a groundwater collection trench comprised of blast-fractured bedrock with a downgradient extraction well field. The EWGCS consists of blast-shattered bedrock 860 m long, up to 30 m deep and up to 10 m wide. Over 140,000 kg of blasting agent, loaded into blast holes having an accumulated length exceeding 40 km, were used to produce 150,000 m^3 of modified ground. Groundwater collected and conveyed by the EWGCS is removed at the downgradient end via four extraction wells for on-site volatile organic compound (VOC) treatment. Rock blasting created new fractures and widened nearby existing fractures, increasing bedrock porosity from less than 1 to 10 percent, and increasing hydraulic conductivity from 10^{-4}/ 10^{-5} to 10^{-2} cm/sec. Extensive testing conducted during the field demonstration and construction phases, coupled with site geologic and hydrogeologic models, verified the designed permeability was attained. Groundwater quality monitoring to assess the effectiveness of the remediation systems has been performed since 1987, allowing for comparison of the EWGCS with the previous extraction well system. Groundwater extraction rates, VOC concentrations and mass removal estimates over the past five years indicate EWGCS operation has increased groundwater extraction and VOC removal rates. Recent chemistry data shows the EWGCS has caused VOC concentrations to drop below detection limits in the southern end, possibly caused by enhanced diffusion of the VOC mass by regional groundwater level reduction developed by the widening of existing fracture systems during blasting. Overall, the EWGCS has achieved the design goal by meeting and surpassing the previous system's effectiveness in VOC removal.

Introduction

Site Description

Modern Landfill is located in York County, south-central Pennsylvania (Figure 1). The facility includes two non-contiguous landfills and is included in the state and county waste management plans. A portion of the eastern landfill includes a 27.7 ha (66-acre) unlined landfill, which was placed on the USEPA Superfund List in 1984. Capping and installation of a groundwater pump-and-treat system were chosen for the 66-acre landfill remedy. The groundwater system was installed in 1985 and was modified in 1992 based on remedial investigation findings (Golder, 1990).

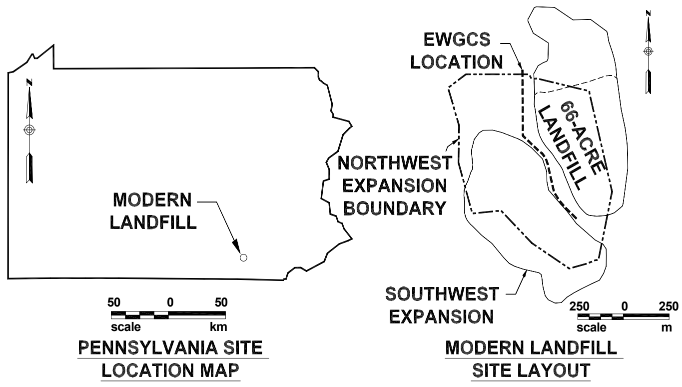

Figure 1. Site location and layout.

Project Description

A new Northwest Expansion at Modern Landfill was planned to respond to York county waste management needs. Horizontal expansion areas provided only limited airspace, and new greenfield areas would be needed to respond to long-term waste management plans. By using the area between the two non-contiguous landfills, airspace could be increased to 23 million m^3 with limited use of additional adjacent greenfield area for horizontal expansion. However, the expansion required the replacement of 16 wells of the Western Groundwater Extraction System (WGES), located between the two existing landfills, with an equivalent system. The screening of equivalent extraction systems included deep rock blasting, hydrofracking, tunneling, and horizontal drilling. The most cost effective and technically feasible alternative was the installation of a deep bedrock blast trench with a downgradient groundwater collection station (Rust Environment & Infrastructure, 1995). Detailed evaluation of this alternative indicated a bedrock blast-shattered zone 20-30 m deep, 8-9 m wide and 860 m long would act as a an effective conduit to a single groundwater collection point located north of the expansion footprint. A detailed understanding of the site's geologic and hydrogeologic setting was based on the evaluation of this alternative. Pilot field testing and extensive monitoring of a 125 m long demonstration section of the EWGCS (Golder 1997) were used to complete the final hydrogeologic design and proposed testing program for the installation of the remaining EWGCS (Golder 2000).

Construction of the remaining EWGCS section was completed between May-December 1999 following approval of the Northwest Expansion permit by the Pennsylvania Department of Environmental Protection in April 1999. The installation of the entire EWGCS required 40 km of blasthole drilling and 140,000 kg of explosives to produce 150,000 m^3 of modified ground. The blasting construction methods used are described in more thorough detail in Cameron and others, 2001. The verification of EWGCS hydrogeologic parameters required more that 500 hours of constant rate pumping tests, water level monitoring at over 50 observation points, and daily flow monitoring of construction dewatering activities.

Geology and Hydrogeology

Geologic Setting

The site is located within the Conestoga Valley Section of the Piedmont Physiographic Province. Through various site investigations, geology was interpreted based on data obtained through regional geologic mapping, trench mapping, outcrop mapping, and drilling. The site is underlain by Lower Cambrian low-grade metamorphic rocks, including (from oldest to youngest): Harpers Formation phyllite, Antietam Formation meta-sandstone, and Vintage Formation dolomite. The bedrock has been isoclinally folded into a synform structure dipping 60-80^o

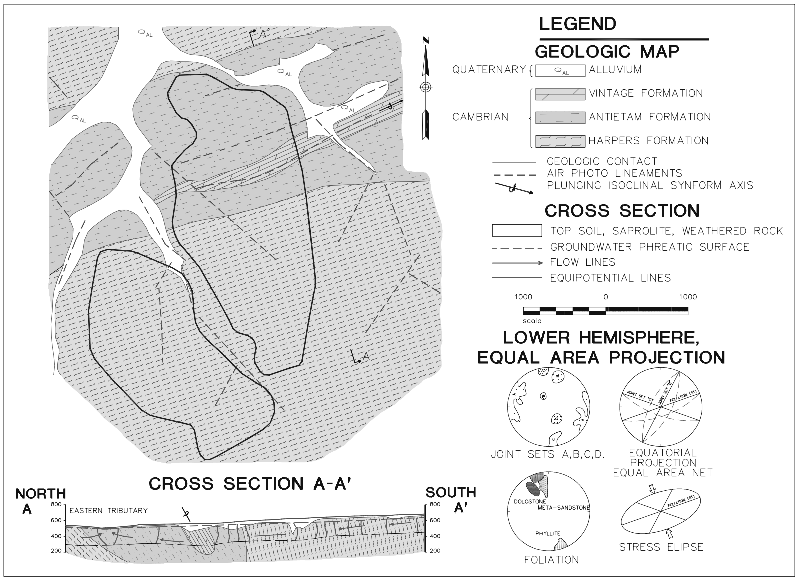

Figure 2. Modern Landfill geologic map.

to the south-southeast, with a low angle axial dip to the east-northeast and an overturned southern limb. The Vintage dolomite lies within the core of the synform. Foliation and associated small-scale isoclinal folds, cleavage and kink folds are present in outcrops and rock core. Major fracture systems are parallel, perpendicular and diagonal to foliation strike. A widespread mantle of weathered in-place clayey saprolite can attain significant thickness (up to 18 m) in areas of enhanced weathering, such as intersecting subsurface discontinuities and lithologies containing increased carbonate content.

Hydrogeologic Setting

Groundwater flows generally from south to north. A secondary porosity, derived from rock mass discontinuities, controls groundwater flow. A comprehensive three-dimensional model of subsurface hydraulic conductivity was produced from data obtained through extensive subsurface investigation, monitoring and testing. Over 250 hydrogeologic tests, including constant rate pumping tests, slug tests and drill stem packer tests have been completed for various site investigations. The most important structural features controlling groundwater flow are: main fracture systems; geologic contacts between different rock units; foliated Harpers Formation phyllite; and alternating low and high permeability zones within the dolomite. The phyllite and dolomite produce anisotropic flow patterns. Hydraulic conductivity ranges from 10^{-5} cm/sec in areas devoid of major discontinuities, to 10^{-3} cm/sec along major discontinuities. In all geologic units beneath the site, the range of hydraulic conductivity is greatest above a depth of 30 m. Below this depth, the range of the values decreases for any given depth by at least one order of magnitude.

Blasting Effects and System Operation

The rock blasting created new bedrock fractures and widened nearby existing fractures, increasing bedrock porosity from 1.5 to 10 percent, and increasing hydraulic conductivity by two orders of magnitude, from 10^{-4}-10^{-5} cm/sec to low 10^{-2} cm/sec. Surface heave of the fractured bedrock, and post-blast down-hole video surveys of nearby boreholes and wells provided evidence of the increase in porosity. To collect shallow groundwater, the clayey saprolite overlying the fractured bedrock was replaced with a sand-filled trench.

The EWGCS operates passively due to a natural horizontal hydraulic gradient and induced upward vertical hydraulic gradient. These gradients are maintained once constant groundwater removal is initiated at the downgradient end of the system. The fractured rock allows for collection and conveyance of contaminated groundwater. Figure 3 shows an equipotential cross section of the demonstration portion of the EWGCS.

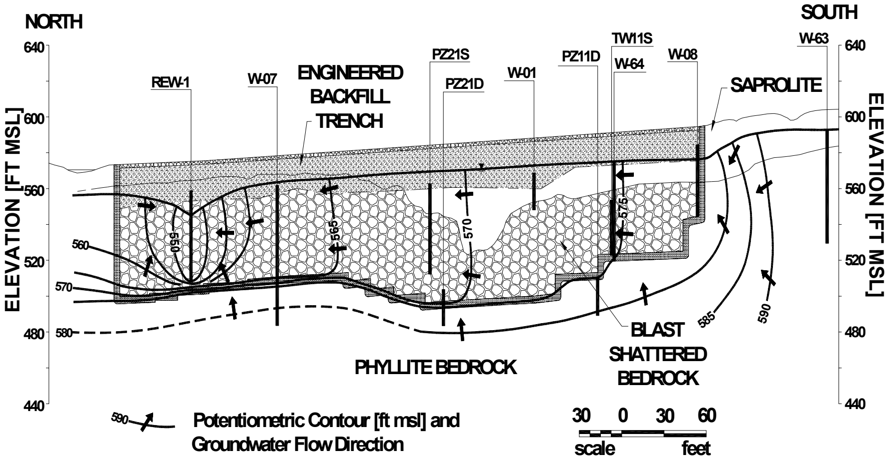

Figure 3. Equipotential cross section of the demonstration portion of the EWGCS.

Hydrogeologic Testing

Field Procedures

Constant rate pumping tests were conducted using temporary wells placed at the downgradient end of each 150 m segment. Temporary piezometers and existing monitoring wells were used as observation wells. Pumping wells and piezometers installed within the blasted bedrock were installed using continuous casing drilling methods (e.g., ODEX). Eight constant rate pumping tests ranging from 24 to 100 hours were conducted in temporary and permanent extraction wells. To reduce background construction "noise" generated by blasthole drilling and excavation, the tests were conducted when drilling and blasting operations ceased. Groundwater extracted during the pumping tests was directed to the on-site treatment plant.

Automated data logging transducers were used to measure drawdown and recovery data, and totalizing flowmeters were used to measure flow rates. Rising head slug tests using transducers were conducted after aquifer conditions had reached equilibrium. Daily groundwater levels and construction dewatering flow rates were also measured to monitor operational performance and for long-term testing. A more detailed description of the field testing procedures is presented in Smerekanicz and others, 2001.

Testing and Analysis Approach

Literature regarding detailed hydrogeologic testing in blast-shattered bedrock has been limited to drawdown and yield pumping tests (Begor and others, 1989). Recent advances in pressure measurement and computer processing allow the use of the pressure derivative method to analyze test data to determine the complex aquifer geometries, such as those associated with rock blasting. The pressure derivative method was developed for the petroleum industry (Bourdet and others, 1989; Ostrowski and Kloska, 1988). The derivative method uses curve matching techniques, as well as response as a whole, from very early time data to the last recorded point. The flow behavior of the aquifer, as well as the infinite radial flow regime, are determined using the method. As the derivative test is represented in one term of the diffusivity equation, which is the governing equation for transient-pressure behavior models of well test analysis, the derivative response is more sensitive to flow geometry differences (e.g., small phenomena of interest such as blast-induced fracturing).

To verify rock blasting was sufficient to produce the required low 10^{-2} cm/sec hydraulic conductivity, constant rate pumping tests, slug tests, and long-term vertical head tests were conducted. The derivative tests required highly accurate pressure transducer and flow control equipment. Pilot testing of the first 125 m demonstration project allowed for selection of suitable analysis methods. Due to the extreme range of aquifer heterogeneities produced by rock blasting, a unique testing and analysis approach was developed. This approach used traditional analytical methods for aquifers of infinite areal extent (i.e. Theis, Jacob and Theis recovery, Krusemann and de Ridder, 1992), slug tests of individual piezometers (i.e. Bower and Rice, 1976 and Hvorslev 1951), analytical methods allowing for bounded aquifer conditions (Interpret/2, Scientific Software Intercomp, 1994), and transient simulations (Modflow, McDonald and Harbaugh, 1988).

Traditional analysis methods assume homogenous aquifers of infinite areal extent and cannot apply entirely to EWGCS boundary conditions; however, early time data can be used to evaluate the blast-shattered zone properties. To analyze bounded, finite extent radial flow models (i.e., closed rectangle, open-ended rectangle and channel boundaries), Interpret/2 analysis was used to estimate enhanced permeability hydrogeologic parameters using detailed derivative curve matching. The use of channel boundary analytical models (i.e., two parallel no flow boundaries) produced the best fit to the field data. Numerical modeling using Modflow allowed incorporation of additional aquifer heterogeneities such as blast-shattered bedrock, overbreak, intact bedrock, saprolite and sand-filled shallow trench. The numerical simulations were developed using an iterative approach until simulated drawdown data reasonably matched observation data. A more detailed description of the testing and analysis methods is presented in Gheorghiu and others, 2001.

During the pilot testing program in 1997, groundwater chemistry of the system was monitored for a six-month period. Groundwater removed by the demonstration project, and groundwater between the demonstration project and the landfill were monitored for leachate indicator parameters consistent with the site's quarterly monitoring parameters. These parameters include VOCs, inorganics, metals and field parameters. Monitoring of these parameters has occurred quarterly during operation of the EWGCS.

Hydrogeologic Testing Results

Results consistently proved that blasting was increasing hydraulic conductivity by 1.5 to 2 orders of magnitude, from $10^{-4}/10^{-5}$ to low 10^{-2} cm/sec, regardless of lithology and extent of saprolite cover. Hydraulic conductivity test results ranged from 1.0-4.8 x 10^{-2} cm/sec, with an average of 2.0 x 10^{-2} cm/sec. Derivative analysis identified dominant aquifer behavior characteristics (Figure 4). Early time data of inner boundary effects (borehole storage and skin effects), middle time formation response (flow along blast-shattered bedrock), and late time channel boundary effects (flow from intact bedrock to blast-shattered bedrock) were observed in each of the constant rate pumping tests.

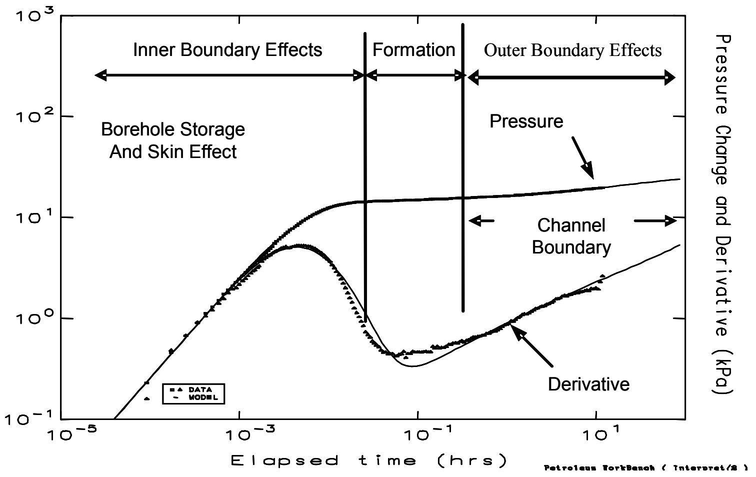

Figure 4. Dominant aquifer characteristics determined through derivative analysis of pumping test data.

A close match to test data pressure and derivative were produced using numerical modeling analysis (Figure 5). Through an iterative approach, numerical modeling allowed for characterization of the highly variable hydrogeologic conditions, i.e. the borehole storage, skin effect, sand pack, overburden, sand trench, blast-shattered bedrock, overbreak, and intact bedrock. Results indicated low 10^{-2} cm/sec conditions were being created by the blasting. The numerical model was also used to analyze long-term operation once the system was permanently started. Daily flow rate measurements of permanent extraction well ESW-4 matched the predicted starting flow rates (above 100 gpm) and the approach to steady-state conditions (50-60 gpm, Figure 6).

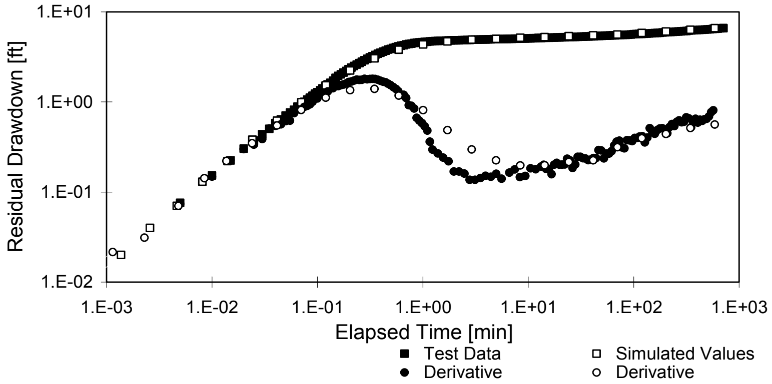

Figure 5. Numerical model simulation of pumping test data.

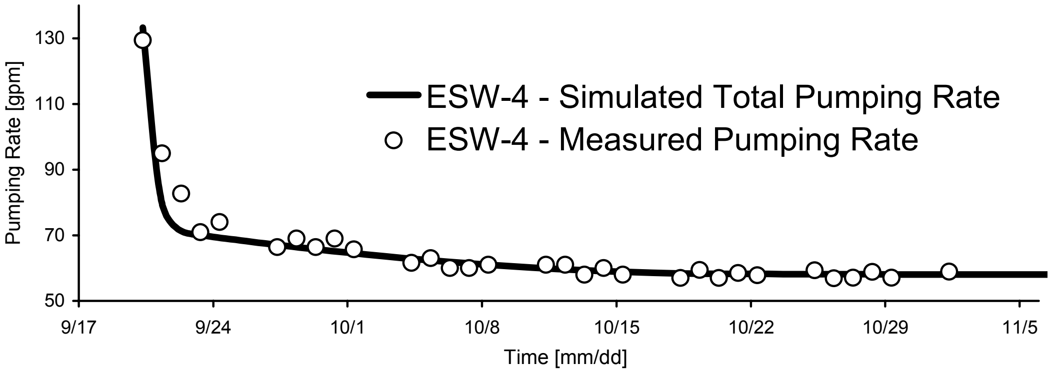

Figure 6. Numerical model simulation of long-term groundwater pumping rate.

Groundwater Chemistry Results

During the demonstration phase of the project, monitoring wells were placed between the landfill and the extraction system to monitor groundwater chemistry during the six-month demonstration phase. The shallow (15 m) and deep (30 m) monitoring wells showed a decrease in VOC concentration by as much as a factor of four (Figure 7). This indicated that the installation and operation of the EWGCS could not only be an equivalent replacement for the conventional extraction well system but could also increase the VOC removal rate.

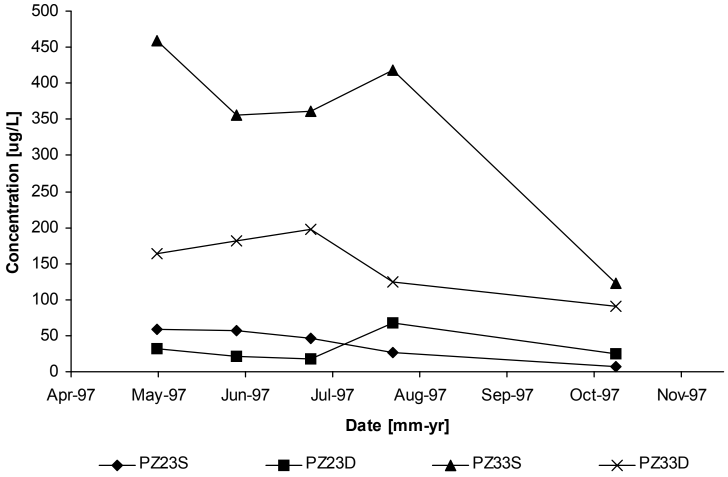

Figure 7. VOC trends in demonstration phase monitoring wells.

Five Year Assessment

Portions of the EWGCS were brought on line beginning in mid summer 1999, and the entire EWGCS length began full operation in January 2000. Mid 2004 marks the first five years of continuous operation of the EWGCS, allowing for an equivalent comparison of the EWGCS with the previous Western Groundwater Extraction System (WGES). Since 1987, Modern Landfill has completed annual groundwater assessment reports summarizing pumping rates and groundwater chemistry data to assess the effectiveness of the extraction systems. Groundwater extraction rates are monitored weekly, and groundwater chemistry is monitored quarterly/annually. A yearly summary of the total groundwater extracted, average VOC concentration and estimated VOC mass removed for both the WGES and the EWGCS is provided in Table 1, and these data are presented graphically in Figure 8.

Table 1 - Annual Extraction System Summary

Year	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**
System	← Western Groundwater Extraction System →								
Flow [m gal]	28.4	24.3	23.5	22.8	19.1	38.1	41.1	38.6	35.9
VOC Concentration [ug/L]	295.5	232.8	110.0	93.4	204.2	118.8	96.5	93.8	97.1
VOCs Removed [kg]	31.7	21.4	9.8	8.1	14.7	17.1	15.0	16.0	15.4
Precipitation [in]	--	--	--	--	28.7	43.4	54.1	51.4	39.9

Year	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**Average**
System	←Western Groundwater Extraction System→				← EWGCS →				
Flow [m gal]	37.2	34.5	38.8	34.1	47.8	47.9	40.4	50.4	**35.5**
VOC Concentration [ug/L]	82.3	90.9	92	97	75	83.6	113.8	79.6	**113.1**
VOCs Removed [kg]	14.6	13.5	16.1	13.0	11.9	12.4	14.1	14.7	**14.2**
Precipitation [in]	53.8	35.6	44.7	45.7	44.5	33.3	40.0	56.4	**44.5**

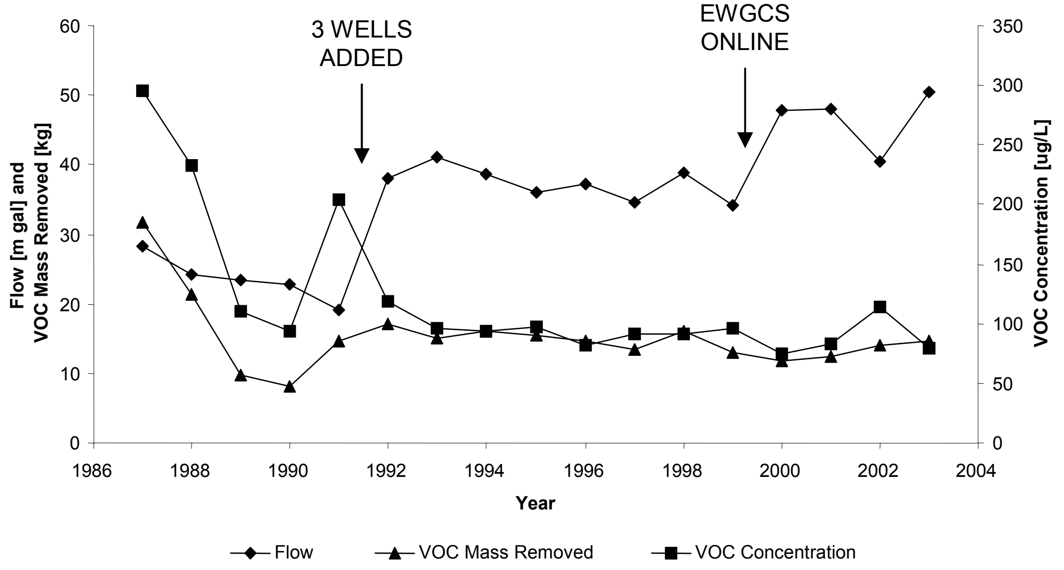

Figure 8. Flow, VOC concentration and VOC mass removal trends.

In 1991, three extraction wells were added to the WGES, and the flow rate and extracted VOC mass trends increase after this time. In 1999-2000, the entire western groundwater extraction well network was replaced by the EWGCS. After 2000, an increase in the flow rate occurred, indicating the capacity of the EWGCS is greater than the previous system. The average VOC concentration in the extracted groundwater is declining, and the estimated VOC mass removed is increasing, from 11.9 kg in 2000 to 14.7 kg in 2003.

Table 2 contains a comparison of the average flow, VOC concentration, VOC removal and precipitation of the two time periods the systems have been active (i.e., 1992 - 1999 for the WGES, and 2000 - 2003 for the EWGCS). The data indicate flow has increased by 25.1 percent, while the VOC concentration and VOC mass removed have decreased by 18.7 and 12.0 percent, respectively. The data also indicate the increase in flow cannot be attributed to changes in precipitation levels, as the precipitation was slightly less during the EWGCS operational period.

Table 2 - Comparison of WGES and EWGCS Performance

	Flow [m gal]	VOC Concentration [ug/L]	VOCs Removed [kg]	Precipitation [in]
1992-1999 Average (WGES)	37.3	107.9	15.0	46.05
2000-2003 Average (EWGCS)	46.6	87.7	13.2	43.56
Change	+9.4	-20.2	-1.8	-2.49
Percent Change	+25.1%	-18.7%	-12.0%	-5.40%

Conclusions

Monitoring the EWGCS for the past five years indicates that while the groundwater extraction rate has increased, and the VOC concentrations have decreased, the estimated VOC removal rate has increased by 4.8 kg. The decline in VOC concentration is attributed to the continued operation of the remedial systems and is consistent with long-term trends. However the increased pumping rate (by about 25 percent) has increased the VOC removal rate for the past five years. The monitoring indicates the EWGCS is not only equivalent to the previous conventional extraction well system (WGES), but is removing VOC mass at a faster rate.

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Biographical Sketches

Mr. Smerekanicz is a Senior Project Geologist and Associate at Golder Associates, and manages geotechnical and environmental projects, including rock blasting for excavations, road cuts, and remediation systems. He was the on-site resident geologist for design and implementation the large bedrock remedial system at Modern Landfill that received the Year 2000 Outstanding Groundwater Remediation Project Award from NGWA (subject of this paper). Golder Associates Inc., 540 North Commercial Street, Suite 250, Manchester, New Hampshire, 03101-1148 Tel.: 603/668-0880 Fax: 603/668-1199 e-mail: jay_smerekanicz@golder.com

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