# SITE CHARACTERIZATION REPORT – HYDROLOGIC CHARACTERIZATION

## HYDE PARK LANDFILL SITE
## TOWN OF NIAGARA, NEW YORK

**Prepared For:**

**Miller Springs Remediation Management, Inc.**
**Glenn Springs Holdings, Inc.**

**Prepared by:**

**Services Environmental, Inc.**
**S. S. Papadopulos & Associates, Inc.**
**Conestoga-Rovers & Associates**

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**FEBRUARY 28, 2003**

TABLE OF CONTENTS

TABLE OF CONTENTS

Page

## LIST OF FIGURES

## LIST OF FIGURES



## LIST OF TABLES



## LIST OF PLATES



## LIST OF APPENDICES

## 1.0 INTRODUCTION

This report has been prepared for Miller Springs Remediation Management, Inc. (MSRM) to support a hydrogeologic recharacterization of the Hyde Park Landfill Site (the Site). The Site is located in the Town of Niagara, New York. Figure 1-1 presents a Site location map.

In February 2002, MSRM submitted a report, *Site Characterization Report: Revised Geologic and Hydrogeologic Characterization* (SCR-G), to the U.S. EPA and the New York State Department of Environmental Conservation (the Agencies). That report described an extensive field and office investigation of the Site completed in 2001. The SCR-G presented a new hydrogeologic framework for the bedrock aquifer. The previous hydrogeologic characterization defined three flow intervals in the bedrock: the Upper, Middle, and Lower Bedrock. The new framework has eleven discrete bedding-parallel flow zones separated by aquitards. This framework is consistent with published regional studies by Johnston (1964), Kappel and Tepper (1992), and Yager (1996).

Defining a framework was an important step in the Site recharacterization. However, at the time the SCR-G was completed, there were neither water-level nor water quality data to support an interpretation of groundwater flow within the framework. The SCR-G proposed additional investigations to complete the Site characterization. These activities were initiated in 2002 and completed in early February 2003. This report, *Site Characterization Report: Hydrologic Characterization* (SCR-H) summarizes the investigations and findings of the investigations regarding groundwater flow.

The scope of the SCR-H was defined in the *Workplan for the Site Characterization Report - Hydrologic Characterization: Hyde Park Landfill* dated April 5, 2002; and the *Supplement to the Workplan* date May 31, 2002. Together, these documents are considered to be the Workplan for the study described here.

A total of 113 piezometers were installed for the SCR-H investigation. The objectives and location selection criteria for the piezometers were described in the SCR-G. Each of the piezometers was developed and tested to determine the transmissivity. From mid-December 2002 through January 2003, groundwater levels were monitored in the piezometers with electronic data recorders, which recorded water levels at 10-minute intervals. To assess hydraulic interconnections within and between flow zones, the Bedrock NAPL Plume Containment System purge wells were shut down for 17 days in January 2003.

The data collected for this study have resulted in an understanding of groundwater flow in the discrete flow zones. These data will be used to develop a new numerical model of the Site and to develop recommendations for monitoring the performance of the Bedrock NAPL Plume Containment System. The monitoring recommendations and groundwater modeling are currently in the planning stage. It is anticipated that the model will be provided to the Agencies at the end of April 2003 and a monitoring plan will be submitted about one month later.

The hydraulic testing and water-level data collected for the SCR-H are presented and described here. This is an extensive data set. The hydraulic analyses include approximately 1,000 pages of graphs and calculations. Due to the size of the database and the extensive graphical interpretations, the data and detailed analyses are provided in an Adobe Acrobat format on a compact disk (CD-ROM) enclosed with this report. The water-level monitoring includes nearly

1,000,000 water-level measurements. These data are summarized in the report using potentiometric surface maps, presented in their entirety as hydrographs, and are also provided in a Microsoft Access Database on the enclosed CD-ROM. Discussions of significant observations made during the testing are presented in the report.

The results of the SCR-H hydraulic testing and monitoring support the framework defined in the SCR-G. The SCR-G idealized the flow zones and aquitards as regionally extensive layers with uniform hydraulic properties. The results of the SCR-H investigation identify spatial variations in transmissivity within the flow zones. Some observations made during the December 2002 to January 2003 monitoring cannot be explained with our current level of understanding and require additional examination before definitive conclusions can be presented. Thus, this report may be amended as new data are collected and interpretations are refined.

The hydrologic conditions at the Site are complicated by the existence of numerous monitoring wells that are open across more than one flow zone. These wells act as conduits for the transfer of groundwater and potentiometric head. One particular well, bedrock purge well PW-1L, was identified as a problem following the shutdown of the bedrock purge wells. A packer was installed to eliminate this particular interconnection between flow zones. However, there are still many long open-interval wells at the Site that interconnect flow zones. Some, if not all, of these wells should be closed to ensure that the recharacterization of the Site hydrogeology is completed properly, and that an effective performance monitoring program can be designed and implemented.

In addition to closing long open-interval wells, MSRM proposes to sample a subset of the piezometers for water quality to better understand the three-dimensional groundwater flow. A discussion of the wells to be sampled and the decision criteria for selecting these wells will be submitted to the Agencies for review following the submission of this report.

The investigations described here have been completed by MSRM and a team of consultants:

- Services Environmental, Inc (SEI) - Formerly Sayko Environmental Data Analysis (SEDA);
- S. S. Papadopulos & Associated, Inc. (SSPA); and
- Conestoga Rovers & Associates, Inc. (CRA).

MSRM, Glenn Springs Holdings, Inc. (GSHI) and these consultants represent the "technical team". This report is the work product of the technical team.

## 2.0 SCOPE OF WORK

The purpose of the SCR-H study and report was to characterize groundwater flow conditions within the hydrogeologic framework of eleven discrete flow zones defined in the SCR-G. The framework is a simple geometry that synthesized historical Site geologic and hydrogeologic data, the findings of an extensive geophysical investigation completed in 2001, and published regional geologic and hydrogeologic investigations. Although the framework definition was completed in the SCR-G, no reliable hydrologic data (groundwater levels and hydraulic properties) were available to characterize groundwater flow conditions in the individual flow zones.

In 2002, a total of 113 piezometers were installed to monitor discrete flow zones. An extensive hydraulic testing program and water-level study were completed to evaluate groundwater flow and to refine the SCR-G conceptual hydrogeologic framework, as necessary. The following section presents details of the field and desktop efforts completed for the SCR-H.

## 2.1 INSTALLATION OF PIEZOMETERS

### 2.1.1 Selection of Locations

The SCR-H investigation studied the Site on a scale that would allow a general understanding of the flow system over a large area, approximately 1 square mile. Twenty widespread locations were selected to install clusters of multi-level monitoring piezometers. The locations of these piezometer clusters are shown in Figure 2-1. The term "location" as used here refers to a single cluster of piezometers. For example, at the B2 location, there were three existing bedrock wells (B2U, B2M, and B2L) that were retrofit with four piezometers (B2U-06, B2M-07, B2M-09, and B2L-11); this is one location. The nomenclature B2U-06 indicates a piezometer completed in flow zone six (FZ-06) that was constructed in an existing well B2U. A total of 113 piezometers were installed for the SCR-H.

Of the twenty locations, fourteen were existing monitoring wells that could be retrofit with multilevel piezometers. Six locations required drilling new boreholes. To the extent practicable, locations with non-aqueous phase liquids (NAPL) were avoided due to the potential for NAPL to block the piezometer screens.

### 2.1.2 Design of the Piezometers

The piezometer design was based on experience, investigation of practices at other sites, and practical constraints of construction. Key considerations in the design analysis were that:

- Each piezometer must be hydraulically tested;
- Each piezometer could be sampled, if necessary, for water quality parameters;
- The water levels from the piezometers must be measurable with a high level of confidence;
- Each piezometer would be instrumented with an electronic water-level recorder;

- Each piezometer must have as small a diameter as possible to eliminate wellbore storage effects that slow the response of the piezometer to changes in the flow-zone water level; and
- The piezometers should be completed as "stickups" to eliminate the potential for surface water infiltration and to facilitate access to the piezometers in snow conditions.

Numerous multilevel monitoring devices were reviewed. Based on this review, it was determined that the most effective installation to address these design considerations was a simple, small-diameter, screened piezometer. Commercial multilevel systems allow for electronic water-level monitoring; however, their monitoring instrumentation is usually specialized for the specific system and expensive compared to widely used instruments from Telog and In-situ. To accommodate standard monitoring instruments, the well diameter had to be at least 0.75 inches. The well diameter was also an important consideration regarding hand water-level measurements. As the diameter of the piezometer decreases it becomes more difficult to lower a depth-to–water (DTW) tape down the piezometer. Solinst Canada Limited has a proven Continuous Multichannel Tubing (CMT) Multilevel monitoring system; however, based on their experience, a DTW tape can be lowered no more than 65 feet before the tape sticks on the sides of the piezometer. Under pumping conditions, over 20% of the piezometers at Hyde Park have a depth to water greater than 65 feet.

The piezometer design selected and installed at Hyde Park was a 1-inch inside diameter (ID) diameter screen and casing. Each screen is 2 feet long. The screen was placed in the center of the flow zone. Except for FZ-11, a sand filter pack was placed from one foot below to one foot above the screen. In FZ-11 the filter pack was typically installed from the bottom of the well/boring, to 7 feet above the top of FZ-11. The 7-foot distance is approximately halfway between FZ-11 and FZ-10. Below FZ-11 is the Rochester Shale; no flow zones were identified in this formation. The intervals between the screen-sand intervals were filled with bentonite pellets. Near the Landfill, stainless steel screen and casing were installed. Away from the Landfill, PVC screen and casing were installed.

### 2.1.3 Selection of Piezometer Monitoring Intervals

#### 2.1.3.1 Flow Zones Monitored

Based on practical considerations of piezometer design and constructability, it was not possible to monitor every flow zone. As a result, flow zones FZ-03, FZ-08, and FZ-10 were eliminated from the monitoring program. Justification for this decision was provided in the SCR-G report. The data collected during the SCR-H supports the basis presented in the SCR-G for eliminating these flow zones.

#### 2.1.3.2 Picking Flow-Zone Monitoring Intervals

The groundwater flow zones were identified in the SCR-G by analyzing geophysical logs of 134 wells at the Site. As described in the SCR-G, parallel planes were fit to the geophysical data using least-squares analysis. The results demonstrated that, within measurement precision, the planes were a perfect fit to the data. Thus, a parallel plane idealization of the flow zones was defined and continues to be used for Site-wide approximation of the flow-zone elevations.

Utilizing the mathematical equations for each flow zone, the elevations of the flow zones can typically be predicted to approximately ±3 feet across the Site.

To ensure that the piezometers were installed at the proper depths, each of the wells to be retrofit and the six new boreholes were video logged. The videos were inspected to identify fracture intervals at elevations near the mathematically predicted flow zones. This exercise was useful for identifying approximately half of the flow zones; the water in the wells was frequently cloudy or disturbed by cascading water, making visual identification of fractures impossible for the other flow zones.

Due to the difficulties encountered using video logs to identify flow zones, and the success of packer testing that had been performed at existing wells (described in Appendix A), the new boreholes E6, F6, H5, and I1 were packer tested to aid in flow-zone identification. At these locations, the flow zones were assumed to be the high transmissivity intervals at or near a predicted flow-zone elevation.

A summary of the intervals monitored by the new piezometers is presented on Table 2-1. As-built piezometer details are included on the CD-ROM that accompanies this report. Maps showing the locations of the piezometers in each flow zone monitored are presented in Figures 2-2 through 2-9.

#### 2.1.4 Piezometer Construction

Two types of piezometer constructions were installed in the SCR-H investigation: retrofits of existing wells and installations in new borings. Fourteen existing well clusters were retrofit with piezometers. The existing wells were 3.9-inch diameter cored holes. A maximum of three 1-inch ID piezometers could be practically installed in the existing wells. Six new boreholes were installed for six piezometer clusters. The new boreholes were 6-inch diameter holes and could accommodate up to eight 1-inch ID piezometers. For the new boreholes, a 12-inch diameter hole was drilled 2 feet into bedrock and a 6-inch steel casing was installed and grouted in place. The grout was allowed to set over a 24-hour period, after which the borehole was completed.

The following steps describe the field procedures followed during the construction of the piezometers.

1. Sound the depth of the well/boring to be used for the piezometer installation(s) and compare to the recorded drilled depth of the well/boring. If there is a large (>5 feet) discrepancy between the original installed depth and the sounded depth, or if the sounded depth is higher than the deepest "flow zone" to be monitored, re-drill the bottom portion of the well/boring.

2. Develop/re-develop borehole to as silt-free a condition as possible.

3. If necessary, install bentonite to the level of the bottom of the sand pack of the deepest monitoring interval. Bentonite chips or gelatin-coated bentonite tablets can be used. The bentonite should be tamped during installation using a weighted measuring tape.

4. Install the screen and riser for the deepest monitoring interval. Hold the piezometer in place with a clamp. Fine-tune the depth of the screen by measuring the total depth of the piezometer. All installation measurements are referenced to the top of the well casing.

5. Slowly install the sandpack to the predetermined depth (generally 1-foot above the screen). The sandpack should be installed through a tremie pipe and enough time should be allowed for the sand to settle before continuing. The sandpack should be measured and tamped continuously during installation using a weighted tape measure.

6. Install a bentonite seal to the bottom of the sand pack of the next monitoring interval. The bentonite should be installed through a tremie pipe. For intervals less than 5-feet in length use gelatin-coated bentonite tablets. For intervals greater than 5-feet in length bentonite chips can be used.

7. Repeat steps 4 through 6 until the last piezometer is installed.

8. Complete the installation by installing a minimum of five feet of bentonite above the uppermost sand pack. The bentonite should be installed into the overburden or bedrock casing where possible.

9. Trim the riser pipes from the piezometers such that the deepest installation has the shortest stick-up and the shallowest installation has the tallest stick-up. The lowest stick-up should be at least one foot above grade, and the highest no more that 2 feet above grade.

10. Develop each of the new piezometers by pumping.

Each piezometer cluster was completed as a stickup finish. A 2.5' x 2.5' square concrete pad was poured around each cluster and a locking 2' x 2' x 2' stainless steel box was installed to protect the piezometers. This installation has been very effective, allowing the installation and securing of multiple data loggers, preventing infiltration of water, and allowing the clusters to be located in the snow. There has been no vandalism of the protective boxes to date.

### 2.1.5 Survey

Upon completion of the new piezometers, a survey was completed of the new piezometers and existing monitoring wells to ensure that all elevations and horizontal coordinates were accurate. Horizontal coordinates were referenced to the 1983 North American Datum (NAD 83) and elevations were referenced to the 1929 National Geodetic Vertical Datum (NGVD29).

Due to the new survey results, relatively minor changes in horizontal coordinates were made for several wells. The coordinates of many of the existing wells were originally determined by transforming the original survey in the Site coordinate system to the NAD 83 coordinate system. In general, the previous vertical elevations were accurate. Minor changes were made to the elevations of some monitoring wells to conform to the new survey.

## 2.2 HYDRAULIC TESTING

The following hydraulic testing activities were undertaken as part of the SCR-H study:

- Slug testing of all existing Lower Bedrock wells;
- Packer testing of selected existing well clusters and new multiple-completion wells;
- Slug testing of all new flow-zone piezometers;
- Slug testing in packed-off intervals of PW-2M; and
- Slug testing following the installation of a packer in PW-1L.

A detailed description of all hydraulic testing is provided in Appendix A. The enclosed CD-ROM includes graphs of the analyses of the hydraulic tests.

## 2.3 MONITORING PROGRAM

Upon completion of the 113 piezometers, an electronic water-level recorder was installed in each well. Continuous monitoring of water levels began on December 16, 2002 after all of the transducers were field-calibrated and their proper operation verified.

### 2.3.1 Water-Level Monitoring/Shutdown Test

The hydrogeologic framework defined in the SCR-G was a major change in the Site conceptual model. The water-level data from the monitoring wells that intersected multiple flow zones were of questionable value for the analysis of groundwater flow conditions. Thus, the data collected from the new piezometers and presented here effectively represent the entire hydrologic database for the Site.

The Workplan defined an 8-week period of water-level monitoring including the shutdown and restart of the Bedrock NAPL Plume Containment System. The overburden collection systems appear to have little short-term influence on the bedrock water levels and remained operational during the monitoring period. Electronic water-level recorders (from Telog Instruments) were installed in every piezometer and programmed to collect an instantaneous water-level reading every 10 minutes. Existing instrumentation in the bedrock purge wells was used to monitor water levels and pumping rates. Manual water-level measurements were taken in all of the piezometers and the accessible purge wells on a weekly basis.

The following tests were completed in December 2002 and January 2003:

- Water-level monitoring under pumping conditions: December 16 to January 7;
- Water-level monitoring under shutdown conditions: January 7 to January 24;
- Isolating and pumping FZ-09 in PW-2M at 10 gpm for 8 hours on January 10;
- Pumping PW-2M at 30 gpm for 24 hours between January 11 and 12;
- Isolating FZ-09 from FZ-10 and FZ-11 at PW-1L on January 21 (the packer will remain in place until recommendations for pumping at PW-1L are developed); and

- Water-level monitoring during the restart of the bedrock purge wells beginning on January 24 and ending on February 10, 2003.

#### 2.3.2 May/June 2001 Shutdown

In May and June 2001, the bedrock purge wells were shut down to allow for an upgrade to the water treatment system. An extensive data collection effort was implemented during that shutdown. The shutdown data were thoroughly reviewed by the technical team in 2001, but no report was issued. These data were being reviewed at the same time that the new hydrogeologic framework of eleven flow zones was being developed. It was recognized that the data from the long open-interval monitoring wells were of no use for assessing the groundwater flow in the context of the eleven discrete flow zones. As a result, the decision was made not to submit a separate report on the May/June 2001 shutdown test. The entire data set was submitted to the Agencies in 2001 in a Microsoft Access database format.

The data collected in the May/June 2001 shutdown test were useful in planning and assessing the results of the SCR-H monitoring. Therefore, hydrographs of the data collected in the May/June 2001 have been provided here in Appendix B. The hydrographs for the May/June 2001 shutdown were prepared using the same elevation and time axes scaling as hydrographs for the current shutdown. This allows a direct overlay (comparison) of the hydrographs from these two different tests.

### 2.4 OVERBURDEN SEDIMENTS, TOP OF BEDROCK AND FLOW-ZONE SUBCROPS

#### 2.4.1 Overburden Sediments

The overburden is typically a glacial basal till on top of the bedrock, overlain by glaciolacustrine silts and clays. The hydraulic conductivity of these sediments was a significant question with respect to the hydrogeologic model. The overburden could act as an aquifer, or an aquitard, depending on the hydraulic conductivity. Previous testing has shown that the glaciolacustrine silts and clays have relatively low hydraulic conductivity. However, descriptions of the till in well logs suggested that the material was sand and gravel with potentially high hydraulic conductivity. To determine the hydraulic properties of the overburden, 24 samples were collected at four locations for grain-size analyses. Eight of these samples were also sent for permeameter testing.

#### 2.4.2 Top of Bedrock

Top-of-bedrock surface contours were presented in the SCR-G. Additional drilling in 2002, evaluation of historical data, and additional data derived from historical maps of sewers, tunnels, and an abandoned railroad cut were used to revise the top-of-bedrock surface contours.

### 2.4.3 Flow-Zone Subcrops

Flow-zone subcrops are defined by the intersection of the top-of-bedrock surface map and the flow-zone planes. A map of the subcrops was presented in the SCR-G. Because the top-of-bedrock surface was refined for the SCR-H, the flow-zone subcrops were accordingly revised.

## 2.5 TUNNELS, SEWERS AND THE RAILROAD

Tunnels and sewers are cut into the bedrock near the Site for storm and wastewater control. These cultural features often have a significant influence on groundwater flow. However, until groundwater-level data were available for discrete flow zones, the influence could not be identified and a detailed assessment of the tunnels and sewer system had not pursued before the SCR-H.

As part of the SCR-H, historical maps were located and reviewed to determine the locations and elevation of these features. During this review, an abandoned railroad cut into the bedrock was also identified. These features can influence groundwater flow. Utilizing the new hydrogeologic framework, the piezometer water-level data, and the locations of the tunnels, sewers, and the railroad cut, an understanding of the influence of these features on groundwater flow has been gained.

## 3.0 RESULTS

## 3.1 HYDROSTRATIGRAPHY

### 3.1.1 Overburden

The overburden sediments in contact with the bedrock are generally described as till or lacustrine silts and clays. Both the till and the silts and clays have a relatively low hydraulic conductivity. The grain-size analyses provided in Appendix A show a high silt and clay content (50% to 98% by weight). These fine sediments fill the pore space between the sand and gravel that may be present, and reduce the hydraulic conductivity by several orders of magnitude compared to clean sand and gravel. The results of the grain-size analyses are consistent with the low hydraulic conductivities determined from the permeameter and slug tests. The hydraulic properties of the overburden are discussed in more detail in Section 3.2.1.

There are widespread areas of surficial fill related to community and industrial development. Fill materials, including reworked native sediments, construction debris, and non-native fill are encountered across much of the Town of Niagara. In most cases, the fill described in well logs appears to be a veneer of redistributed native materials and most likely has low hydraulic conductivity. Where cuts have been made to install sewers and railroads, a gravel bedding is typically lain in the bottom of the cuts. This bedding can create a network of highly transmissive conduits. These drains have an impact on bedrock groundwater flow where the sewers and railroad cut to and into the bedrock. The locations of the sewers and tunnels are discussed in Section 3.1.4.

### 3.1.2 Bedrock

The bedrock underlying the Site is the Lockport Group. The Lockport Group consists of relatively uniform layers of limestone, dolostone, and thin shale beds. The flow zones identified in the SCR-G are within the Lockport Group, and the very top of the Clinton Group, which underlies the Lockport Group. The uppermost formation in the Clinton Group is the DeCew Formation. The DeCew is also considered to be part of the active groundwater system beneath the Site. Below the Decew is the Rochester Shale. The Rochester Shale represents a regional aquiclude and defines the bottom to the active flow system at the Site. A detailed discussion of the bedrock stratigraphy in the Niagara Falls area is presented in the SCR-G and Brett et al. (1995).

Based on the analysis of bedding at the Site (presented in the SCR-G), bedding in the Lockport Group strikes N 69°E, and dips approximately 39 feet per mile (0.74%) to the south. In the vicinity of the Site, the strike and dip are very uniform. A cross-section along dip is presented in Figure 3-1. The geology, as interpreted from bedrock cores collected during Site investigations, is presented.

The top-of-bedrock surface contour map was updated for this report. The current interpretation of the top of bedrock on a regional- and local-scale is presented in Figures 3-2 and 3-3, respectively. Figure 3-4 presents the flow zone subcrops, the intersection of the new bedrock surface and the predicted flow zone planes.

### 3.1.3 Flow Zones and Subcrops

The flow zones were defined in the SCR-G. The analyses presented in the SCR-G showed that the flow zones could, within the precision of our measurements, be represented as a set of parallel planes. Figure 3-1 includes the predicted flow-zone planes on the geologic cross section.

The flow-zone subcrops have been estimated by intersecting the top-of-bedrock surface with the flow-zone planes defined in the SCR-G. The locations of the flow-zone subcrops and the wells and piezometers intersecting each flow zone are shown in Figures 2-2 through 2-9.

### 3.1.4 Tunnels, Sewers, and the Abandoned Railroad Line

The locations of the tunnels and sewers were identified and mapped as part of the SCR-H investigations. The locations of these features, as well as reported elevations of inverts (the bottom of the tunnel or sewer) and pipe diameters are presented on Plate 1. On the Plate, the lines showing the sewer and tunnel locations are dashed where the tunnel or sewer intersects the bedrock and solid where they are in the overburden. The source of this information dates back to the 1800's and the accuracy of the elevations has not been confirmed. However, the elevations are generally consistent with data from recent field studies and are considered reliable.

Vertical shafts connect the sewers and tunnels. These shafts are at least 70 years old and do not appear to be lined to prevent the infiltration of groundwater. Where the shafts intersect a flow zone, they may act as local drains and cause a decline in the flow-zone water level. Flow zones FZ-06 and FZ-07 appear to be influenced by the vertical shafts.

All of the tunnels and sewers shown on Plate 1 discharge to the tunnel running parallel to the Gorge. This tunnel drains southward and discharges to the Niagara Falls publicly-owned treatment works (POTW). The water is treated prior to discharge to the Niagara River. During periods of high runoff, the tunnel is designed to overflow directly to the Niagara River via the Garfield Street tunnel.

In addition to the tunnels and sewers, an abandoned NYC Railroad line was identified between the Landfill and the Gorge. The approximate location of the railroad is shown on Plate 1. The railroad was constructed in the 1800s and was cut into the bedrock from approximately Garrett Avenue and north. It appears that wells ABP-8 and APW-2 intercept the railroad cut. The railroad appears to head to a cut in the bedrock located at the north end of Hyde Park Boulevard, and may have gone down into the Gorge from this location. Further assessment of the railroad cut will be preformed. The fill material described in the boring logs for ABP-8 and APW-2 appears to be the native silts and clays with some wood and cinders mixed in. The fill reported in well logs does not appear to be highly transmissive.

It is likely that the sewers and the railroad were laid in a gravel bedding. The gravel likely acts as a drain and depresses water levels. Based on inspection of the potentiometric contours presented in Sections 3.4 and 3.5, the sewers are clearly influencing potentiometric levels in flow zones FZ-01 to FZ-05. Flow zone FZ-06 and lower are not intercepted by the sewers but may be influenced by vertical shafts connecting the sewers with the tunnels. Flow zone FZ-06 is intercepted by the abandoned NYC Railroad line. The bedding in the railroad cut may be intercepting some groundwater from FZ-06.

## 3.2 HYDRAULIC TESTING

### 3.2.1 Overburden Hydraulic Conductivity

Hydraulic conductivity values for the overburden were compiled from the results of slug tests in monitoring wells and from laboratory permeameter tests. There were 38 hydraulic conductivity values obtained from slug tests, 37 of which were conducted between 1987 and 1990. One slug test was conducted in a 1-inch diameter well temporarily installed near I1 in September 2002. The slug test results were analyzed statistically and are shown as a probability plot in Figure 3-5. The slug test results range from about 0.0007 ft/day to 0.9 ft/day. The statistical analysis suggested that the hydraulic conductivities are log-normally distributed with a median hydraulic conductivity of about 0.05 ft/day.

Laboratory permeameter tests were conducted on eight samples collected during the SCR-H field activities. The Overburden samples were collected at the locations of the new multiple-completion wells C3, F6, I1, and J6. The estimates of hydraulic conductivity derived from the permeameter tests range from about 0.00007 ft/day to 0.03 ft/day. This range is lower than the results of the slug tests, as is commonly observed in the comparison of laboratory and field permeability tests.

Grain size distributions were also developed for 24 sediment samples collected during the SCR-H field activities. The samples were collected at the locations of the new multiple-completion wells C3, F6, I1, and J6. The grain size analyses show fines content ranging from 50% to 98%. Based on past experience, the content of fines, e.g., silt and clay, control the hydraulic conductivity of sediments. Very low hydraulic conductivity ($<0.1$ ft/day) is expected for sediments having greater than 20% fines. The grain size analyses provide a qualitative confirmation of the low hydraulic conductivity of the Overburden at the Site.

The hydraulic conductivity values indicate that the overburden materials have low hydraulic conductivity and represent an aquitard overlying the bedrock flow system. Except in the gravel bedding of sewers, the abandoned railroad cut, or other utilities, the groundwater flow within the overburden is most likely vertical, replenishing the bedrock groundwater.

### 3.2.2 Lower Bedrock Well Slug Testing

The Lower Bedrock wells (installed to address the requirements of the *Stipulation on Requisite Remedial Technology Program*, the RRT) were installed based strictly on geology and generally intercept FZ-10 and FZ-11. Whereas, the open interval of the Middle and Upper Bedrock wells were influenced by the elevation of the top of bedrock and, as a result, intercepted different flow zones depending on the location of the well. Based on the review of geophysical data during the SCR-G (and confirmed by packer testing during the SCR-H), FZ-11 is generally much more transmissive than FZ-10. Given the consistent construction and the probability that a slug test in a Lower Bedrock monitoring well would represent FZ-11, all accessible Lower Bedrock wells at the Site were slug tested to determine transmissivity. A total of 38 wells were tested, with duplicate tests conducted in five wells. This section provides a brief overview of the testing. A complete description of the testing program and the methods of interpretation, and details for each test are provided in a separate report in Appendix A.

The slug tests were executed by monitoring water-level recovery following the rapid addition of 2 gallons of clean water to each well (approximately 3 feet of initial displacement). Water levels were recorded at 5-second intervals (a 1-second interval was used for several wells that responded rapidly). The water level in the less transmissive wells was monitored for 24 hours. This relatively long monitoring period has made it possible to estimate transmissivities as low as 0.001 $ft^2$/day, defining the "detection limit" for the slug tests. A specialized approach was developed for this investigation to analyze the results from tests in which the initial displacement was introduced gradually with respect to the recovery. This approach is described in a technical note that accompanies the report in the Appendix A.

The results of the Lower Bedrock well slug testing are presented in Figure 3-6. The hollow circles in Figure 3-6 represent low transmissivity values. A value of 1 $ft^2$/day has been selected here as a lower cut-off. This cut-off represents about 0.1% of the total transmissivity of the bedrock above the Rochester. The results confirm that there are large areas in the vicinity of the Site where flow zones FZ-10 and FZ-11 have very low transmissivity.

### 3.2.3 Packer Testing

The Workplan specified packer testing at 15 wells, five of which were to be retrofit with piezometers (two locations). The actual testing consisted of 21 wells, nine of which were retrofit with piezometers (four locations). The wells tested are shown in Figure 3-7 and are listed below:

- AGW-1U (subsequently retrofit);
- AGW-1M (subsequently retrofit);
- AGW-1L (subsequently retrofit);
- AGW-2M;
- AGW-2L;
- B1M;
- B1L;
- BC3U;
- D2U (subsequently retrofit);
- D2M (subsequently retrofit);
- D2L (subsequently retrofit);
- F1U;
- F1M;

- F2L (subsequently retrofit);
- H1U;
- H1M;
- H1L;
- J1U;
- J1M;
- J5M (subsequently retrofit); and
- J5L (subsequently retrofit).

In addition to the packer tests in existing wells, complete transmissivity profiling was conducted at four of the six new boreholes. The new boreholes were tested prior to installation of piezometers, to assist in the selection of the screen positions. The tested wells are listed below:

- E6 (location CMW-11 in the Workplan);
- F6 (location F-8 in the Workplan);
- H5 (location H-1OB in the Workplan); and
- I1 (location I-5 in the Workplan).

The packer testing was conducted with a combination of slug tests and constant-rate pumping tests. The length of a typical test interval was 5.2 feet for the existing wells, and 5.4 feet for the new borings (the packers used have a sliding end and, as a result, the packer spacing changes as a function of the boring diameter). Each packed-off interval was first slug tested. If a rapid recovery was observed, a pumping test was conducted immediately. If the slug test recovered slowly, no pumping was done. The slug tests were generally monitored for no more than 10 minutes. These procedures allowed for rapid screening, and made it possible to test a larger number of wells than was originally planned. The greatest time was spent on the critical high-transmissivity intervals, and the duration of efforts on low-transmissivity intervals was minimized, while still allowing detection of transmissivities as low as 0.001 $ft^2$/day.

A total of 268 packer tests were conducted, of which 259 could be analyzed. The remaining nine tests could not be analyzed due to either packer or transducer malfunction.

The results of the packer testing have been assembled in summary plots that supplement the 2-page summaries of the geophysical data developed previously. The summary plots are included in Appendix A.

Figure 3-8, a probability plot of the packer-test results, provides a clear illustration of the range and variability of the data. The transmissivity estimates have a large range, from 0.001 $ft^2$/day up to almost 10,000 $ft^2$/day. The linearity of the central portion of the plot suggests that the transmissivity values fit a lognormal distribution.

The median transmissivity estimated from the packer tests is 0.2 $ft^2$/day. This value represents a composite average from all of the transmissivity values including flow zones and aquitards. As shown on the profiles for each well, the transmissivities estimated between the flow zones are generally very low, typically much less than 1.0 $ft^2$/day. The results of a statistical analysis of the properties of the aquitards between the flow zones are presented in Section 3.2.6.3.

### 3.2.4 Flow-Zone Piezometer Slug Tests

All flow-zone piezometers were slug-tested. The slug tests were conducted to quantify the distribution of transmissivity in the discrete flow zones at the Site. Each of the 113 new piezometers was tested. Duplicate and triplicate tests were conducted in 28 piezometers in which the response was either very rapid or irregular.

The slug tests were executed by monitoring the recovery in the water level following the rapid addition of 1 liter of clean water to each piezometer (approximately a 6-foot displacement). Water-level changes were monitored at varying intervals, depending on the local transmissivity of the flow zone. Piezometers that exhibited a rapid response were re-tested with monitoring at 1-second intervals, the highest frequency available with the Telog dataloggers. Since the piezometers have only 1-inch diameter riser pipes, their "resolution" for the estimation of low transmissivities is much higher than for the existing 3.9-inch diameter monitoring wells. However, responses in high transmissivity areas dissipate much more rapidly.

The results of the piezometer slug tests have been included on the summary plots of the geophysical, borehole flowmeter, and packer-test results. The results have also been analyzed statistically and used to develop transmissivity distributions for the individual flow zones. The transmissivity distributions are discussed in Section 3.2.6.2.

### 3.2.5 Observations From Hydrographs

In addition to the quantitative testing described above, the hydrographs presented in Appendix B provide indirect indications of the transmissivity in the vicinity of each piezometer. Flow zones are relatively thin fracture zones. If a flow zone is saturated, the groundwater in that flow zone is under confined or semi-confined conditions. A piezometer completed in a transmissive zone should exhibit a response to fluctuations in barometric pressure. Piezometers with no barometric response are likely to have very low transmissivity.

Low transmissivity is also indicated by a slow and constant recovery condition. Several wells, for example D2M-07 and F4L-11, exhibit a slow steady rise in the water level. This appears to be recovery following the purging of the piezometers during development. To reduce wellbore storage, the piezometers were constructed with relatively small diameter, 1-inch ID riser pipes. This design minimizes the time lag for water-level recovery in the piezometer. The time lag is defined as the time required for the piezometer to register a change in the water level in the formation (Hvorslev, 1951). It was estimated that the very slowly recovering piezometers were located in areas with transmissivities less than 0.001 $ft^2$/day.

All of the hydrographs were inspected as a verification check on the transmissivity values determined by packer and slug testing. The hydrographs were not used to quantify transmissivity.

#### 3.2.6 Summary of Bedrock Transmissivity Testing

The SCR-H provides a basis for defining hydraulic properties and calibration of a numerical groundwater flow model. Critical to the model is the transmissivity zonation. The zonation defines a continuous interpretation of the transmissivity within each flow zone and hydraulic properties of the aquitards separating the flow zones.

Piezometers were not installed in FZ-03, FZ-08, and FZ-10. The transmissivity distributions for these flow zones have been assembled from the results of the packer testing. For the remaining flow zones, the results from the piezometer slug tests were assumed to provide the most reliable transmissivity estimates. The results of the packer testing were used to supplement the transmissivity distributions at locations where no piezometers were installed. Locations where transmissivity estimates appear inconsistent have been noted and the interpretations from all tests have been checked.

##### 3.2.6.1 Average Flow-Zone Transmissivities

A total of 168 transmissivity values were compiled for the 11 flow zones at the Site. A statistical analysis was developed for the transmissivities of the individual flow zones. The results of this analysis are shown in Figure 3-9. The statistical analysis provides a clear impression of the variability of the transmissivity in each flow zone, and of the relative contributions of each flow zone to the total transmissivity.

The median transmissivities for the flow zones are listed on the following table and are plotted in Figure 3-10.

**Average flow-zone transmissivities**

| Flow zone | Median transmissivity ($ft^2$/day) | Sample Size | Range of transmissivities ($ft^2$/day) |
|---|---|---|---|
| FZ-01 | 70 | 6 | 0.5 to 410 |
| FZ-02 | 9 | 11 | 0.5 to 90 |
| FZ-03 | 0.3 | 6 | 0.05 to 40 |
| FZ-04 | 0.6 | 15 | <0.001 to 420 |
| FZ-05 | 1.1 | 16 | <0.001 to 360 |
| FZ-06 | 0.9 | 22 | <0.001 to 220 |
| FZ-07 | 0.3 | 24 | <0.001 to 2,600 |
| FZ-08 | 1.0 | 12 | <0.001 to 240 |
| FZ-09 | 90 | 26 | <0.001 to 2,300 |
| FZ-10 | 0.03 | 10 | <0.001 to 50 |
| FZ-11 | 1.8 | 20 | <0.001 to 520 |

The complete probability curves and the average values provide a consistent indication that the dominant flow zones at the Site are FZ-01, FZ-02, FZ-09, and FZ-11. Based on our inspection of the overall results we conclude that in general:

- The most transmissive flow zones are FZ-01 and FZ-09;
- The transmissivities of FZ-03 through FZ-08 are low; and
- The transmissivity of FZ-10 is very low, similar to an aquitard.

#### 3.2.6.2 Distribution Of Transmissivity In Each Flow Zone

Maps of transmissivity distributions in each flow zone are presented in Figures 3-11 through 3-21. A relative zonation of the relative transmissivity (high, medium, or low with no numeric transmissivity value associated) has been presented for each flow zone. These zonations were developed during the data evaluation to support the data interpretation. The zonations were developed by examining the results of the hydraulic testing (including the Lower Bedrock well slug tests), the piezometer water-level records, and the long-term responses of the Lower Bedrock wells. They will be refined by calibration of the numerical flow model currently under development.

FZ-01

The transmissivity values estimated for FZ-01 are shown in Figure 3-11. The transmissivity values for the six locations in FZ-01 range from 0.5 to 410 $ft^2$/day, with a median value of about 70 $ft^2$/day, the highest median transmissivity value of all flow zones. There is no clear zonation for transmissivity in FZ-01.

FZ-02

The transmissivity values estimated for FZ-02 are shown in Figure 3-12. The transmissivity values estimated for the 11 locations in FZ-02 range from 0.5 to 90 $ft^2$/day, with a median value of about 9 $ft^2$/day. The transmissivity values have been divided into three zones.

FZ-03

Although no piezometers were completed in FZ-03, transmissivity data are available from the packer testing. The transmissivity values estimated for FZ-03 are shown in Figure 3-13. The six transmissivity values for FZ-03 range from 0.05 to 40 $ft^2$/day, with a median value of about 0.3 $ft^2$/day. The transmissivities are low (<1 $ft^2$/day) in the vicinity of the Site.

FZ-04

The transmissivity values estimated for FZ-04 are shown in Figure 3-14. The transmissivity values for 15 locations in FZ-04 range from very low (<0.001 $ft^2$/day) to 420 $ft^2$/day, with a median value of about 0.6 $ft^2$/day. The transmissivity values have been divided into two zones. The transmissivities are generally low (<1 $ft^2$/day) in the vicinity of the Site.

There is an apparent anomaly among the transmissivity values. The transmissivity values at locations F1 and F2, about 400 feet apart, are different by five orders of magnitude. The packer-test transmissivity estimate at F1U in FZ-04 was 0.03 $ft^2$/day, the transmissivity value from the F2U-04 piezometer slug test was 420 $ft^2$/day. The test data were reviewed and both transmissivity estimates are considered to be reliable. As indicated by the transmissivity zonation, the transmissivity can change greatly over a short distance. Further, these changes may be contrasts between two large areas of high and low transmissivity, and not simply localized conditions.

FZ-05

The transmissivity values estimated for FZ-05 are shown in Figure 3-15. The transmissivity values for 16 locations in FZ-05 range from very low (<0.001 $ft^2$/day) to 360 $ft^2$/day, with a median value of about 1.1 $ft^2$/day. The transmissivity values have been divided into two zones. The transmissivities are generally low (<1 $ft^2$/day) south of the Landfill.

There is an apparent anomaly among the transmissivity values. A very low transmissivity (<0.001 $ft^2$/day) was estimated from the D2U-05 packer test. The piezometer slug-test analysis yielded a transmissivity of 30 $ft^2$/day for D2U-05. This is similar to the transmissivity value of 20 $ft^2$/day at D1U-05. D2U-05 tracked barometric pressure and responded similarly to D1U-05; these observations support a transmissivity much greater than 0.001 $ft^2$/day. The value of 30 $ft^2$/day for D2U-05 is assumed to be correct.

FZ-06

The transmissivity values estimated for FZ-06 are shown in Figure 3-16. The transmissivity values for 23 locations in FZ-06 range from very low (<0.001 $ft^2$/day) to 220 $ft^2$/day, with a median value of about 0.9 $ft^2$/day. The transmissivity values have been divided into three zones. The transmissivities are generally low (<1 $ft^2$/day) to the west of the Landfill, and high to the east and south.

There is an apparent anomaly in FZ-06. The piezometer slug-test transmissivity at F2M-06 is significantly lower than the packer-test result from F1M at FZ-06. The F2M-06 piezometer slug-test transmissivity has been confirmed to be low. As indicated by the transmissivity zonation, the transmissivity can change greatly over a short distance. Further, these changes may be contrasts between two large areas of high and low transmissivity, and not simply localized conditions.

FZ-07

The transmissivity values estimated for FZ-07 are shown in Figure 3-17. The transmissivity values for the 24 locations in FZ-07 range from essentially zero (<0.001 $ft^2$/day) to 2,600 $ft^2$/day, with a median value of about 0.3 $ft^2$/day. The zonation of transmissivity in FZ-07 is relatively complex. As a starting point for the model we have assigned the transmissivity values to three zones. The narrow band running across the middle of the Landfill represents a transition zone between an area of low transmissivity east and south of the Site, and a zone of very high transmissivity north of the Site. The water-level monitoring has demonstrated that the piezometers in the high-transmissivity zone are connected to the NYPA Forebay and closely follow its water-level fluctuations.

The reported piezometer slug-test transmissivity for J5M-07 is likely an underestimate. Triplicate slug tests showed very rapid recovery – too rapid for a definitive slug-test interpretation, even at a timing interval of 1-second.

There is an apparent anomaly among the transmissivity values in FZ-07. At E6-07, the packer testing indicated essentially zero transmissivity (<0.001 $ft^2$/day). This is not consistent with the transmissivity of 2 $ft^2$/day estimated from the piezometer slug test. We have reviewed the packer-test results and concluded that the packer-test results at E6-07 are reliable. The packer T estimates above, at, and below FZ-07 exhibited low transmissivity.

FZ-08

Although no piezometers were completed in FZ-08, transmissivity data are available from the packer testing. The transmissivity values estimated for FZ-08 are shown in Figure 3-18. The 12 transmissivity values for FZ-08 range from essentially zero (<0.001 $ft^2$/day) to 240 $ft^2$/day, with a median value of about 1 $ft^2$/day. There are no clear zones of transmissivity in FZ-08.

FZ-09

The transmissivity values estimated for FZ-09 are shown in Figure 3-19. The transmissivity values for 25 locations in FZ-09 range from essentially zero (<0.001 $ft^2$/day) to 2,300 $ft^2$/day, with a median value of about 90 $ft^2$/day. As indicated by the transmissivity values plotted in Figure 3-19, FZ-09 has high transmissivity in the vicinity of the Site. As a starting point for the model we have assigned the transmissivity values to three zones, similar to the zonation for FZ-07. West of the Landfill, the piezometers exhibited strong responses to bedrock pumping. North of the Landfill, the piezometers are connected to the NYPA Forebay and closely follow its fluctuations in level.

The piezometer slug test at B2M-09 of 40 $ft^2$/day is much lower than the packer-test transmissivity estimated at FZ-09 in B1M. The transmissivity value determined from the B2M-09 slug test is likely an underestimate as the test response was not adequately resolved, even at a timing interval of 1-second.

The piezometer slug-test transmissivity reported for J5M-09 is relatively low. The J5 packer-test transmissivity estimates for intervals straddling FZ-09 are 0.2 and 2,300 $ft^2$/day, with the larger value presented on Figure 3-19. The J5M-09 piezometer intercepts only a portion of the packer-test interval with the 2,300 $ft^2$/day transmissivity.

The packer-test transmissivity for FZ-09 at I1 was 120 $ft^2$/day; the piezometer slug test was <0.001 $ft^2$/day. Based on a review of the packer-test results, it appears that the I1-09 is completed above FZ-09 at this location; I1-09 will longer be used for flow zone interpretation.

FZ-10

Although no piezometers were completed in FZ-10, transmissivity data are available from the results of the packer testing. The transmissivity values estimated for FZ-10 are shown in Figure 3-20. The values for FZ-10 range from essentially zero (<0.001 $ft^2$/day) to 50 $ft^2$/day, with a median value of about 0.03 $ft^2$/day. There are no clear zones of transmissivity in FZ-10.

It is interesting to note that the median transmissivity value for FZ-10 is equal to the median transmissivity of the bedrock between flow zones, i.e. the aquitards. It may be inappropriate to consider FZ-10 a flow zone.

FZ-11

The transmissivity values estimated for FZ-11 are shown in Figure 3-21. This figure includes both the piezometer data and the data from the slug test of the Lower Bedrock wells presented in Section 3.2.2. The transmissivity values in FZ-11 range from essentially zero (<0.001 $ft^2$/day) to 520 $ft^2$/day, with a median value of about 1.8 $ft^2$/day. The zonation of transmissivity in FZ-11 is relatively complex.

The zonation presented on Figure 3-21 was developed by considering the results of the hydraulic testing (including the Lower Bedrockslug testing), the long-term water-level data from Lower Bedrock wells, and the responses observed in the FZ-11 piezometers. The Lower Bedrock wells are generally open across either only FZ-10 and FZ-11, or only FZ-11. Therefore, the historical water-level data from the Lower Bedrock wells can be used to supplement the evaluation of conditions in FZ-11. Long-term hydrographs for the Lower Bedrock wells are plotted on Figure 3-22. The Lower Bedrock wells with very low transmissivity were removed from the data set as the water levels are unreliable. This figure shows three distinct subzones monitored by the Lower Bedrock wells (plus the three AFW wells located adjacent to the Gorge). Figure 3-22 has grouped these subzones with a letter, **A** to **D**.

**A** Water levels in G1L, G2L, G3L, and G5L are approximately the same and exceptionally high compared to all other Lower Bedrock wells.

**B** Water levels in AGW-2L, AGW-3L, D5L, H1L, H3L, H4L, J1L, J3L, J4L, JH1L, and PMW-3L are all similar and are approximately equal to the water level in the NYPA Forebay.

**C** Water levels in B1L, B2L, C1L, C2L, CD1L, D4L, E2L, and PWM-1L are all similar. These wells responded to the shutdown of the bedrock purge wells in May 2001; none of the abovementioned Lower Bedrock wells responded to the shutdown.

These three subzones appear to act totally independently of each other. It appears that there must be areas of low transmissivity separating these subzones. Group **D** includes the AFW well located at the Gorge.

The most important feature in FZ-11 is a zone of relatively high transmissivity immediately west of the Landfill. The three piezometers located in this zone, B2L-11, D1L-11, and PMW-1L-11, were the only piezometers that exhibited recoveries following the shutdown of the bedrock purge wells. However, Lower Bedrock wells B1L, B2L, C1L, C2L, CD1L, D4L, E2L, and PWM-1L all responded to the May 2001 shutdown. Thus, the extent of this high transmissivity zone is well defined.

The packer-test transmissivity of 0.01 $ft^2$/day at F2L at FZ-11 is probably not reliable. The response observed during the test was irregular. It appears that the F2L-11 piezometer slug-test transmissivity of 1.3 $ft^2$/day is more representative.

The piezometer slug test at I1-11 indicated a very low transmissivity. The packer-test transmissivity of 0.05 $ft^2$/day, still very low, corresponds to an interval between FZ-10 and FZ-11, not intercepted by I1-11.

#### 3.2.6.3 Transmissivities Of The Aquitards Between The Flow Zones

The results of petrophysical testing of drill core samples conducted as part of the SCR-G indicated that the intact bedrock at the Site has very limited ability to conduct water. The intrinsic permeabilities of the core samples reported in Appendix F of the SCR-G varied from $5.8\times10^{-4}$ to $5.3\times10^{-1}$ millidarcies (equivalent hydraulic conductivity values are $4\times10^{-10}$ to $4\times10^{-7}$ cm/sec). This range is consistent with literature values reported for intact dolostone (Table 2.2, Freeze and Cherry, 1979). The hydraulic conductivity of the intact rock is so low that it is expected that even between the flow zones, any groundwater flow occurs through fractures and not the rock matrix. For comparison of these hydraulic conductivity values with the packer-test transmissivity results, $4\times10^{-10}$ to $4\times10^{-7}$ cm/sec are equivalent to transmissivities of $6\times10^{-6}$ to 0.006 $ft^2$/day.

Results from the packer testing have been used to obtain representative properties of the aquitards between the flow zones. A separate set of transmissivities was extracted from the packer-tests results, corresponding to the results from those intervals that did not intersect the predicted elevation of a flow zone (±2 feet). This set comprised 120 of the 259 packer tests. A probability analysis was developed with these data. The results of the analysis are presented in Figure 3-23.

The probability plot indicates that the majority of the aquitard transmissivities follow a log-normal distribution. Although the transmissivities have a wide range, the majority of values are well below 1 $ft^2$/day. There are a few values of transmissivity above 1 $ft^2$/day, but they appear to be outliers from the log-normal distribution.

As indicated on Figure 3-23, the median aquitard transmissivity value is 0.03 $ft^2$/day. It is important to bear in mind that transmissivity is a horizontal property. The groundwater flow within the aquitards is primarily vertical and is controlled by vertical hydraulic conductivity. The aquitard transmissivity values presented here will be used as a starting point for numerical groundwater flow modeling. The vertical hydraulic conductivity of the aquitards will ultimately be estimated through model calibration.

#### 3.2.6.4 Transmissivity Of The Bedrock Above Flow Zone 1

An extensive evaluation of the bedrock above FZ-01 has not been performed. There are few data and no wells completed above FZ-01. Based on inspection of video logs from G1U, H1U, H5, and I1, and observations of high water loss during drilling at H5, the bedrock above FZ-01 is highly fractured. Large voids are visible in video logs. Figure 3-24 presents four photos captured from the G1U video log. Two photos show large openings in the bedrock above FZ-01. Two others are more typical of the rock below FZ-01, relatively smooth and free of large voids. The highly fractured rock appears to be separated from FZ-01 by an aquitard at least 5 feet thick.

The rock above FZ-01 subcrops south of the landfill area and would not be affected by the Landfill. However, this zone is highly fractured and may be considered in the modeling. Although no transmissivity tests were completed in this fractured zone, it was sufficiently transmissive that during the drilling of H5 this portion of the rock had to be grouted to control the loss of drilling water.

Johnston (1964) described the upper 15 feet of bedrock in the Niagara region to be highly fractured and weathered. In the SCR-G, a review of the fracture frequency concluded that there was no exceptionally fractured zone in the shallow bedrock beneath the Site. However, the video inspections of G1U, H1U, H5, and I1 had not been completed at the time of that report. The highly fractured and weathered bedrock described by Johnston may only occur in the rock above FZ-01 and is not an issue of concern with respect to the Hyde Park Site.

#### 3.2.6.5 Transmissivity Of The Rochester Shale

The Rochester Shale underlies FZ-11. This formation has very low hydraulic conductivity and is considered to be a continuous aquiclude at the Site. Kappel and Tepper (1992) indicate that at the regional scale, the low hydraulic conductivity of the Rochester Shale prevents the downward movement of groundwater from the Lockport Group. Novakowski and Lapcevic (1988) provide data that indicate there is an overpressured natural-gas reservoir within and below the Rochester Shale.

For the purposes of modeling, the Rochester Shale will continue to be defined as a no-flow boundary.

## 3.3 HYDROGRAPHS

Hydrographs of the water-level data have been prepared and are presented in Appendix B. Four types of hydrographs are presented:

- Hydrographs for Individual Wells;
- Hydrographs showing all of the piezometers in a single flow zone;
- Hydrographs showing all of the piezometers at a single location; and
- Hydrographs for the purge wells with the pumping rates included.

The hydrographs are critical tools for analysis of groundwater potentiometric conditions and flow-zone transmissivity. For example, in FZ-09 a group of piezometers responded identically to each other and the response was clearly driven by water-level fluctuations in the NYPA Forebay. There were no other influences on the water levels in these piezometers. These piezometers are monitoring a common transmissive zone within a flow zone. Other FZ-09 piezometers exhibit no influence of the Forebay but recovered by 30 feet when the bedrock purge wells were shut down.

These simple observations demonstrate that there are at least two distinct transmissive zones within FZ-09. Using this process of inspection, an understanding of the hydrogeologic system has been developed. The Figures included in this report present the understanding developed by the technical team after a thorough review and analysis of the hydrographs presented in Appendix B and the transmissivity and hydraulic conductivity results presented in Appendix A.

## 3.4 FLOW-ZONE WATER LEVELS UNDER PUMPING CONDITIONS

In the following subsections, potentiometric surface contours are presented and discussed for each flow zone under pumping conditions. The water levels used for contouring were the 24-hour average water level in piezometers on January 6, 2003. Average water levels were selected rather than an instantaneous water level to better reflect the typical conditions in the flow zone. Barometric influences in all flow zones and daily fluctuations in water levels in FZ-07 and FZ-09 of up to 8 feet in response to the NYPA Forebay confound the interpretation of an instantaneous set of water levels.

The contour maps presented in this section show potentiometric head relationships in the flow-zone plane. For discussion purposes, groundwater flow within one flow zone is described as horizontal flow. The potentiometric surface maps do not indicate flow in the vertical direction. Vertical flow is particularly critical in FZ-01 to FZ-05. Groundwater within these zones travels both horizontally within the flow zone, and vertically downward into deeper flow zones. Based on groundwater flow modeling completed for the Site and reported in the *Groundwater Modeling Study: Final Report* dated February 19, 2001, the vertical component of groundwater flow is significant. Groundwater travels only a relatively limited horizontal distance before migrating vertically from one flow zone into a deeper flow zone.

In reviewing the potentiometric surface maps it is important to consider the hydraulic boundaries. To the north, flow zones FZ-01 to FZ-05 subcrop before encountering the NYPA Forebay. FZ-06 to FZ-11 outcrop in the Forebay. To the west, the flow zones either subcrop before the Niagara River Gorge or outcrop in the Gorge. To the east, all flow zones intersect the NYPA conduits. Where the flow zones are saturated in the NYPA Forebay and conduits, the potentiometric head will be fixed by the water level in the Forebay or conduit. This is very evident in the FZ-07 to FZ-11 potentiometric surface maps. During the SCR-H study, the average Forebay water level ranged from approximately 553 to 558 ft MSL. To the south there are no hydraulic boundaries until the Upper Niagara River is encountered. The southern boundary is so distant that the influence relative to the north, east, and west boundaries, is relatively insignificant.

The potentiometric surface contour maps present water levels for the piezometers and for the purge wells. Where the piezometers are labeled "dry", there is no water in the piezometer, or the water level in the piezometer was at or below the predicted elevation of the flow zone. Where purge wells are labeled "dry", the pumping level is below the flow zone. The value posted next to a "dry" location is the elevation of the flow zone, not the level of the water standing in the piezometer, or the pumping level that is far below the flow zone.

The water levels from the piezometers were respected in contouring unless:

- the response in hydrograph and transmissivity data suggested that the water level had not recovered to the level of the surrounding formation, or
- the water level was clearly influenced by a nearby long open-interval well interconnecting flow zones.

The water levels provided for purge wells were not used directly in the contouring. It is recognized that there can be significant well losses near the well bore and that a pumping level may not be representative of the water level in the aquifer several feet from the well. Purge well influences were considered in the preparation of contours based on the responses observed during the purge well shutdown.

### 3.4.1 FZ-01

The potentiometric surface contours for FZ-01 are presented in Figure 3-25. This Figure shows northeast and southwest horizontal components of groundwater flow from the eastern portion of the landfill. Horizontal flow at the subcrop is parallel to the subcrop, consistent with a no-flow boundary created by the subcrop encountering the low hydraulic conductivity till.

FZ-01 is intersected by a north-south running sewer line cut into bedrock along Hyde Park Boulevard. Sewer invert elevations are posted on Figure 3-25 and Plate 1. The invert elevations appear to match the potentiometric surface if it were continued to Hyde Park Boulevard. Assuming that the sewer lies in a bed of permeable gravel, it appears that the sewer acts as a drain for FZ-01 at this location.

Based on the modeling study completed in February 2001 there is a significant component of vertical groundwater flow. The modeling results are consistent with strong downward vertical hydraulic gradients from FZ-01 down to FZ-06. It is unlikely that groundwater from the immediate area of the Landfill would discharge to the sewer at Hyde Park Boulevard. It is more likely that groundwater flows a relatively short distance in the horizontal direction before migrating vertically into a deeper flow zone.

Purge well PW-6UR intercepts FZ-01; it is also open continuously through FZ-05. This well was producing less than 1 gpm at the time of shutdown. The influence of pumping is not perceptible in the contours, nor was there an apparent response to pumping in FZ-01 following the shutdown of the bedrock purge wells.

### 3.4.2 FZ-02

The potentiometric surface contours for FZ-02 are presented on Figure 3-26. This figure shows northeasterly and a southwesterly horizontal components of groundwater flow from the landfill. Horizontal flow at the subcrop is parallel to the subcrop, consistent with a no-flow boundary at the subcrop.

FZ-02 is intersected by an east-west trending sewer line cut into bedrock south of Maple Street. The sewer appears to be a drain for FZ-02. It is unlikely that groundwater from the immediate vicinity of the Landfill would reach this point of discharge. It is more likely that groundwater in FZ-02 flows a relatively short distance in the horizontal direction before migrating vertically into a deeper flow zone.

The operational purge wells that are open across FZ-02 are listed below.

| *Purge Well* | *Pumping Rate (gpm) ** | *Pumping Level Above or Below Flow Zone 2* | *Flow Zones Intercepted* |
|---|---|---|---|
| PW-4U | 0.5 | Below | 02 .. 05 |
| PW-5UR | 3.4 | Below | 02 .. 05 |
| PW-6UR | 1.2 | Below | 01 .. 05 |

* the pumping rate is the total from all flow zones intercepted

The influence of pumping is not perceptible in the potentiometric surface contours for FZ-02, nor was there a significant water-level response following the shutdown of the bedrock purge wells.

### 3.4.3 FZ-04

The contours of the potentiometric surface for FZ-04 are presented on Figure 3-27. This Figure shows northeasterly and a southwesterly horizontal components of groundwater flow from the landfill. Horizontal flow at the subcrop is parallel to the subcrop, consistent with a no-flow boundary at the flow-zone subcrop.

FZ-04 is intersected by a south-north sewer line cut into bedrock along Hudson Drive. FZ-04 is also intercepted for a short distance, approximately at University Court, by an east-west trending sewer beneath Lafayette Street. Both of these sewers act as drains for FZ-04. It is unlikely that groundwater from the immediate vicinity of the Landfill would reach this point of discharge. It is more likely that groundwater flows a relatively short distance in the horizontal direction before migrating vertically into a deeper flow zone.

The operational purge wells that that are open across FZ-04 are listed below.

| *Purge Well* | *Pumping Rate (gpm)** | *Pumping Level Above or Below Flow Zone 4* | *Flow Zones Intercepted* |
|---|---|---|---|
| PW-2UR | 0.3 | Below | 03 .. 05 |
| PW-4U | 0.5 | Above | 02 .. 05 |
| PW-5UR | 3.4 | Equal | 02 .. 05 |
| PW-6UR | 1.2 | Below | 01 .. 05 |
| PW-10U | 6 | Above | 03 .. 06 |

* the pumping rate is the total from all flow zones intercepted

The influence of pumping is not perceptible in the potentiometric surface contours for FZ-04.

### 3.4.4 FZ-05

The potentiometric surface contours for FZ-05 are presented in Figure 3-28. This figure shows a southwesterly horizontal component of groundwater flow from the landfill along the subcrop. A groundwater divide is present along the east side of the Landfill. East of the divide, groundwater flows to the east. West of the divide, the Landfill side, groundwater flows westerly, towards the subcrop.

The 580 ft MSL potentiometric contour wraps around the landfill and suggests the influence of pumping in FZ-05. Eight purge wells intersect FZ-05. Other than PW-10U and PW-5UR, these wells yield little water. FZ-05 did not show a significant response to the shutdown of the bedrock purge wells. It is likely that the "drawdown" indicated by the 580 ft MSL contour is related to drainage of water from FZ-05 into a lower flow zone through one of several long open-interval monitoring or purge wells.

FZ-05 is intersected by a south-north trending sewer line cut into bedrock along Hudson Drive. The sewer trench first intercepts FZ-05 between CMW-9SH and CMW-11SH and continues to intercept FZ-05 northward to the subcrop. It is likely that the sewer acts as a drain for FZ-05 at this location. At location E6, there is an upward gradient from FZ-05 to FZ-04. Although the Hudson Drive sewer does not cross FZ-05 this far south, groundwater in FZ-05 may be flowing upward to the sewer in this area. It is unlikely that groundwater from the immediate vicinity of the Landfill would reach the Hudson Drive sewer. It is likely that groundwater flows a relatively short distance in the horizontal direction before migrating vertically into FZ-06.

Operational purge wells that that are open across FZ-05 are listed below.

| *Purge Well* | *Pumping Rate (gpm)** | *Pumping Level Above or Below Flow Zone 5* | *Flow Zones Intercepted* |
|---|---|---|---|
| PW-1U | <0.1 | Below | 05 .. 06 |
| PW-2UR | 0.3 | Below | 03 .. 05 |
| PW-3M | 0.1 | Below | 05 .. 09 |
| PW-4U | 0.5 | Above | 02 .. 05 |
| PW-5UR | 3.4 | Below | 02 .. 05 |
| PW-6UR | 1.2 | Above | 01 .. 05 |
| PW-7U | 1 | Below | 05 .. 06 |
| PW-10U | 6 | Above | 03 .. 06 |

* the pumping rate is the total from all flow zones intercepted

The influence of pumping is not perceptible in the potentiometric surface contours for FZ-05, nor was there a significant water-level response following the shutdown of the bedrock purge wells.

### 3.4.5 FZ-06

The potentiometric surface contours for FZ-06 are presented in Figure 3-29. This is the first flow zone with a significantly different flow pattern than observed in FZ-01 through FZ-05. A large dry area in this flow zone is indicated in Figure 3-29. The potential for drying up a portion of the flow zone was anticipated prior to the testing. However, the large area over which the flow zone becomes "dry" was not expected.

The term “dry” is used where the water level in a piezometer is at or below the elevation of the flow zone. At these locations the flow zone is not fully saturated; however, there is likely a limited flow of groundwater within a dry zone. Water will seep into the flow zone from the overlying aquitard and flow down-dip like surface runoff. The direction of flow would be controlled by the dip of the flow zone rather than potentiometric head. This flow would move down dip, but not up or across dip. Given this conceptual model of a dry area, potentiometric contours were drawn within the dry areas to match the predicted elevation of the flow zone, and thereby indicating a strictly down-dip flow. These contours are drawn as dashed lines to indicate an estimated contour.

Visual evidence of the dry area interpreted on Figure 3-29 is shown in Figure 3-30, a photo of the Niagara Gorge taken from the Canadian side of the Niagara River. This photo was presented in the SCR-G. The seeps visible on Figure 3-30 are from FZ-06. There is no seepage from FZ-06 north (left on the photograph) of the AFW-2 piezometers. The seep appears south of the AFW-2 piezometers. The seep location is consistent with the interpretation of the dry area presented on Figure 3-29.

The large dry area is important with respect to containment. When a flow zone is dry, the limited groundwater that may be present will flow down dip until it encounters a drain (vertical fracture, well, sewer, or tunnel) or saturated groundwater conditions. South of the dry area, down-dip, the hydraulic gradient is toward the dry area. The potentiometric contours presented on Figure 3-29 suggest a large area of hydraulic containment.

With the exception of PW-10U, water levels in the purge wells are below FZ-06. At PW-10U, the water level is approximately 572 ft MSL, well above the water levels in FZ-06. It appears that in PW-10U groundwater is flowing from FZ-05 into FZ-06 under pumping conditions. Although 5 to 6 gpm is being pumped from PW-10U, groundwater is entering PW-10U from FZ-05 at rates greater than 5 or 6 gpm; the additional water is flowing into FZ-06. It is known that the water entering PW-10U comes from FZ-05 because, although PW-10U also intercepts FZ-04, there was no significant water yield from FZ-04. To prevent the downward flow from FZ-05 into FZ-06, either PW-10U must be pumped at a higher rate, or FZ-06 must be sealed at this location. Sealing FZ-06 in PW-10U would eliminate flow from FZ-05 into FZ-06, thereby expanding the containment area in FZ-06.

The horizontal sewer lines that intersect FZ-01 to FZ-05 are above FZ-06 and do not appear to affect conditions in FZ-06. However, several vertical shafts in the sewer system intercept FZ-06. These shafts are dry as they drain to the Gorge tunnel that runs north-south along the Gorge, and can drain water from the flow zones that are intercepted. It is not possible to determine with the current data how much, groundwater is captured from FZ-06 by the vertical shafts. However, the non-pumping recovery data suggest that these shafts are effecting drawdown in FZ-06.

The abandoned NYC Railroad cut intersects FZ-06 near piezometer C3-06. The railroad cut continues to cross FZ-06 northward through APW-2 and beneath the Robert Moses Parkway. The railroad cut has been backfilled to grade. Wells APW-2 and ABP-8 appear to have been drilled through the fill material. Descriptions of the fill suggest that it consists primarily of silts and clays having low hydraulic conductivity. However, it is likely that there is a highly conductive bedding material that was placed for the railroad. This bedding likely receives water from FZ-06 where the bedding is in direct contact with FZ-06. It is not known precisely at this time how the railroad cut and bedding influence groundwater flow in FZ-06.

The operational purge wells that are open across FZ-06 are listed below.

| *Purge Well* | *Pumping Rate (gpm)** | *Pumping Level Above or Below Flow Zone 6* | *Flow Zones Intercepted* |
|---|---|---|---|
| PW-1U | <0.1 | Below | 05 .. 06 |
| PW-2M | 30 | Below | 06 .. 09 |
| PW-3M | 0.1 | Below | 05 .. 09 |
| PW-4M | <0.1 | Above | 06 .. 09 |
| PW-6MR | 4.2 | Below | 06 .. 09 |
| PW-7U | 0.5 | Below | 06 |
| PW-8U | 3.4 | Below | 06 |
| PW-8M | <1 | Below | 06 .. 09 |
| PW-9U | 1.2 | Below | 06 |
| PW-10U | 6 | Above | 05 .. 06 |

* the pumping rate is the total from all flow zones intercepted

### 3.4.6 FZ-07

The potentiometric surface contours for FZ-07 are shown in Figure 3-31. The contours show a pattern typical of a capture zone with a pumping well near PW-2M and a regional flow direction to the west.

The flow direction from east to west is the result of the source of the water. Groundwater in FZ-07 comes from vertical infiltration and apparently from the NYPA Forebay and conduits. The contribution from the NYPA Forebay and conduits is suggested by the water level in the piezometers to the east and north of the Landfill. These levels are slightly lower than the average water level in the Forebay, approximately 554 ft MSL on January 6. The water level in the conduits (actually in the excavation surrounding the conduits) is expected to be approximately the same as the Forebay. The communication of this area of potentiometric heads between 552 and 553 ft MSL with the Forebay/conduits is demonstrated by the hydrographs for AGW-1M-07, I1-07, J5M-07, and J6-07; they match almost perfectly the water-level fluctuations in the Forebay (hydrographs are in Appendix B).

The water levels in D1M-07 and D2M-07 are of particular interest because the monitoring wells D1M and D2M were originally installed to monitor hydraulic gradient reversal for evaluation of the performance of the Bedrock NAPL Plume Containment System. Piezometers were installed in these wells to determine if carefully constructed piezometers monitoring a single flow zone would allow gradient monitoring. The transmissivity at piezometer D1M-07 is very low and the water level did not respond at all to pumping (see hydrograph in Appendix B); this water level is considered to be unreliable. D2M-07 has a slightly higher transmissivity, responds to pumping, and its water level is considered to be representative of FZ-07. Even with the great care taken in constructing the piezometers, the hydraulic gradient indicated by D1M-07 and D2M-07 does not appear to represent the actual conditions within FZ-07. Clearly, these data demonstrate that natural variability within the bedrock prevent precise hydraulic gradient monitoring.

There is a large dry area west of the Landfill. This dry area was predicted by intersecting the potentiometric contours with the predicted flow-zone plane. AFW-2M-07 is the only piezometer within the dry area. The potentiometric surface contours were prepared assuming that this area was dry. If this area were saturated (water levels above the elevation of the flow zone) the hydraulic gradient would be toward the Landfill from Meadowbrook Drive east, demonstrating groundwater containment by the bedrock purge wells. Thus, the data from FZ-07 demonstrate a large area of hydraulic containment under pumping conditions.

The dry zone encompasses several of the vertical sewer shafts. These shafts will drain water from whatever saturated and transmissive fractures that they intersect. The rate at which water leaks into the vertical shafts and how large an influence this has on a flow zone is unknown and cannot be quantified with the existing data. However, the potentiometric contours for pumping and non-pumping conditions in FZ-07 suggests that the vertical shafts "drawdown" the water level in FZ-07.

The operational purge wells that are open across FZ-07 are listed below.

| *Purge Well* | *Pumping Rate (gpm)** | *Pumping Level Above or Below Flow Zone 7* | *Flow Zones Intercepted* |
|---|---|---|---|
| PW-2M | 30 | Below | 06 .. 09 |
| PW-3M | 0.1 | Below | 05 .. 09 |
| PW-4M | <0.1 | Above | 06 .. 09 |
| PW-6MR | 4.2 | Below | 06 .. 09 |
| PW-8M | <1 | Equal | 06 .. 09 |

* the pumping rate is the total from all flow zones intercepted

### 3.4.7 FZ-09

The contours of the potentiometric surface in FZ-09 are shown in Figure 3-32. The contours show a large area where the water levels are essentially flat, a zero gradient. The piezometers in this area also exhibited over 30 feet of recovery following shutdown of the bedrock purge wells. A very similar area of flat gradient and high recovery was observed in the May/June 2001 shutdown test. These 2001 data were reviewed and used to guide the interpretation of the potentiometric surface contours presented in Figure 3-32. All Middle Bedrock wells are open across FZ-09. FZ-09 is by far the most transmissive flow zone in the area of the flat gradient. Because of the high transmissivity of FZ-09, water levels in the Middle Bedrock wells will be nearly the same as the water level in FZ-09. The similarity of water levels in FZ-09 and the Middle Bedrock wells was confirmed by several measurements made in the Middle Bedrock wells in January 2003 (the data are available on the CD-ROM included with this report).

A small dry area is shown in Figure 3-32. This dry area is interpreted based on water-level measurements and the recovery response. Prior to shutdown, the water level in the zero-gradient area was approximately 518.3 ft MSL. After shutdown, the dry area gradually became smaller as the interface between the dry area and the saturated zone moved northwest toward the Gorge. This interpretation is supported by observations of Seep 1 (FZ-09) along the NYPA Access Road. Prior to shutdown, the Gorge face near APW-1 and APW-2 was inspected; no seeps were observed at Seep 1. On January 13, six days after shutdown, Seep 1 was flowing.

Groundwater in FZ-09 comes from vertical infiltration and from the NYPA Forebay and conduits. The contribution from the NYPA Forebay and conduits is demonstrated by the water level in the piezometers to the east and north of the Landfill. These levels are slightly lower than the average water level in the Forebay, approximately 554 ft MSL on January 6. The communication of this area of potentiometric heads between 553 and 554 ft MSL with the Forebay/conduits is further demonstrated by the hydrographs for AGW-1M-09, H5-09, J5M-09, and J6-09; they match almost perfectly the water-level fluctuations in the Forebay (hydrographs are in Appendix B).

The operational purge wells that are open across FZ-09, are listed below

| *Purge Well* | *Pumping Rate (gpm)** | *Pumping Level Above or Below Flow Zone 9* | *Flow Zones Intercepted* |
|---|---|---|---|
| PW-1L | 9 | Below | 06 .. 09 |
| PW-2M | 30 | Below | 06 .. 09 |
| PW-3M | 0.1 | Below | 05 .. 09 |
| PW-4M | <0.1 | Above | 06 .. 09 |
| PW-6MR | 4.2 | Below | 06 .. 09 |
| PW-8M | <1 | Above | 06 .. 09 |

* the pumping rate is the total from all flow zones intercepted

The potentiometric surface contours for FZ-09 demonstrate a large area of hydraulic containment under pumping conditions.

### 3.4.8 FZ-11

The contours of the potentiometric surface in FZ-11 are shown in Figure 3-33.

More than any other flow zone, historical water-level data from the Lower Bedrock wells can be used to evaluate conditions in FZ-11. As a result, the response observed in FZ-11 during the January 2003 shutdown can be supplemented with the observations made during the May 2001 shutdown (the hydrographs are in Appendix B). Lower Bedrock wells: B1L, B2L, C1L, C2L, CD-1L, D1L, and D4L all responded by over 30 feet during the shutdown in May 2001. Well E2L responded by 14 feet and D2L by about 2.5 feet. These wells responded very slowly, suggesting that they were completed in lower transmissivity areas of FZ-11.

In addition to the information from Lower Bedrock wells collected during the shutdown in May 2001, weekly manual water-level measurements were obtained in selected Lower Bedrock monitoring wells during the current investigation. These water-level measurements were used to supplement the FZ-11 dataset. The water-level measurements obtained in these wells may be used in contouring because the Lower Bedrock wells all intersect the same flow zones, namely FZ-10 and FZ-11, or only FZ-11. As discussed in Section 3.2.6.2, FZ-10 has a low transmissivity, therefore water levels in Lower Bedrock wells are typically representative of conditions in FZ-11. The contours present on Figure 3-33 indicate a large area of containment in FZ-11, extending west almost to the former railroad, northwest to the APW wells, north to at least AGW-1L-11, and south to F2L-11. PW-1L is responsible for this containment. PW-2L is a low yield well. PW-3L has a relatively high yield but appears to be pumping from the transmissive zone containing the J- and H-wells and piezometers. This conclusion is based primarily on the observation that non-pumping water levels in PW-3L generally match the J and H FZ-11 piezometers.

The water levels in the G-wells are exceptionally high compared to all other Lower Bedrock wells. As discussed in Section 3.2.6.2 regarding transmissivity zonation in FZ-11, there appears to be a connection between the transmissive zone in which the G-wells are completed and the shallow bedrock. This connection has not been identified in the field but is evident from the elevation of water levels in the G-wells and a general water-level fluctuation consistent with shallow bedrock wells.

The low water level at I1-11 likely reflects the low transmissivities at this location. Given the hydraulic boundary conditions surrounding the Site, the water at I1-11 cannot be going to the NYPA conduits or Forebay; the water levels in those features averaged approximately 550 ft MSL during the testing, much higher than I1-11. The transmissivity at I1-11 is very low. The response observed during the shutdown test period suggests that the water level is very slowly recovering, likely to a level closer to the average level in the Forebay. It is also possible that the low water level at this piezometer could be the result of pumping east or southeast of the Site.

The operational purge wells that are open across FZ-11, are listed below

| *Purge Well* | *Pumping Rate (gpm)** | *Pumping Level Above or Below Flow Zone 11* | *Flow Zones Intercepted* |
|---|---|---|---|
| PW-1L | 9 | Above | 10 .. 11 |
| PW-2L | <0.1 | Above | 10 .. 11 |
| PW-3L | 4 | Above | 10 .. 11 |

* the pumping rate is the total from all flow zones intercepted

The potentiometric surface contours for FZ-11 demonstrate a large area of hydraulic containment under pumping conditions.

## 3.5 RESPONSE TO SHUTDOWN AND RECOVERED CONDITIONS

The Bedrock NAPL Plume Containment System purge wells were shut down for 17 days, from January 7 to January 24, 2003. During this time it was expected that the hydraulic gradients would return to conditions representative of a groundwater system in which there had never been any pumping.

Based on a review of the data, fully-recovered hydraulic gradients were observed in FZ-01 to FZ-05. This conclusion is based on an observation that there was no substantive response to the shutdown observed in FZ-01 to FZ-05. Non-pumping gradients also appear to have been attained in FZ-09. As discussed previously, the data from FZ-11 are still being evaluated. FZ-06 and FZ-07 may not have fully recovered during the shutdown.

The observation that FZ-06 and FZ-07 may not be fully recovered requires elaboration. If there were no pumping and no long open-interval wells interconnecting flow zones, a general downward hydraulic gradient is expected in the bedrock beneath the Site. However, 17 days following the shutdown of the bedrock purge wells, groundwater levels in FZ-06 and FZ-07 were still below the levels in FZ-09. This head relationship is not consistent with the expected downward gradient. Thus, these flow zone may not be fully recovered.

An alternative explanation for lower than expected water levels in FZ-06 and FZ-07 is that groundwater is being extracted from FZ-06 and FZ-07 even under "non-pumping" conditions. There is no known pumping from the Lockport Formation in the vicinity of the Site. However, the vertical sewer shafts between the Landfill and the Gorge penetrate the Lockport Formation. These vertical shafts may act as pumping wells and may be lowering the groundwater level in FZ-06 and FZ-07; therefore the water levels in these flow zones may reflect fully recovered conditions with additional leakage from adjacent man-made features.

It is difficult to quantify the influence of the wells and shafts that interconnect or receive water from the flow zones. The influence is most apparent under non-pumping conditions. As discussed in Section 3.7, the influence of PW-1L interconnecting FZ-09 and FZ-11 is significant and was readily identified during a review of groundwater levels about one week after the shutdown. Because the influence was large, the number of candidate wells interconnecting FZ-09 and FZ-11 was limited (PW-1L and JH1L), and because a 12-inch diameter packer was available, the interconnection could be tested quickly at PW-1L. Where the influence is less apparent and the number of candidate wells large, identifying individual interconnections is difficult.

In the following discussion of non-pumping conditions, potential interconnections are described. These observations were based on a review of the voluminous data set, examination of many different explanations, and technical team discussions. The best way to evaluate the influence of these interconnections is to eliminate them. This can be achieved by abandonment of existing wells. Interconnections cannot be eliminated in sewer cuts and shafts in the bedrock.

### 3.5.1 FZ-01 to FZ-05

With the exception of one piezometer, the recovery response in FZ-01 to FZ-05 to the pumping shutdown was less than 1 foot, and in general was not detectable. Even where there appeared to be 1 foot of response, ambient fluctuations in water levels were large enough to make an assessment of the recovery response difficult.

The one piezometer with a clear recovery response was PMW-1U-05. This well recovered by approximately 4 feet. However, the closest purge well, PW-2U, is 280 feet away and pumps at an average rate of about 0.3 gpm. A 4-foot response seems unusually large in comparison to the response observed in other piezometers. It is likely that the response observed in PMW-1U-05 was related to recovery in a deeper flow zone that was connected vertically through one of the pumping or monitoring wells with an open interval intersecting both FZ-05 and a deeper flow zone. There are a number of potential wells that fit this description. However, identifying the particular well(s) connecting the flow zones is not critical to the current evaluation and has not been pursued. It is important to recognize that this effect occurs, and that as long as long open-interval wells exist, a "recovery response" in one flow zone may be related to pumping in a different flow zone.

The recoveries observed in FZ-01 to FZ-05 were small compared to the contour intervals of 5- and 10-feet presented on the pumping conditions potentiometric maps in Section 3.4. Contours of non-pumping data would not be substantively different from the pumping-conditions potentiometric surfaces. Therefore, non-pumping potentiometric surfaces were not prepared for FZ-01 to FZ-05.

Groundwater in FZ-01 to FZ-05 is likely contained by the pumping in FZ-06 to FZ-11. This was predicted in the modeling analysis submitted to the Agencies in March 2001 (SSP&A, 2001). Although the previous model did not simulate a discrete system of flow zones, the model did capture the fundamental elements of the water balance and the hydrologic boundary conditions, the most critical factors to a simulation. The strong vertical flow predicted in the shallow bedrock is a reasonable interpretation.

### 3.5.2 FZ-06

The potentiometric surface contours for FZ-06 17 days after shutdown are presented in Figure 3-34. As described in the introduction to Section 3.5, FZ-06 and FZ-07 did not recover to expected levels. This is likely related to insufficient time for total recovery to occur, or to the utilities and vertical shafts that cut into bedrock and that may be draining FZ-06.

Based on the potentiometric contours and the dry area presented on Figure 3-34, it appears that the railroad cut intercepting FZ-06, and possibly the vertical shafts on Lafayette Street and along the Gorge, are responsible for maintaining this portion of FZ-06 in a dry condition.

Under non-pumping conditions, groundwater migrating from the Landfill in FZ-06 would either:

- be intercepted by these utilities and discharge to the tunnel that runs along the Gorge and is collected and treated at the Niagara Falls POTW, or
- migrate vertically into FZ-07 through vertical fractures or long open-interval wells.

### 3.5.3 FZ-07

Figure 3-35 presents the potentiometric surface contours for FZ-07 17 days after shutdown of the bedrock purge wells. The surface is very similar to the FZ-06 potentiometric surface but 10 to 20 feet lower than FZ-06 between the Landfill and the Gorge. As discussed for FZ-06, the groundwater levels are either not fully recovered, or are greatly influenced by the sewer network. Although none of the sewers, trenches or the railroad cut across FZ-07, the vertical shafts connecting sewers with the tunnels cross the entire thickness of the Lockport. The vertical shafts on Lafayette Street and along the Gorge appear to be draining FZ-07.

Under non-pumping conditions, groundwater migrating from the Landfill in FZ-07 would either:

- be intercepted by these utilities and discharge to the tunnel that runs along the Gorge and is collected and treated at the Niagara Falls POTW, or
- discharge to the Gorge.

### 3.5.4 FZ-09

Figure 3-36 presents the potentiometric surface contours for FZ-09 17 days after shutdown of the bedrock purge wells. This surface is simple and requires no sewers, tunnels, or long open intervals to explain. The primary reason for the simplicity of the FZ-09 potentiometric surface is that FZ-09 is highly transmissive over a large area. Long open-interval wells that intercept FZ-09 have a relatively small influence on the FZ-09 water level. This was demonstrated when a packer was installed in PW-1L. Water levels in FZ-09 changed by 3 feet (small compared to the 10-foot contour interval), but changed by 20 feet in FZ-11.

The potentiometric surface shows a relatively shallow gradient from behind (east of) the Landfill, to approximately halfway between the Landfill and the Gorge. This shallow gradient reflects a zone of relatively high transmissivity. Approximately halfway between the Landfill and the Gorge the gradient increases by a factor of 30 to 50. This significant increase in gradient is the result of a significant decrease in transmissivity of FZ-09. This observation is important to the modeling and is reflected in the transmissivity zonation presented on Figure 3-21.

As described previously, it appears that groundwater enters FZ-09 from the NYPA Forebay and conduits. The non-pumping conditions support the conclusion. First, the water level in the area north and east of the Landfill match the average Forebay level on January 23, approximately 557 ft MSL. The water levels did not recovery higher than the Forebay level, suggesting a strong connection (consistent with the high transmissivity zone north of the Landfill). Finally, the high transmissivity area between the Landfill and the Gorge, indicated by a high recovery following shutdown, recovered to approximately the level of the Forebay. The westerly flow under non-pumping conditions suggests that some water from the Forebay and the conduits leaks into the aquifer and flows toward the natural discharge area at the Gorge.

Under non-pumping conditions, groundwater migrating from the Landfill in FZ-09 would discharge to the Gorge.

### 3.5.5 FZ-11

Figure 3-37 presents the potentiometric surface contours for FZ-11 17 days after shutdown of the bedrock purge wells. With the possible exception of B2L-11 and D1L-11, it appears that water levels had not fully recovered by this time. The contours show three areas of nearly flat gradient. These areas correspond to the high transmissivity areas described in Section 3.2.6.2.

Under non-pumping conditions, groundwater migrating from the Landfill in FZ-11 would discharge to the Gorge.

## 3.6 HYDRAULIC TESTING AT PW-2M

PW-2M intersects four flow zones: FZ-06, FZ-07, FZ-08, and FZ-09. This well is the most productive bedrock well at the Site with a yield greater than 40 gpm. This well has never been tested to identify the flow zones that contribute most of the supply to the well. The Workplan called for:

- Removing the pump from PW-2M;
- Running slug tests using a double-packer system with a packer spacing of approximately 4 feet. The packers would be raised 3 feet between slug tests. The objective was to identify the transmissive flow zones in the well; and
- Running an 8-hour pumping test in the three most transmissive flow zones.

The pump was removed on January 7, and slug testing began on January 8. Not all of the planned testing could be conducted in the well. Groundwater levels had recovered less than expected and FZ-06 was dry. PW-2M was slug tested on January 8 and 9, from the bottom of the well up to an elevation where the well was filled with water; this section of the well included FZ-07, FZ-08, and FZ-09. After the slug testing was completed, the packers were set between 539 and 544 ft MSL to isolate FZ-06. The packers remained inflated between January 9 and 13. During this period the water level did not recover up to FZ-6.

The slug testing indicated that FZ-09 was the only interval tested that was sufficiently transmissive to run a pumping test. On January 13, the packers were set to pump from FZ-09. An 8-hour test was run at 10 gpm. The effect of pumping was observed in FZ-09 at five piezometers (D1M-09, D2M-09, F2M-09, F4M-09, and PMW-1M-09).

On January 14, the packer system was removed and the high capacity pump originally in PW-2M was installed. The pump was started and run for approximately 24 hours at 30 gpm. The response to this pumping is clearly evident as a decline in the water level in FZ-09 piezometers mentioned previously, as well as the piezometers at C3-07, G1M-07, and D1L-11. PW-2M was shutdown on January 15, and not restarted until January 24. The well was shutdown over this period to allow for a more complete observation of recovery to the full system shutdown.

The PW-2M pumping data have been reviewed but not analyzed to estimate hydraulic properties. The objective of the testing was to identify the areas of response to pumping at PW-2M, and the magnitude of that response. The results of the hydraulic testing at PW-2M demonstrate that FZ-09 is the dominant flow zone at the well.

### 3.7 HYDRAULIC TESTING AT PW-1L

Water levels in B2M-09 and B2L-11 were observed to track each other closely during the shutdown. This response suggested that there was an external mechanism coupling the two piezometers. Pumping well PW-1L is located about 500 ft from the B2 piezometers, and is open across both FZ-9 and FZ-11. To test the possibility that PW-1L is acting as a conduit, the two flow zones were isolated in PW-1L. This was accomplished on January 21 by removing the pump from the well and inflating a packer just above FZ-10. The results of the installation of a packer in PW-1L are shown in Figure 3-38. A brief summary of the results of the installation of the packer is presented here. The testing is described in detail in a technical note in Appendix A.

As shown in Figure 3-38, prior to the installation of the packer, the recovered water levels in B2M-09 and B2L-11 were 552 ft and 545 ft MSL, respectively. Immediately following the inflation of the packer in PW-1L, the water levels in the two piezometers began diverging.

Within one day, the water levels in B2M-09 and B2L-11 equilibrated to new levels of 554 ft and 531 ft, respectively, a difference of 23 feet. The response to installing a packer in PW-1L was very significant.

After the packer was installed in PW-1L, slug tests were conducted above and below the packer. The transmissivity estimated for the interval below the packer (FZ-11) was 500 $ft^2$/day. This transmissivity can be attributed primarily to FZ-11. The transmissivity estimated for the interval above the packer, primarily due to FZ-9, was 2300 $ft^2$/day, in excess of four times the transmissivity of FZ-11.

A quantitative analysis of the data collected during the PW-1L packer is also presented in the technical note in Appendix A. The Sokol (1963) analysis of water level averaging across multiple flow zones was applied to match the observed composite water level in FZ-09/11 prior to installation of the packer. Using the observed water levels in the isolated flow zones and the estimated transmissivity contrast, a composite water level of 551 ft MSL was predicted. This matched closely the water levels in B2M-09 and B2L-11 prior to the installation of the packer in PW-1L.

The data collected following the installation of a packer at PW-1L provide proof that PW-1L acts as a conduit between FZ-9 and FZ-11.

## 4.0 CONCLUSIONS AND RECOMMENDATIONS

The data collected during the SCR-H studies have demonstrated that the conceptual hydrogeologic framework presented in the SCR-G is a reasonable description of the system. That framework presented in the SCR-G was highly idealized to provide a tractable model that could be monitored and evaluated. The SCR-H data provide a basis for refining that framework. The spatial distributions of hydraulic properties within the bedrock are better understood. Groundwater-level data from the flow-zone piezometers have provided a better understanding of where and how groundwater is flowing. The SCR-H results are a major step in understanding groundwater at the Hyde Park Site.

The findings of the SCR-H lead to the following conclusions:

- Demonstrate large areas of hydraulic containment in flow zones FZ-06, FZ-07, FZ-09, and FZ-11. It likely that the containment within FZ-08 is some average of FZ-07 and FZ-09);
- Demonstrate that Bedrock NAPL Plume Containment System purge wells in FZ-01 to FZ-05 are generally low yielding and have limited cones of depression.
- Suggest that there is a significant vertical component of groundwater flow in FZ-01 to FZ-06;
- Demonstrate that the use of piezometer pairs is impractical for monitoring the performance of the Bedrock NAPL Plume Containment System.
- Provide direction for planning water quality monitoring in FZ-01 to FZ-05 to assess the horizontal versus vertical migration of Site parameters;
- Demonstrates that under non-pumping conditions, water from the NYPA Forebay and conduits is entering FZ-07 and FZ-09, and flow westerly toward the Gorge;
- Demonstrates that the primary source of supply for PW-2M is derived from FZ-09. PW-2M is the primary bedrock purge well at the Site; and
- Demonstrates that PW-1L acts as a conduit between FZ-9 and FZ-11, causing water levels in the two flow zones to equilibrate in the vicinity of the well.

The findings of the SCR-H have also led to several important Action Items:

- Remaining long open-interval wells should be abandoned by filling the open interval with a low-permeability grout or bentonite.
- Groundwater quality samples should be collected from selected piezometers to assess the horizontal versus vertical migration of Landfill-related parameters.
- FZ-06 in purge well PW-10U should be sealed to prevent the transfer of groundwater from FZ-05 into FZ-06.

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