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GZA
GeoEnvironmental, Inc.

Engineers and Scientists

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Mr. Robert Evers
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Subject: Hydrogeologic Site Investigation Report
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Dear Mr. Evers:

GZA GeoEnvironmental, Inc. (GZA) is pleased to provide the attached Hydrogeologic Site Investigation Report for the Indian Point Energy Center. The report provides a summary of the investigative methods, findings/conclusions and recommendations for work conducted from September 2005 through the end of September 2007.

If you have any questions, please contact either David or Matt.

GZA appreciates the opportunity to provide continued support to Enercon Services and Entergy.

Sincerely,

GZA GEOENVIRONMENTAL, INC.

David M. Winslow /MGA

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APPENDICES

ACRONYMS

ADT	Aquifer Drilling and Testing
AGS	Advanced Geological Services
ALARA	As Low As Reasonably Achievable
AREOR	Annual Radiological Environmental Operating Report
ATV	Acoustical Televiewer
CSS	Containment Spray Sump
CSB	Chemical Systems Building
CSM	Conceptual Site Model
EPA	Environmental Protection Agency
EVS	Environmental Visualization Software
GA	Geophysical Applications, Inc.
GPR	Ground Penetrating Radar
GZA	GZA GeoEnvironmental, Inc.
IP	Indian Point
IP1-CSB	Indian Point Unit 1 Chemical Systems Building
IP1-FHB	Indian Point Unit 1 Fuel Handling Building
IP1-SFDS	Indian Point Unit 1 Sphere Foundation Drain Sump
IP1-SFPS	Indian Point Unit 1 Spent Fuel Pool
IP1-CB	Indian Point Unit 1 Containment Building
IP2-FSB	Indian Point Unit 2 Fuel Storage Building
IP2-PAB	Indian Point Unit 2 Primary Auxiliary Building
IP2-SFP	Indian Point Unit 2 Spent Fuel PoolS
IP2-TB	Indian Point Unit 2 Turbine Generator Building
IP2-TY	Indian Point Unit 2 Transformer Yard
IP2-VC	Indian Point Unit 2 Vapor Containment
K	Hydraulic Conductivity
NGVD 29	National Geodetic Vertical Datum of 1929
NYSDEC	New York State Department of Environmental Conservation
MGM	Million Gallons per Minute
MNA	Monitored Natural Attenuation
MW	Monitoring Well
NEI	Nuclear Energy Institute
NCD	North Curtain Drain
NRC	Nuclear Regulatory Commission
OCA	Owner Controlled Area
OTV	Optical Televiewer
RWST	Reactor Water Storage Tank
RQD	Rock Quality Designation
SFDS	Sphere Foundation Drain Sump
SFP	Spent Fuel Pool
SOP	Standard Operating Procedure
SSC	Structures, Systems and Components
TGB	Turbine Generator Building
TY	Transformer Yard
USGS	United States Geological Survey
VC	Vapor Containment

EXECUTIVE SUMMARY

This report presents the results of a two-year comprehensive hydrogeologic site investigation of the Indian Point Energy Center (Site) conducted by GZA GeoEnvironmental, Inc. (GZA). The study was initiated in response to an apparent release of Tritium to the subsurface, initially discovered in August of 2005 during Unit 2 construction activities associated with the Independent Spent Fuel Storage Installation Project. These investigations were subsequently expanded to include areas of the Site where credible potential sources of leakage might exist, and encompassed all three reactor units. Ultimately, these investigations traced the contamination back to two separate structures, the Unit 2 and Unit 1 Spent Fuel Pools (SFPs). The two commingled plumes, resulting from these SFPs releases, have been fully characterized and their extent, activity and impact determined. The two primary radionuclide contaminants of interest were found to be Tritium and Strontium. Other contaminants, Cesium, Cobalt, and Nickel, have been found in a subset of the groundwater samples, but always in conjunction with Tritium or Strontium. Therefore, while the focus of the investigation was on Tritium and Strontium, it inherently addresses the full extent of groundwater radionuclide contamination. The investigations have further shown that the contaminated groundwater can not migrate off-property to the North, East or South. The plumes ultimately discharge to the Hudson River to the West.

Throughout the two years of the investigation, the groundwater mass flux and radiological release to the Hudson River have been assessed. These assessments, along with the resulting Conceptual Site Model, have been used by Entergy to assess dose impact. At no time have analyses of existing Site conditions yielded any indication of potential adverse environmental or health risk. In fact, radiological assessments have consistently shown that the releases to the environment are a small percentage of regulatory limits.

SOURCES OF CONTAMINATION

As stated above, the investigations found that the groundwater contamination is the result of releases from the Unit 2 and the Unit 1 SFPs. Our studies found no evidence of any release from Unit 3.

The predominant radionuclide found in the plume from the Unit 2 SFP pool is Tritium. The releases were due to: 1) historic damage in 1990 to the SFP liner, with subsequent discovery and repair in 1992; and 2) a weld imperfection in the stainless steel Transfer Canal liner identified by Entergy in September 2007, and repaired in December 2007. To the extent possible, the Unit 2 pool liner has been fully tested and repairs have been completed. The identified leakage has therefore been eliminated and/or controlled by Entergy. Specifically, Entergy has: 1) confirmed that the damage to the liner associated with the 1992 release was repaired by the prior owner and is no longer leaking; 2) installed a containment system (collection box) at the site of the leakage discovered in 2005, which precludes further release to the groundwater; and 3) after an exhaustive liner inspection, identified a weld imperfection in the Transfer Canal liner that was then prevented from leaking by draining the canal. The weld was then subsequently repaired by Entergy in mid-December 2007. Therefore, all identified Unit 2 SFP leaks have been addressed. Water likely remains between the Unit 2 SFP stainless steel liner and the concrete walls, and thus additional active leaks can not be completely ruled out. However, if they exist at all, the data indicate they must be small and of little impact to the groundwater.

The Unit 1 plume is characterized by Strontium from legacy leakage of the Unit 1 fuel pools. At present, the Unit 1 pools have been drained with the exception of the Unit 1 West Fuel Pool which still contains spent fuel. This West Pool leaks water under the fuel building and is responsible for the Unit 1 Strontium groundwater plume discovered in 2006. Prior to that time, the previous owner had identified leakage from the West Fuel Pool in the 1990's and was managing the leakage by collecting it from a re-configured footing drain that surrounded the fuel building. However, based on the groundwater investigation, it has been determined that the pool leakage management program was not successful in collecting all of the leakage. As a result, uncollected contaminants released from the Unit 1 Spent Fuel Pools, past and present, have been observed during the groundwater investigation effort at various locations near the site of Unit 1. In response to the finding that the leak collection system was not functioning as believed, Entergy promptly initiated a program to reduce the concentration of radionuclides in the Unit 1 West Pool's water, beginning in April 2006, via enhanced demineralization water treatment. The planned fuel removal and pool draining will completely eliminate this release source by year end 2008.

EXTENT OF CONTAMINATION

The groundwater contamination is, and will remain, limited to the Indian Point Energy Center property, because the migration of Site contaminants is controlled by groundwater flow, which, in turn, is governed by the post-construction hydrogeologic setting. Plant construction required reduction in bedrock surface elevations and installation of foundation drains. These man-made features have lowered the groundwater elevations beneath the facility, redirecting groundwater to flow to the West towards the Hudson River; and not to the North, East or South. Because of the nature and age of the releases, groundwater contaminant migration rates, and interdictions by Entergy to eliminate/control releases, the groundwater contaminant plumes have reached their maximum spatial extent and should now decrease over time.

LONG TERM MONITORING

Long term groundwater monitoring is ongoing; a network of multi-level groundwater monitoring installations has been established at the facility. These "wells" are located downgradient of, and in close proximity to, both existing and potential release locations. Groundwater testing is performed quarterly on the majority of these wells, with the rest remaining on standby to provide added detail, if required. The resulting information is provided on a yearly basis to the Nuclear Regulatory Commission

(NRC). The information is used to assess changes in groundwater relative to dose impact assessment and to detect future releases, should they occur.

In addition to the groundwater samples from the network of monitoring wells, Entergy obtained various off-Site samples of environmental media including off-Site wells, reservoirs and the Hudson River. In addition, Entergy participated in a fish sampling program with the NRC and New York State Department of Environmental Conservation (NYSDEC). None of the samples analyzed, including the samples split with regulatory agencies, detected any radioactivity in excess of environmental background levels.

GZA believes that the recommended remediation technology discussed below will cause the concentrations of radionuclides in the groundwater plumes to decrease over time. The continued monitoring of groundwater is expected to demonstrate that trend and support the conclusion that the identified leaks have been terminated. However, GZA expects that contaminant concentrations will fluctuate over time due to natural variations in groundwater recharge and that a potential future short term increase in concentrations does not, in and of itself, indicate a new leak. It is further emphasized that the groundwater releases to the river are only a small percentage of the regulatory limits, which are of no threat to public health.

PROPOSED REMEDIATION

GZA has recommended the following corrective measures to Entergy, which they are implementing:

1. Repair the identified Unit 2 Transfer Canal liner weld imperfection (completed December 2007).
2. Continue source term reduction in the Unit 1 West Pool via the installed demineralization system (ongoing until completion of No. 3 below).
3. Remove the remaining Unit 1 fuel and drain the West Pool (in-process).
4. Implement long term groundwater monitoring (in-process).

The proposed remediation technology is source elimination/control (Nos. 1 and 3 above) with subsequent Monitored Natural Attenuation, or MNA. MNA is a recognized and proven remedial approach that allows natural processes to reduce contaminant concentrations. The associated monitoring is intended to verify that reductions are occurring in an anticipated manner. The Indian Point Energy Center Site is well suited for this approach because: 1) interdictions to eliminate or reduce releases have been made; 2) the nature and extent of contamination is known; 3) the contaminant plumes have reached their maximum extent; and 4) the single receptor of the contamination, the Hudson River, is monitored, with radiological assessments consistently demonstrating that the releases to the environment are a small percentage of regulatory limits, and no threat to public health or safety.

1.0 INTRODUCTION

This report presents the results of hydrogeological studies performed by GZA GeoEnvironmental, Inc. (GZA) at the Indian Point Energy Center (IPEC) in Buchanan, New York (Site). See **Figure 1.1**[1] for a Locus Plan. The report was prepared by GZA under the terms of an agreement with Enercon Services, Inc. for Entergy Nuclear Northeast, and describes services completed between September 2005 (the beginning of our services) and September 2007.

Our investigations were conducted in a cooperative and open manner. Entergy provided full and open access and there were regular and frequent meetings with representatives of the United States Nuclear Regulatory Commission (NRC), the United States Geological Survey (USGS), and the New York State Department of Environmental Conservation (NYSDEC). Further, we presented our preliminary findings at a number of external stakeholder and public meetings.

From the onset of the investigations, GZA routinely computed the groundwater mass flux[2] and associated radiological release to the Hudson River. Using these data, the potential impacts of releases to the river were assessed by Entergy and compared to existing regulatory thresholds. At no time did these analyses yield any indication of potential adverse environmental or health risk as assessed by Entergy as well as the principal regulatory authorities. In fact, radiological assessments have consistently shown that the releases to the environment are a small percentage of regulatory limits, and no threat to public health or safety. In this regard, it is also important to note that the groundwater is not used as a source of drinking water on or near the Site.

This report documents two years of comprehensive hydrogeological investigations. The text of the report describes Site conditions, GZA's investigations, and findings, and presents conclusions and recommendations. Supporting information is provided in tables, on figures and in appendices. To understand how we formed our opinions, it is important to review the report in its entirety, including **Appendix A** Limitations.

1.1 PURPOSE

The overall purpose of our services was to identify the nature and extent of radiological groundwater contamination that originates at IPEC, and assess the hydrogeological implications of that contamination. More specifically, our objectives were to:

- Identify the nature and extent of radiological groundwater contamination;
- Establish the sources of the radiological groundwater contamination;

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[1] Figures referenced by specific number are contained as full size drawings in Volume 3 of this report. Additional smaller scale figures, photographs, etc. are embedded within the text for immediate reference.
[2] Flux (or mass flux) is defined as the amount of groundwater that flows through a unit subsurface area per unit time.

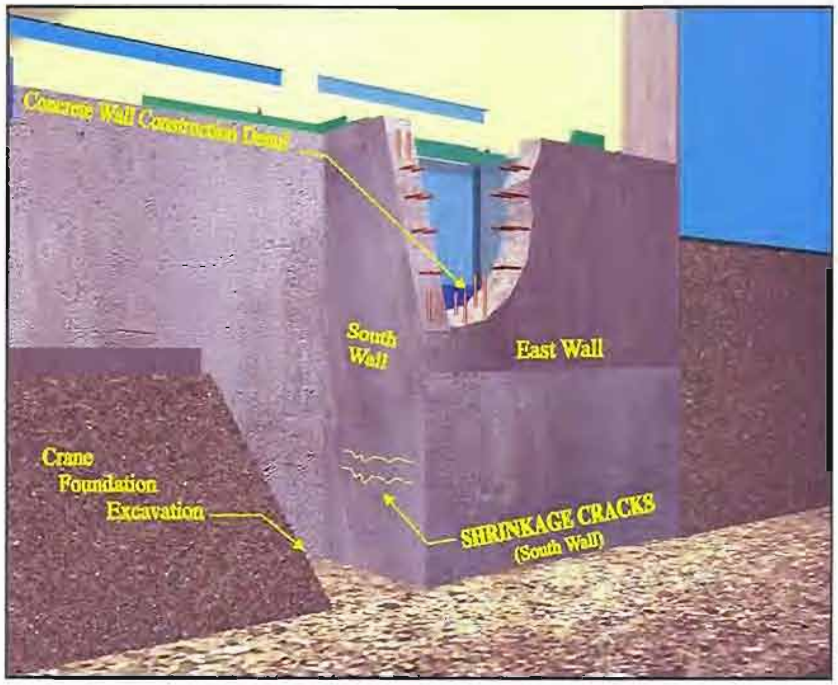
- Evaluate the mechanisms controlling the groundwater transport of radiological contamination;
- Estimate both the mass of groundwater transporting contaminants, and the radiological activity associated with these contaminant pathways;
- Develop a groundwater monitoring network that addresses IPEC's short term and long term needs, and is consistent with the Nuclear Energy Institute's (NEI's) Groundwater Protection Initiative; and
- Recommend, as required, appropriate remedial measures.

1.2 BACKGROUND

In August 2005, Entergy was excavating in the Unit 2 Fuel Storage Building (IP2-FSB) Loading Bay, adjacent to the South wall of the Spent Fuel Pool (IP2-SFP), in preparation for installation of gantry crane foundations required for the Independent Spent Fuel Storage Installation Project (see **Figure 1.2** and the following illustration).

IPEC LOOKING EAST FROM ABOVE THE HUDSON RIVER

While removing existing backfill material from along the South wall of the SFP, two shrinkage cracks in the concrete pool wall (about 1/64" wide) were observed (refer to **Section 8.1** for additional information). The concrete wall in the area of these cracks appeared damp.



UNIT 2 SFP SHRINKAGE CRACKS IDENTIFIED IN SEPTEMBER 2005

Initially, a temporary, plastic membrane collection device was installed to facilitate water retention and sampling as there was no visibly free-flowing liquid. Analyses of the collected moisture indicated that it had the radiological and chemical characteristics of IP2-SFP water. The primary radioactive constituent was Tritium. This finding initiated work to terminate the known release from these shrinkage cracks. Permanent containment of the release, and prevention of any further migration into the subsurface, was accomplished by installing a waterproof physical containment ("collection box") over the two shrinkage cracks prior to backfilling the gantry crane foundations and SFP wall. This containment was then piped to a permanent collection point such that any future leakage from the crack could be monitored[3]. In addition, Entergy also began extensive investigations of the stainless steel liner in the Unit 2 Fuel Pool itself, as well as the integral Transfer Canal. Subsurface investigations were also started to evaluate if the groundwater had become contaminated from the release.

[3] Subsequent monitoring has indicated that the leakage from the crack, which had only been typically as high as 1.5 L/day (peak of about 2 L/day) from its discovery through the fall of 2005, has since fallen off dramatically. (L=liters).

As part of these early investigations, Entergy sampled groundwater on September 29, 2005 from a nearby existing downgradient monitoring well, MW-111. This monitoring well is located between the IP2-SFP and the downgradient Hudson River to the West (see **Figure 1.3** for well location). The analysis results, reported on October 5, 2005, indicated an elevated Tritium concentration. The elevated Tritium in MW-111 was consistent with a release from the shrinkage cracks that had migrated into the on-Site groundwater. Entergy therefore began an extensive investigation to understand the extent of the Unit 2 groundwater contamination and potential impacts to the environment.

Although the early subsurface investigations were focused primarily on potential sources of contamination, the project team also reviewed: regional hydrogeological information, plant design/construction details, and available Site-specific groundwater monitoring results. This early work led to three conclusions:

- The recently identified shrinkage cracks had resulted in releases of Tritium to the groundwater;
- It was unlikely that contaminated groundwater was migrating off-property to the North, East or South; and
- Tritium-contaminated groundwater likely had, and would continue to, migrate to the Hudson River to the West.

In response to these three early conclusions, Entergy tasked GZA with developing a network of groundwater monitoring wells. The primary objectives for this network were to facilitate comprehensive investigation of the IP2-SFP Tritium release location, as well as evaluate the potential for releases at other locations across the Site. Additional objectives included:

- Monitoring of the southern boundary of the Site (previously identified by others as downgradient);
- Monitoring attenuation of the contaminant plume(s) identified on-Site;
- Early detection of leaks in areas of ongoing active operations, should they occur in the future; and
- Monitoring of the groundwater adjacent to the Hudson River to provide the required groundwater data for Entergy's radiological impact evaluations.

The groundwater monitoring network ultimately developed by GZA, and supported by Entergy, was comprised of shallow and deep installations at 59 monitoring locations. These installations were completed in both soil overburden and bedrock. The installations generally include multi-level instrumentation which allows acquisition of depth-discrete groundwater samples and automatic recording of depth-specific groundwater elevations via electronic pressure transducers. The wells were drilled in a phased manner, with resulting data being used to modify and guide the work of subsequent investigations. This iterative progression is in accordance with the Observational Method[4] approach (see **Section 2.0**).

During the course of the expanded investigations in 2006, Strontium-90 was detected in, and downgradient of, the western portion of the Unit 2 Transformer Yard (IP2-TY). While the transformer yard is located immediately downgradient of the Unit 2 Spent Fuel Pool (IP2-SFP), the source of this Strontium in the groundwater could not reasonably be associated with a release from the IP2-SFP. This conclusion was particularly appropriate when evaluated in light of the sampling data from the upgradient transformer yard wells and ultimately from wells directly adjacent to the SFP itself. The ongoing subsurface investigation program was therefore further expanded to encompass not only the IP2-SFP source area, but also other potential sources across the entire Site, including Units 1 and 3. These subsequent phases of investigation ultimately established the retired Unit 1 plant as the source of the Strontium contamination identified[5] in the groundwater. More specifically, the Unit 1 fuel storage pool complex, where historic legacy pool leakage was known to exist, was confirmed as the Strontium source. This fuel pool complex is collectively termed the Unit 1 Spent Fuel Pools (IP1-SFPs). Following detection of radionuclides in the groundwater associated with IP1-SFPs, Entergy accelerated efforts to reduce activity in the IP1-SFPs, along with acceleration of the already ongoing planning for the subsequent fuel rod removal and complete pool drainage.

As indicated above, later phases of the investigations encompassed the entire Site, including all three Units (IP1, IP2 and IP3). These investigations found no evidence of releases to the groundwater from the IPEC Unit 3 plant complex. In this regard, it is important to note that the design and construction of the IP3-SFP incorporates a secondary leak detection telltale drain system, in addition to the primary stainless steel liner. The earlier Unit 1 and Unit 2 SFPs were not designed with this feature.

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[4] a. *Use of the Observational Method in the Investigation and Monitoring of a Spent Fuel Pool Release*. Barvenik. et. al., NEI Groundwater Workshop, Oct. 2007.

b. *Use of the Observational Method in the Remedial Investigation and Cleanup of Contaminated Land*. Dean, A.R. and M.J. Barvenik. The Seventh Geotechnique Symposium - Geotechnical Aspects of Contaminated Land, sponsored by the Institution of Civil Engineers, London. Volume XLII, Number 1, March 1992.

c. Advantages and Limitations of the Observational Method in Applied Soil Mechanics, Peck, R.B., Geotechnique 1969, No. 2, 171-187.

[5] In addition to Strontium, other radionuclides (Nickel, Cobalt and Cesium) were also sporadically detected in groundwater. These other radionuclides were continuously assessed within the context of the overall hydrologic model. Based upon their occurrence, Strontium, in combination with Tritium, provides full delineation of radiological groundwater plumes at the IPEC Site.

2.0 SCOPE OF SERVICES

This section outlines the scope of our two-plus year-long investigation. Consistent with well established hydrogeologic practices, GZA followed the Observational Method. That is, GZA developed a Conceptual Site Model (see **Section 3.0**) that described our understanding of groundwater flow and contaminant transport at IPEC, and performed investigations to test the validity of our model. In response to test data, we revised the model and/or performed additional testing to clarify findings. This iterative, step-wise phased approach allows for better focused testing, and a more comprehensive review of data. It also reduces the chances of missing critical information, and generally completes studies in less time. GZA executed the scope in three phases.

2.1 PHASE I

Phase I investigations commenced in September 2005. Consistent with the concerns raised by the observed IP2-SFP crack leakage, the Phase I investigation program focused on: 1) Identifying the groundwater flow paths which would intercept potential releases from IP2-SFP; and 2) Evaluating groundwater contaminant fate and transport mechanisms in this area of the facility. This work included:

- Identification, retrieval and evaluation of historic geologic, hydrogeologic and geotechnical reports to form the basis of our initial Conceptual Site Model (CSM);
- Development of an initial CSM;
- Identification, retrieval and evaluation of historic facility Site plans and construction details pursuant to the impact of man-made features on groundwater flow directions and Tritium migration, with subsequent refinement of the CSM;
- Installation of nine groundwater monitoring wells, a number of which contained multiple sampling levels, in the area of the Tritium release;
- Installation of four stilling wells[6], three within the Discharge Canal and one in the Hudson River, to allow groundwater elevations to be compared to these surface water elevations (to evaluate if the Hudson River is the ultimate discharge point for any potential IP2-SFP release);
- Performance of elevation and location surveys to establish reference points for groundwater elevation measurement;
- Installation of electronic pressure transducers in newly drilled boreholes and previously existing wells to continuously monitor groundwater elevation fluctuations, as influenced by climatic/seasonal variability, tidal influences and the drilling of nearby boreholes (to assess interconnections between boreholes at different locations);
- Geophysical borehole testing to provide further bedrock fracture identification, location and groundwater flow information;

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[6] Stilling wells are typically constructed of slotted pipe or well screen. They are placed in surface water bodies to house pressure transducers for water level measurement. Their purpose is to dampen-out high frequency pressure fluctuations in the water body, typically due to flow-induced turbulence, such that more representative readings can be obtained. Stilling wells are not included as monitoring wells with reference to numbers of monitoring wells installed.

- Packer testing of specific bedrock boreholes to provide initial depth-specific groundwater samples, measurement of depth-specific groundwater elevations and flow capacity of the fracture zones;
- Completion of the boreholes as screened overburden wells, open bedrock wells, or multi-level monitoring wells as appropriate for the subsurface conditions encountered;
- Testing of open bedrock and screened boreholes to measure formation groundwater flow capacity;
- Ground Penetrating Radar (GPR) analysis of the key locations to evaluate top of bedrock elevations relative to preferential groundwater flow through soil backfill;
- Sampling of groundwater from the monitoring wells and analyzing the samples for Tritium and gamma emitters; and
- Computation of the groundwater flux and radiological activity to the Hudson River for use by Entergy in their dose computations.

2.2 PHASE II

Phase II investigations commenced in January 2006. The focus of this work was to: 1) Confirm initial findings; 2) Better estimate the quantity of contaminated groundwater at the facility that discharges to the Hudson River; and 3) Establish a network of wells suitable for identifying potential leaks at all three units across the Site and for long term monitoring of groundwater. This phase of work included:

- Re-evaluation of our CSM to guide the selection of borehole locations and establish testing requirements;
- Identification of accessible areas from which to drill boreholes to measure groundwater elevations and the contaminant concentrations;
- Drilling of 23 additional boreholes through soil and bedrock to depths of up to 200 feet, including coring to provide bedrock core samples for inspection (to locate fractures in the bedrock which likely conduct groundwater flow);
- Performance of elevation and location surveys to establish reference points for groundwater elevation measurement;
- Installation of electronic pressure transducers in newly drilled boreholes to continuously monitor groundwater elevation fluctuations, as influenced by climatic/seasonal variability, tidal influences and the drilling of nearby boreholes (to assess interconnections between boreholes at different locations);
- Geophysical borehole testing to provide further bedrock fracture identification, location and groundwater flow information;
- Packer testing of specific bedrock boreholes to provide depth-specific groundwater samples, measurement of depth-specific groundwater elevations and flow capacity of the fracture zones;
- Completion of the boreholes as screened overburden wells, open bedrock wells, or multi-level monitoring wells as appropriate for the subsurface conditions encountered;
- Conducting tests on open bedrock and screened boreholes to measure formation groundwater flow capacity;
- Ground Penetrating Radar (GPR) analysis of the key locations to evaluate top of bedrock elevations relative to preferential groundwater flow through soil backfill;

- Sampling of groundwater from the monitoring wells and analyzing the samples for Tritium and additional radionuclides of interest (including Strontium, gamma emitters, Nickel-63 and transuranics); and
- Re-computing the groundwater flux and radiological activity to the Hudson River (based on the more current data and refined CSM) for use by Entergy in their dose computations.

2.3 PHASE III

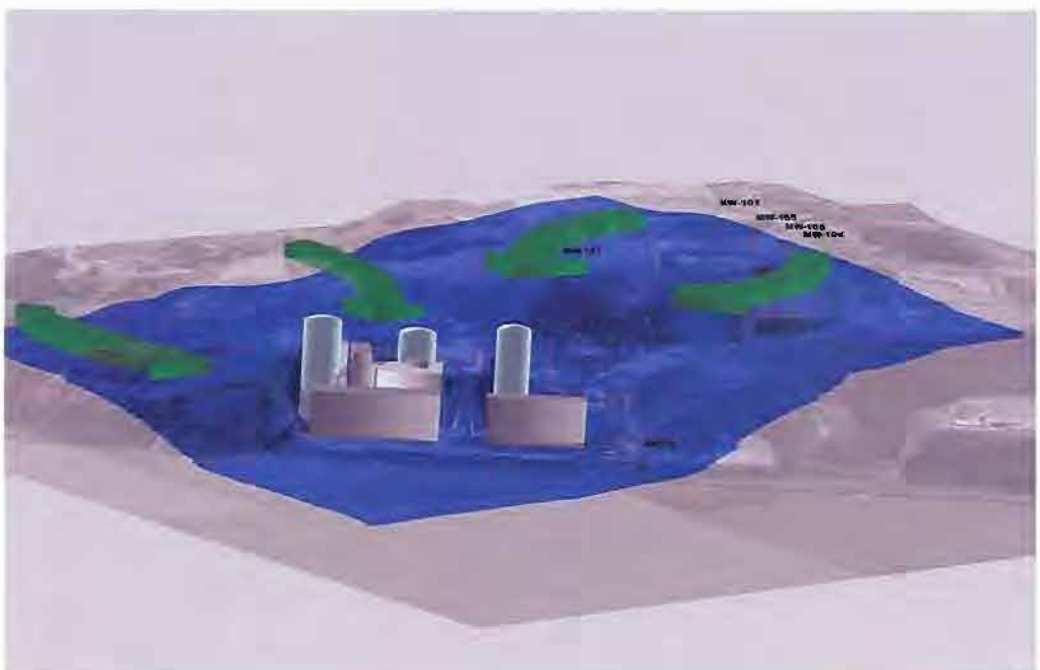
Phase III investigations commenced in June 2006. The focus of the Phase III work was to:
1) Better delineate the extent of Strontium detected during Phase II investigations; and
2) Improve characterization of bedrock aquifer properties to allow evaluation of remedial alternatives. This phase of work included:

- Re-evaluation of our CSM to guide the selection of borehole locations and establish testing requirements;
- Installation of additional wells (MW-53 through MW-67 and U1-CSS) to further delineate the horizontal extent of groundwater contamination (this work was begun in Phase II);
- Installation of deep wells (MW-54, -60, -61, -62, -63, -66, and -67) to establish the vertical extent of contamination;
- Conducting hydraulic tests on boreholes and completed wells to assess the transmissivity of bedrock fracture zones and overburden;
- Installation of electronic pressure transducers in newly drilled boreholes and existing wells to continuously monitor groundwater elevation fluctuations due to climatic/seasonal variability, tidal influences and the drilling of nearby boreholes (to assess interconnections between boreholes at different locations);
- Geophysical borehole testing to provide further bedrock fracture identification, location and groundwater flow information;
- Packer testing of specific bedrock boreholes to provide depth-specific groundwater samples, measurement of depth-specific groundwater elevations and flow capacity of the fracture zones;
- Completion of the boreholes as screened overburden wells, open bedrock wells, or multi-level monitoring wells as appropriate for the subsurface conditions encountered;
- Conducting a 72-hour Pumping Test to assess hydraulic properties of the bedrock as well as to assess the feasibility of managing Tritium-contaminated groundwater through hydraulic containment;
- Performance of a tracer test to better assess contaminant migration and transport mechanisms, particularly in the unsaturated zone;
- Sampling of groundwater from the monitoring wells and analyzing the samples for radionuclides; and
- Re-computing the groundwater flux and radiological activity to the Hudson River (based on the more current data and refined CSM) for use by Entergy in their dose computations.

3.0 CONCEPTUAL HYDROGEOLOGIC MODEL

This section, together with associated figures, constitutes our Conceptual Site Model (CSM). The key components of the model consisted of: the hydrogeologic setting; general groundwater flow patterns; identified contaminant sources; contaminants of potential concern; and identified receptors. GZA used the CSM to guide our investigations, identify and fill data gaps, assess the reasonableness of findings, and develop parameters controlling contaminant transport. It was an iterative process and, as studies progressed, we modified the CSM to better fit observed conditions. With completion of the investigations and further refinement of the CSM, our CSM was consistent with both the Site-specific project data and published data for the area.

The CSM incorporates our understanding of Site construction practices as they influence contaminant migration. Critical in this regard is that, according to construction plans, lean concrete was used as backfill material for foundation walls in a number of locations, primarily associated with Unit 1 structures. We also note that in some areas where construction plans show soil backfill, we found that lean concrete was actually used. This is likely due to the relatively low cost of concrete during the 1950's and the uniqueness of the construction for these first nuclear power plants. At the subsequently constructed Units 2 and 3, it appears soil or blast rock was the material most commonly used as backfill against foundation walls.



SCHEMATIC REPRESENTATION OF GROUNDWATER FLOW INTO THE SITE FROM THE NORTH, SOUTH, AND EAST

3.1 HYDROGEOLOGIC SETTING

The Site watershed is limited in areal extent. GZA assumed that the top of the watershed defines a no-flow boundary in the aquifer. The distance from the upgradient no-flow boundary located at the top of the watershed, to the river, is on the order of 2,200 feet (see **Figure 3.1**). This length limits the volume of precipitation available for aquifer recharge. Recharge is further limited by the density of structures and areal extent of paving, which induces direct run-off. An average annual recharge rate of 5.5 inches per year was initially selected[7] as representative for the Site area, which is the USGS estimated average in Westchester County where IPEC is located.

3.2 GENERAL GROUNDWATER FLOW PATTERNS

Groundwater flow takes place in three dimensions. In general, flow at the top of the watershed is largely downward and flow near the river's edge is largely upward. In the mid-section of the watershed, flows are predominantly horizontal. Based on the location of the Site in the watershed and information indicating that the top of the bedrock is more fractured, GZA initially estimated, and later confirmed that the bottom of the local groundwater flow to be at or above elevation -200 feet (National Geodetic Vertical Datum of 1929[8], NGVD 29)[9]. Note that temporal and spatial variations in areal recharge rates, rock heterogeneities, and tidal influences cause local variations from these general flow patterns. In fact, Site groundwater flow patterns in some areas are dominated by shallow anthropogenic Site features. These features include pumping from building foundation drains, foundation walls, subsurface utilities, and flows in the intake structures and Discharge Canal.

Based upon the regional topography, Site topography (see **Figure 3.2**), anthropogenic influences, and the geostructural setting, even at the initial stages of the investigations GZA expected that groundwater would flow into IPEC from the North, East and South, and then discharge to the Hudson River, with portions of the flow being intercepted by the cooling water intake and Discharge Canal (see **Figure 3.3**). However, based on our review of reports available at the start of the investigations, it was unclear what the role that anisotropic bedrock structure played in groundwater migration. That is, there was information suggesting groundwater flows would have a primarily southern component (see **Section 6.4** for a description of the regional area and Site-specific geologic setting).

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[7] As discussed in **Section 6.0**, the initial average areal recharge rate of 5.5 inches/year was subsequently increased somewhat as we refined our CSM.

[8] The National Geodetic Vertical Datum of 1929 (NGVD 29) is the renamed Sea Level Datum of 1929. The datum was renamed because it is a hybrid model, and *not a pure model of mean sea level*, the geoid, or any other equipotential surface. NGVD 29, which is based on "an averaging" of multiple points in the US and Canada, is the vertical "sea level" control datum established for vertical control surveying in the United States of America by the General Adjustment of 1929. The datum is used to measure elevation or altitude above, and depression or depth below, "mean sea level" (MSL). It is noted that there is no single MSL, because it varies from place to place and over time.

[9] During a mid-phase of the work, we concluded that the bottom of the local groundwater flow may be deeper, more likely between elevations -200 to -350 feet NGVD 29. This conjecture was based on the observed vertical distribution of heads, bedrock fracture patterns, and the observed contaminant concentrations at the time. We therefore increased our drilling depth to 350 feet (multi-level monitoring well installation MW-67) to investigate this issue. Subsequently, the most recent data better fit with a 200-foot-deep flow model.

Based on our studies, including a full-scale Pumping Test and tidal response testing, we have shown that in the area of groundwater contamination, and on the scale of the contaminant plumes, the direction and quantity of groundwater flow can be estimated using an equivalent porous media model. We state this recognizing that an individual bedrock zone may represent flow in a single or limited number of fractures which over a relatively short distance is not representative of average conditions. In terms of our equivalent porous media model, this condition represents an aquifer heterogeneity. However, over sufficient volumes of bedrock (which is the case for the work at IPEC), the bedrock groundwater flux can be estimated based on an equivalent porous media model using Darcy's Law[10].

3.3 IDENTIFIED CONTAMINANT SOURCES

GZA, in conjunction with facility personnel, conducted a review of available construction drawings, aerial photographs, prior reports, and documented releases, and interviewed Entergy personnel to identify potential groundwater contaminant sources.

That review, in conjunction with the observed distribution of contaminants, identified IP2-SFP and IP1-SFPs, along with legacy piping associated with Unit 1, as sources of the radiological groundwater contamination. The locations of these structures are shown on **Figure 3.4.** No release was identified in the Unit 3 area. This finding is consistent with, and reflects, changes in construction practices over time[11]. Refer to **Section 8.0** for additional information pursuant to source area description.

3.4 CONTAMINANTS OF INTEREST

Throughout this report, Tritium and Strontium are discussed as the principal radiological constituents associated with the groundwater contamination investigation performed at IPEC. Both radionuclides served as the most representative contaminant tracer tools from the perspective of frequency of observed occurrence, as well as contaminant transport[12] across the Site. Other radionuclides (primarily Cs-137, Ni-63, Co-60) were more sporadically identified and isolated to specific locations within the Site. These radionuclides are encompassed by the Unit 2 (Tritium) and Unit 1 (Strontium) plumes. We also note these other radionuclides carry a smaller potential radiological impact as compared to Strontium. These contaminants were also continuously assessed within the context of the overall site hydrological model as well as the plume information gleaned from the Unit 1 and Unit 2 plume data. All detected radionuclides have been

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[10] *Interpretation of Hydraulic Tests and Implications Towards Representative Elementary Volume for Bedrock Systems.* Thomas Ballerstero, October 2003, AGU San Francisco.

[11] The absence of Unit 3 sources is attributed to the design upgrades incorporated in the more recently constructed IP3-SFP.

[12] A combination of Tritium and Strontium allow full characterization of radiological groundwater plume nature and extent at the IPEC Site given their divergent behavior in the subsurface. Tritium is completely conserved in the groundwater with no partitioning to natural or anthropogenic subsurface materials. It, therefore, moves with and as fast as the groundwater, and thus serves as an indicator of the leading edge of a recent release. Strontium provides strong partitioning characteristics and long half-life. It is, therefore, an indicator of older, historic releases.

accounted for by Entergy in their dose assessment analyses (radiological impact evaluations). Accounting for these data was performed via USNRC Annual Reporting documents that have been made public (year-end 2005 and 2006) and will continue to be reported on (Refer to RG1.21 report). Additional discussion of the identified sources of contaminants and the properties affecting contaminant migration are provided in **Sections 8.0** and **9.0.**

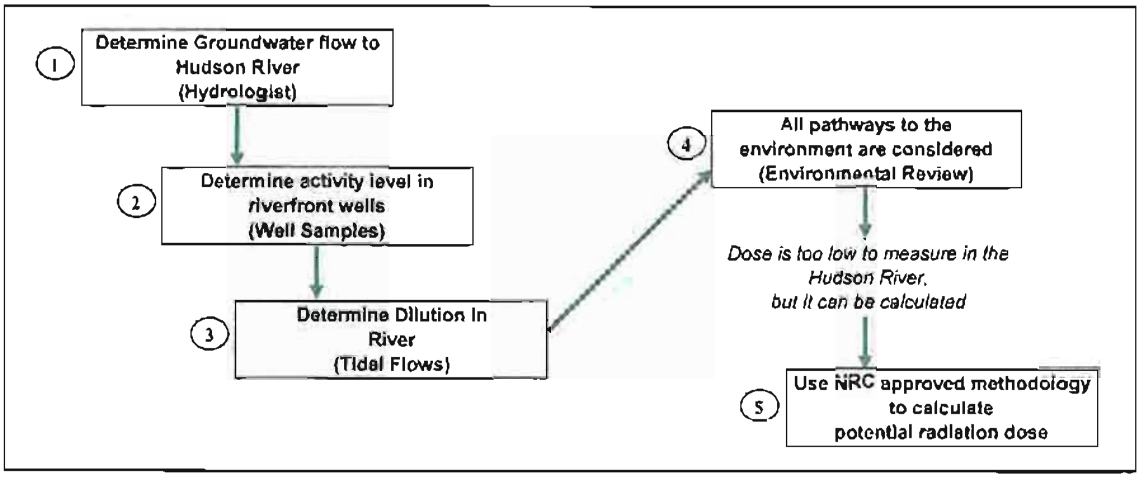
3.5 IDENTIFIED RECEPTORS

The NRC has set forth guidance for calculations of radiation dose to the public, and IPEC follows this guidance for radioactive effluents, including those from groundwater. IPEC is required to perform an environmental pathway analysis to determine the possible ways in which radioactivity released to the Hudson River can cause radiation dose. Receptors for radioactive releases to the environment are considered to be actual or hypothetical individuals exposed to radioactive materials either directly or indirectly.

Title 10 of the Code of Federal Regulations, Part 50 (10CFR50) Appendix I states: "*Account shall be taken of the cumulative effect of all sources and pathways within the plant contributing to the particular type of effluent being considered.*" 10CFR50 Appendix I provides numerical guidelines on liquid releases of radioactivity, such that releases "*will not result in an estimated annual dose or dose commitment from liquid effluents for any individual in an unrestricted area from all pathways of exposure in excess of 3 millirems to the total body or 10 millirems to any organ.*"

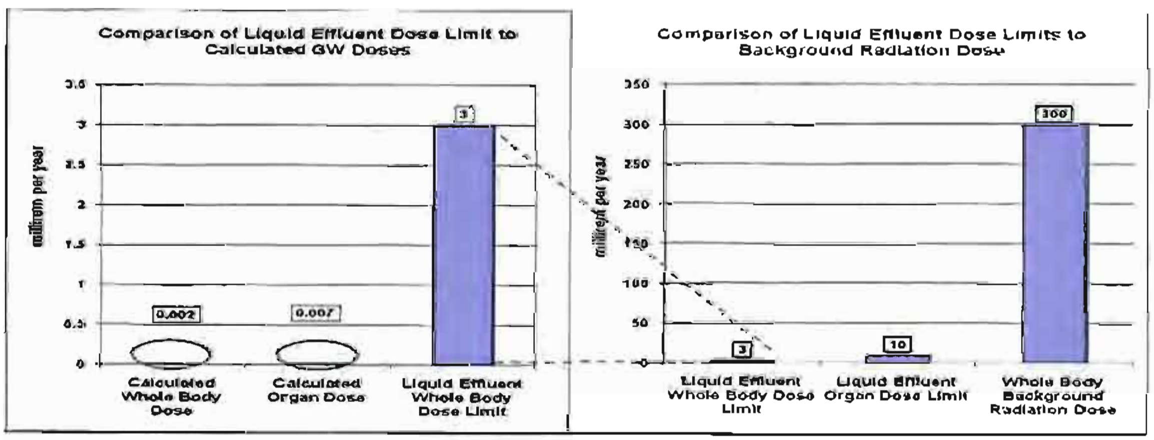
IPEC has reviewed the potential pathways that result in dose to the public and are viable for the Site. Potential pathways considered included drinking water consumption, aquatic foods, exposure to shoreline sediments, swimming, boating, and irrigation. As discussed below, drinking water is not a viable pathway for releases to the Hudson River. Regulatory Guide 1.109, "Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR 50, Appendix I" provides guidance and acceptable methodologies for calculating radiation dose from environmental releases. The NRC guidance uses the maximum exposed individual approach, where doses are calculated to hypothetical individuals in each of four age groups (infant, child, teen, and adult). Maximum individuals are characterized as "maximum" with regard to food consumption and occupancy. Regulatory Guide 1.109 describes a pathway as "significant" if a conservative evaluation yields an additional dose increment of at least 10 percent of the total from all pathways. Based on the above description, the only significant pathway for liquid releases is for consumption of aquatic foods; i.e., Hudson River fish and invertebrates.

The specific methodology used to calculate doses from liquid radioactive effluents is based on NRC guidance and is contained in the Indian Point Offsite Dose Calculation Manual (ODCM). The volume of groundwater traversing the site and discharging into the Hudson River, as estimated by GZA using the data as presented in this groundwater report, is used in conjunction with measured concentrations of radionuclides in groundwater to estimate the total amount of radionuclides to the Hudson River, and their potential dose impact. In 2005 and 2006, groundwater releases resulted in a small fraction of the offsite dose limits established by the NRC for each site. This dose is calculated from measured radionuclides in groundwater, using the methodology in the ODCM. A simplified description of the methodology is shown in the figure below.



SIMPLIFIED GROUNDWATER DOSE CALCULATION METHODOLOGY

Radiation doses are reported annually by IPEC in an NRC-required Annual Radioactive Effluent Report. An overview of the results is shown in the figure below.



COMPARISON OF BACKGROUND, DOSE LIMITS, AND CALCULATED GROUNDWATER DOSE – 2006

For the purposes of this study, the migration of contaminated groundwater is the pathway of interest. The contaminants of interest are not volatile; therefore, they remain in the subsurface bedrock, soil and groundwater until discharge to the river.

There is no current or reasonable anticipated use of groundwater at the IPEC. According to the NYSDEC[13], there are no active potable water wells or other production wells on the

[13] Early in the investigative process, the NYSDEC requested that the New York State Department of Health assess the presence of drinking water supply wells in the vicinity of the Site. The NYSDEC informed Entergy and GZA that no drinking water supply wells were located on the East side of the Hudson River in the vicinity of the Site in June 2006.

East side (Plant side) of the Hudson River in proximity to the IPEC[14]. Drinking water in the area (Town of Buchanan and City of Peekskill) is supplied by the communities and is sourced from surface water reservoirs located in Westchester County and the Catskills region of New York. The nearest of these reservoirs (Camp Field Reservoir) is located 3.3 miles North-Northeast of the Site and its surface water elevation is hundreds of feet above the IPEC, in a cross-gradient direction and several watersheds away. In addition, groundwater flow directions on the Site are to the West towards the Hudson River. Therefore, it is not possible for the contaminated groundwater at IPEC to ever impact these drinking water sources.

Groundwater beneath the IPEC flows to the Hudson River and therefore flows through portions of the river bank and river bottom. The river bank at the Site consists of sections of vertical bulkheads and some rip-rap outside of the contaminated flow zone. The size of the Hudson River and the hydraulic properties of the underlying bedrock preclude natural or pumping-induced migration of contaminated groundwater to the West side of the river. Therefore, conditions at the IPEC pose no threat to potable water supplies.

In summary, the only pathway of significance for groundwater is through consumption of fish and invertebrates in the Hudson River, and the calculated doses are less than 1/100 of the federal limits. As described above, potable water is not a viable pathway and no dose calculations are necessary in that regard.

GZA utilized Environmental Data Resources, Inc. to conduct a search for public water supply wells within 1 mile of the Site. According to records maintained by the USEPA, there were no water supply wells located within the search radii.

[14] According to the Rockland County Department of Health, there are municipal drinking water supply wells operated in Rockland County. GZA formally requested, through a Freedom of Information Law Application (F01-07-004), information regarding the elevation of groundwater in these wells to assess if there was any potential for IPEC to impact these wells. The information was not made available to GZA for security reasons. The closest active drinking water well in Rockland County is over 4.5 miles Southwest of the Site on the West side of the Hudson River.

4.0 FIELD INVESTIGATIONS

This section provides a description of our field activities. The studies were conducted in three phases between October 2005 and September 2007. Field activities were performed, in accordance with general industry practice and regulatory guidelines, to develop and validate our CSM (see **Section 3.0**).

The field exploration program was developed by GZA in cooperation with Enercon and Entergy. A team of GZA engineers, geologists and scientists was present to observe and document drilling efforts, classify soil and rock samples, direct field testing (packer tests, etc.) and collect other hydrogeologic data. Borehole development, well installation and packer testing were performed by GZA and the drilling contractor, Aquifer Drilling and Testing (ADT), New Hyde Park, New York. The exploration program also included the use of geophysical exploration techniques to help identify underground utilities, evaluate the location of the bedrock surface, and evaluate the nature of bedrock fractures in select boreholes. Advanced Geological Services (AGS) and Geophysical Applications, Inc. (GA), both under GZA's oversight, conducted this work.

The following provides a broad overview of our investigations. Refer to subsequent subsections for more information.

Geological Reconnaissance

- Review of Relevant Geological Literature and Previous Reports
- Site Reconnaissance to Observe Outcrops of Bedrock
- Geostructural Logging of the Rock Wall within the IP2-FSB Crane Foundation Excavation

Test Drilling - Planning, Execution, Post-Drill Activity

- Review of Existing Utility Plans
- Surface Geophysical Utility Surveys (to further locate utilities)
- Vacuum Excavation of 39 boreholes (for safety; to reduce risk of encountering underground utilities or structures)
- Test Boring Advancement (bedrock borings, overburden borings)
- Borehole Development (to remove rock cuttings and drill water; preparation for hydraulic testing in boreholes)
- Borehole Geophysical Surveys (to evaluate fractures along the borehole wall)

Monitoring Well Installations

- Bedrock Wells
- Open Rock Wells
- Waterloo Systems
- Nested Wells
- Overburden Wells
- Wellhead Completion

- Wellhead Elevation Surveying

Hydraulic Testing to Evaluate Hydraulic Conductivity of Bedrock

- Specific Capacity Testing
- Rising Head Hydraulic Conductivity Testing (pneumatic and hydraulic slug tests)
- Bedrock Packer Hydraulic Conductivity Testing
- A Pumping Test (a 72 hour Pump Test to evaluate the hydraulic properties of the bedrock)

Water Sampling

- On-Site Sampling of Groundwater, Surface Water and Facility Water
- Off-Site Sampling of Groundwater and Surface Water

Groundwater Elevation Monitoring and Pressure Transducer Data

- Installation of In-Situ and Geokon Transducers
- Data Retrieval

Organic Dye Tracer Testing

- Injection Well Construction
- Tracer Introduction
- Sampling Methods

Geophysical Testing – Identification of Preferential Groundwater Flow Paths

- Ground Penetrating Radar Surveys at Unit 2, Unit 3 and the Owner Controlled Area (OCA) Access Road
- Seismic Refraction, GPR and Electromagnetic Surveys between the Protected Area and southern Warehouse

As-built locations of the explorations are shown on **Figure 1.3**. **Table 4.1** provides a summary of well locations and installation details. The following sections describe the key aspects of the completed work. Explorations logs, test records and additional information are presented in the Appendices.

4.1 GEOLOGIC RECONNAISSANCE

To develop a preliminary understanding of the subsurface conditions expected to occur beneath the Site, GZA reviewed USGS publications relating to the local and regional geology as well as available Site-specific geologic reports. GZA further conducted a reconnaissance of the Site to identify the type of bedrock exposed, relative fracture density and locations of expected overburden. Specifically included was the logging of the rock wall in the construction excavation at Unit 2 (refer to **Section 6.0** for additional detail on Site Geology). This information was used to help design the subsurface investigation methods.

4.2 TEST DRILLING

Forty-seven borings were completed by GZA as part of this program, forty-two of these borings were converted to monitoring installations, one was converted to a recovery well and one was converted to a tracer injection point[15]. Boring logs for the bedrock borings and the additional overburden borings are provided in **Appendix B**. Boring locations and elevations are provided in **Table 4.1**. Final sampling elevations are also provided in **Table 4.1**. Test Boring/Monitoring Installation locations are shown on **Figure 1.3**. In viewing the figure, note that test boring designations are the same as the monitoring installation[16] designations (see **Section 4.3.4**). In addition, a tracer injection point was installed along the side of the casing of MW-30 (see **Section 7.0** for details).

Prior to advancement of the borings, a utility identification and clearance program was implemented to reduce the risk of encountering underground utilities, and to maintain the safety of on-Site personnel during drilling activities. GZA personnel, AGS personnel and Site personnel first performed a reconnaissance of the proposed boring locations. Site personnel then utilized Site plans to assess the potential presence of subsurface utilities in the area of the proposed boring locations. Following this initial screening, AGS personnel performed a surface geophysical survey of the area around the proposed boring locations using GPR and radiofrequency utility locating equipment. The results of the survey were marked on the ground surface using spray paint. Entergy personnel performed a final reconnaissance prior to approving the locations.

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[15] Borings are defined as test sites that were excavated with hand held or mechanical drilling devices. Monitoring installations are defined as boreholes (or wellbores) that were completed to allow groundwater monitoring and generally include multiple monitoring levels over the depth of the boring (either "nested well" casings within one borehole or Waterloo multi-level completions). In several instances, a monitoring installation location designation, such as MW-49, may have two discrete borings, in which case it is counted as two installations, but represented on the figures as a single location for clarity. Attempted borings which met refusal and had to be re-drilled are not included in the boring count.

[16] *Monitoring installations* are commonly referred to as *Monitoring wells*, which in this usage, may include multiple, individual well casings. This generic usage is also used herein.

SURFACE GEOPHYSICAL SURVEY

At thirty nine of the boring locations, overburden was vacuum-excavated until bedrock was encountered, or to the practical limits of the vacuum excavation technique. To further reduce the risk associated with the drilling program, during advancement of the borings to bedrock, a downhole magnetometer was utilized every two feet to assess the presence of metallic objects potentially related to subsurface utilities.

The test borings were performed by ADT with a combination of three drill rigs: a track-mounted CME LC55 rotary drill rig, a truck-mounted CME 75 rotary drill rig, and an electric track-mounted Davie DK 515 rotary drill rig. The original program consisted of advancing borings into bedrock to desired terminal depths using wire line HQ direct rotary coring techniques. This resulted in a nominal 3.85-inch diameter borehole. Where overburden was present, either a four-inch or six-inch casing was installed into the rock and grouted in place.

At certain locations where overburden occurred beyond the bottom of the vacuum-excavated test pits, soil samples were collected at 5-foot intervals, from the bottom of the vacuum-excavated test pit, using a 2-inch outside diameter (OD) split-spoon sampler driven by a 140-pound hammer falling 30 inches, to characterize soils. These samples were visually classified using the Burmister Classification System. At all locations, either vacuum-excavated test pits or hand-excavated test pits were performed to clear utilities prior to advancing boreholes. Grab samples were collected during the advancement of the test pits to visually characterize the overburden soils.

VACUUM EXCAVATION

During the drilling program, rigorous field protocols were implemented to limit the risk of cross-contamination. All down-hole drilling tools, testing equipment, and well materials were steam cleaned or pressure washed prior to use on the Site, subsequent to the completion of a boring, and prior to leaving the Site. Water used during drilling, testing and well installations was drawn from the Buchanan, New York public water supply from on-Site connections. Waste water, waste soil, and decontamination wash water were placed in 55-gallon drums and transferred to Site personnel for proper disposal.

4.2.1 Bedrock Borings

Thirty-eight of the borings were drilled in bedrock, including U1-CSS which was installed horizontally through the East wall of the Unit 1 Containment Spray Sump using hand coring techniques. The borings were completed using rotary techniques with water as the drilling fluid and either permanent 4-inch or temporary 6-inch casing to keep the borehole open through overburden soils. Once rock was encountered, it was cored using HQ-size double-tube core barrels with diamond studded bits in general accordance with ASTM D2113 [6]. Core runs were generally 5 feet in length, with a nominal 3 inch diameter. Shorter or incomplete runs were made when the drilling team believed the core barrel to be blocked.

The rock samples were classified and logged by GZA field personnel, and the descriptions and rock quality designations were reviewed and checked by a Senior GZA Geologist. Rock classification was based on the International Society of Rock Mechanics (ISRM) System with adaptation to suit the identified rock and structure.

The rock core was logged as soon as practical after it was extracted from the core barrel. The following information was generally noted for each core run:

- Depth of core run
- Percent core recovery
- Rock Quality Designation (RQD)
- Rock type, including color, texture, degree of weathering and hardness
- Character of discontinuities, joint spacing, orientation, roughness and alteration
- Nature of joint infilling materials, where encountered
- Presence of apparently water-filled fractures

BEDROCK CORE OBTAINED FROM DRILLING USED FOR EVALUATION OF FRACTURES

During rock coring activities, potable water was used as a drilling fluid to cool and lubricate the core barrel and remove cuttings from the borehole. The drilling fluid was circulated down the borehole around the core that had been cut, flowed between the core and core barrel, and exited through the bit. The drilling fluid then circulated up the annular space and was discharged at the land surface to a mud tub. The volume of water lost during drilling was recorded and later, during development, an attempt was made to remove the amount lost to the formation.

In addition, drilling parameters, such as the type of drilling equipment, core barrel and casing size, drilling rate, and groundwater condition were recorded. Cumulatively, this information provided insights relative to rock conditions, and the potential for the transport of groundwater migration in bedrock fractures.

Bedrock borings ranged in depth from 30 feet below ground surface at MW-33, -34 and -35 to 350 feet below ground surface at MW-67. As described below in **Section 4.4**, the majority of the rock borings were completed as monitoring well locations. One exception was MW-61, which was abandoned when a length of HQ casing separated in the borehole due to drilling difficulties related to a 70-foot length of clay-filled fault gouge, and could not be retrieved. The boring was subsequently grouted and a second boring, designated MW-66, was advanced approximately 10 feet East of the MW-61 location.

As discussed earlier, one boring, U1-CSS, was installed using a hand-held coring machine through the East wall of the IP1-CSS. This borehole was advanced horizontally approximately 70 inches into the bedrock to the East of the Superheater Building.

4.2.2 Overburden Borings

In areas where groundwater was encountered in the overburden deposits, overburden (soil) borings were drilled to further evaluate water quality in the shallow aquifer. Five borings, designated MW-49, -52, -62, -63, and -66 were advanced immediately adjacent to the bedrock boring of the same name. In addition, three overburden borings, designated MW-38 and MW-64, were advanced at stand alone locations. MW-38 was advanced to assess groundwater quality and migration pathways along the Discharge Canal. MW-64 was advanced to determine the backfill material and construction properties of the Discharge Canal as it runs beneath the Superheater Building, and was terminated at a depth of 3 feet when concrete was encountered beneath the slab of the building. Additionally, a tracer injection well (T1-U1-1) was installed within overburden above the North Curtain Drain (NCD) along the North wall of the IP1-FHB.

Seven of the borings were advanced using water rotary techniques and temporary six-inch casing. MW-64 was advanced using a concrete core until lean concrete was encountered under the building slab. Seven of the borings were completed as single monitoring wells.

ADVANCEMENT OF BORINGS ALONG RIVERFRONT

4.2.3 Borehole Development

After drilling was completed and prior to conducting hydraulic tests within a borehole, borehole development was conducted to remove rock cuttings from the borings, which could otherwise restrict water flow into the fractures and alter packer testing results, as well as to remove drilling water lost to the formation during drilling. The boreholes were developed either by pumping and surging with a 3.7-inch surge block and a Grundfos Redi-Flo 2 submersible pump, or by pumping with a submersible pump along the length of the borehole. Sufficient water was pumped out of the borehole to account for water lost during drilling and until well water was visually free of turbidity.

4.2.4 Borehole Geophysical Analysis

Upon completion of borehole development, a suite of geophysical surveys was conducted in select boreholes (borehole geophysics was biased towards the deeper boreholes) by GA of Holliston, Massachusetts to obtain information on the presence of water bearing fractures in the rock. This work took place between November 2005 and July 2007, and involved twenty-three borings MW-30, -31, -32, -33, -34, -39, -40, -51, -52, -53, -54, -55, -56, -57, -58, -59, -60, -62, -63, -65, -66, -67 and RW-1.

GA performed fluid resistivity, temperature and conductivity logging; heat pulse flow meter logging; and optical and acoustical televiewer logging (OTV/ATV). A Mount Sopris model 4MXA or 4MXB logging winch equipped with a Mount Sopris model MGX-11 electronics console recorded conventional logs at each well. All conventional log data was recorded at 0.1-foot depth increments.

Fluid temperature and fluid resistivity logs were recorded during the first downward logging run at each borehole using a Mount Sopris caliper probe with a fluid temperature/fluid resistivity subassembly. These fluid logs were obtained using a downward logging speed of approximately 4 to 5 feet per minute. Caliper data were subsequently recorded while pulling the same probe upward at approximately 10 feet per minute.

ATV data were obtained using an Advanced Logic Technologies (ALT) model AB140 acoustical televiewer probe with a Mount Sopris winch and an ALT model Abox electronics console. ATV data were recorded at 0.01-foot depth intervals with 288 pixels for a 360-degree scan around the borehole wall. Logging speeds were approximately 4 feet per minute with this probe.

OTV data were recorded using an ALT model OB140 probe, also with a Mount Sopris winch and the ALT electronics console. OTV data were stored at depth increments of 0.007 feet, with 288 pixels for each 360-degree scan around the borehole wall. OTV logging speeds were also approximately 4 feet per minute.

A pair of centralizer assemblies positioned the ATV and OTV probes near the middle of each borehole. Each centralizer included four stainless steel bow springs, clamped to the probe housings with brass compression fittings, at positions recommended by the probe manufacturer to minimize the risk of interference with the probes' three internal component magnetometers.

Flowmeter data were recorded with a Mount Sopris model HPF-2293 heat-pulse flowmeter probe at specific depths selected from field graphs of the caliper, fluid temperature and fluid resistivity logs. Flowmeter data were initially recorded under ambient conditions. The same test depths were subsequently repeated while pumping at 0.4 to 0.75 gallons per minute (gpm) with a Grundfos, Fultz or Whale pump. The pump was positioned a few feet below the observed static water level in each well. In some cases, the pump was operated so as to maintain the water level some number of feet below the static level (if the well produced little water and the water level was constantly dropping while pumping).

A detailed description of the geophysical logging results for each borehole is included in **Appendix C.**

4.3 WELL INSTALLATIONS

Bedrock and overburden monitoring installations were constructed in boreholes to allow for future recording of groundwater levels and the collection of groundwater quality samples. Further, we installed nested piezometers in single boreholes to screen multiple levels of bedrock and overburden within a single borehole and alleviate the need for multiple borings in areas not easily accessed. For specific well installation details, refer to the well construction logs provided in **Appendix D**. In addition, eighteen monitoring wells were previously installed at the Site prior to this investigation and included: MW-101, MW-103, MW-104, MW-105, MW-107, MW-108, MW-109, MW-110, MW-111, MW-112, U3-1, U3-2, U3-3, U3-4S, U3-4D, U3-T1, U3-T2 and I-2.

4.3.1 Bedrock Wells

Following borehole advancement and testing, GZA evaluated the rock cores, geophysical logs, and other hydrologic and radionuclide test data to assess fracture spacing and potential yield. Using these data, GZA selected intervals within the boreholes to be completed as permanently screened monitoring wells. The selected well screen intervals were intended to span hydraulically active zones within the bedrock.

4.3.1.1 Open Rock Wells

Four bedrock borings, designated MW-33, -34, -35 and -46, were left as open borehole monitoring points. MW-46 is located in the Unit 3 Transformer Yard (IP3-TY), and MW-33, -34 and -35 are located in the Unit 2 Transformer Yard (IP2-TY) where the water table spans the hydraulically active shallow bedrock. The wetted lengths of the borehole were appropriate for one sampling zone at these locations.

Recovery well RW-1, located in the IP2-FSB truck bay, is also an open borehole. The borehole was installed and a Pumping Test conducted (described in **Section 4.4.4**) to test the feasibility of using hydraulic containment in the vicinity of Unit 2, should it be found appropriate. This location was used as the pumping well during the Pumping

Test. During the interim between completion of the Pumping Test and completion of a hydraulic containment system, a series of temporary packers were installed in the borehole to prevent or limit non-ambient, downward migration of radionuclides through the borehole. RW-1 was also used as a monitoring point during the tracer test.

MW-66 is an open borehole to 200 feet below grade. A Flute liner system was installed in the borehole in September 2007 to limit the vertical migration of contaminants until such time as either a multi-level monitoring well is completed or the boring is abandoned.

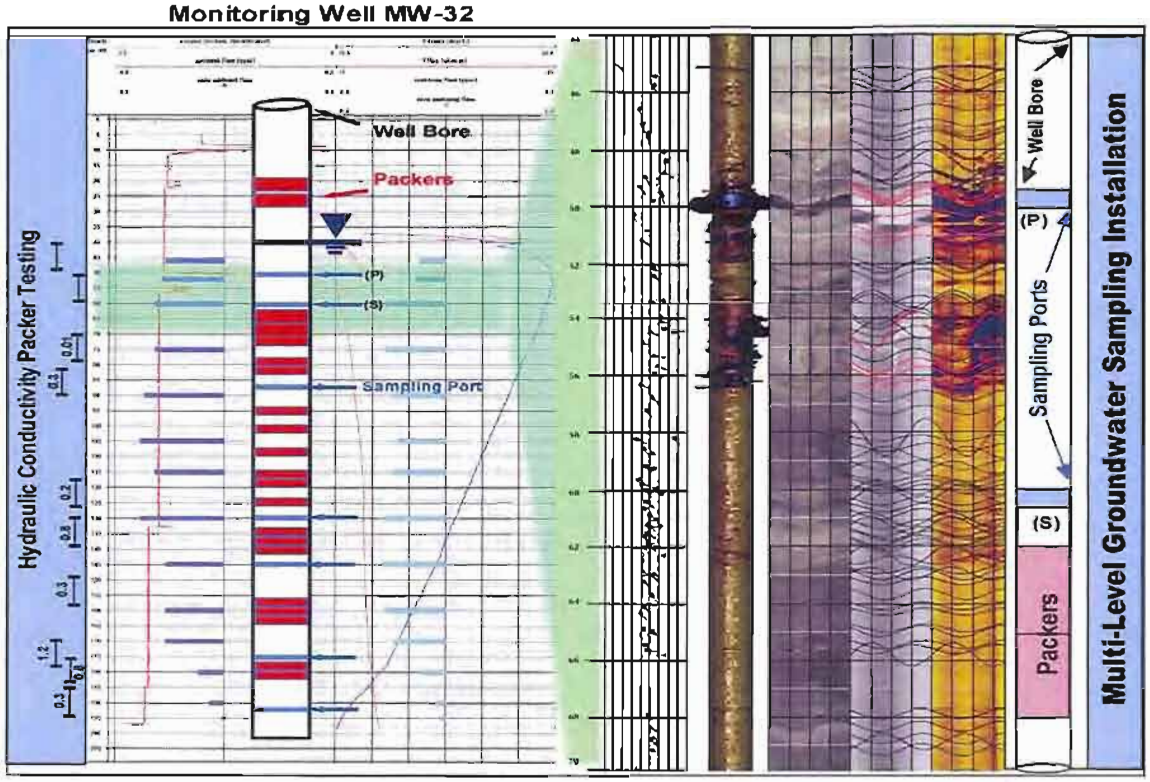
U1-CSS is an open borehole advanced horizontally into the bedrock behind the East wall of the Superheater Building. A watertight flange was mounted to the concrete wall of the IP1-CSS and steel piping was extended vertically upward through the floor of the Superheater Building. The well was completed as a standpipe with shut-off valves and overflow bypass in case of any artesian effect.

4.3.1.2 Waterloo Multi-Level Completion Wells

Twelve borehole locations, designated MW-30, -31, -32, -39, -40, -51, -52, -54, -60, -62, -63, and -67, were completed with Waterloo multi-level sampling systems. The Waterloo system uses modular components which form a sealed casing string of various casing lengths, packers, ports, a base plug and a surface manifold. This configuration allows accurate placement of ports at precise monitoring zones. Stainless steel sampling pumps are connected to the stem of each port and individually connect that monitoring zone to the surface. The Waterloo systems are constructed of 2-inch-diameter Schedule 80 PVC risers with 3-foot-long packers that inflate to fill a 4-inch borehole.

Multiple levels of monitoring ports were installed in each borehole. In several cases, redundant ports were also installed (typically, within approximately two feet of each other). In the borehole, the associated sampling zones are isolated from each other by a series of packers. The monitoring ports are constructed from stainless steel. Each monitoring port has two openings: one for sampling and one for monitoring piezometric pressures. A sampling pump and pressure transducer are dedicated to each monitoring port. Each sampling pump is individually connected to the surface manifold by 0.25-inch nylon tubing. In general, monitoring ports were placed within sampling zones adjacent to the fractures that were observed to be the most hydraulically active. Sampling zone lengths were varied with the objective of making them less than ten feet in length, but longer where either: 1) more low transmissivity fractures were required to allow enough flow for reasonable sampling times, and/or 2) two conductive fractures needed to be captured within a single sampling zone given that the total number of monitoring ports was limited to seven per borehole. Packers were placed at locations where the data (geophysical logging, packer testing, rock core photographs, etc.) indicated that the bedrock was the least fractured. In areas where packer placement could not avoid all fractures, zones with nearly horizontal fractures were favored. The overall objective of packer placement was to achieve a vertical borehole conductivity equal to or less than that of the original bedrock removed from the borehole.

A schematic of the data and analysis process used to design the multi-level installations is included below.



EXAMPLE OF DATA AND ANALYSES USED TO DESIGN MULTILEVEL INSTALLATION

The manifold completes the system at the surface. It organizes, identifies, and coordinates the sample tubing, air drive line tubing, and/or transducer cables from each monitoring zone (see photo below of tubing and cabling during system assembly and installation). The manifold allows connection to each transducer in turn, and a simple, one-step connection for operation of pumps. Dedicated pumps allow individual zones to be purged separately; the manifold also allows for the purging of many zones simultaneously from one borehole to reduce sampling times.

SAMPLING PORTS, TUBING AND CABLING FOR MULTI- LEVEL SYSTEM ASSEMBLY AND INSTALLATION

4.3.1.3 Nested Wells

Nested monitoring wells were installed in 18 locations, designated MW-36, -37, -41, -42, -43, -44, -45, -47, -48, -49, -50, -53, -55, -56, -57, -58, -59, and -65. In general, the nested wells consisted of the installation of one or more one-inch diameter Schedule 80 PVC wells screened at varying intervals in bedrock and a two-inch Schedule 80 PVC well in the shallow West sampling zone of the boring, either in the bedrock or overburden.

In general, well screens consisting of 0.02-inch slotted PVC pipe were installed at lengths between 2 and 10 feet. Once the screened intervals were selected, the PVC well point was lowered into the boring to the desired depth. Appropriately sized filter pack material was placed from one foot below the screened interval to a minimum of one foot above the screened interval. The depth of the filter pack was measured on several occasions during installation to assess the affects of bridging and verify that the filter pack material was placed at the required depths. The intervals between well screens were sealed using bentonite pellets.

4.3.2 Overburden Wells

Three wells, MW-38, -49-26, -52-12 were completed as either two-inch diameter or four-inch diameter groundwater monitoring wells. The wells were constructed of Schedule 40 PVC screen and solid riser to ground surface. A 0.02-inch slot size was selected for the well screens based on existing knowledge of the Site soil conditions. From field observations, the shallow groundwater table was expected to be influenced by daily tidal fluctuations of approximately 2.7 feet. Consequently, well screens were installed such that the top of the screens were above mean high-tide water levels and of sufficient length to accommodate groundwater sampling needs. The annular space around the screen and riser was backfilled with #2 filter sand to approximately 2 feet above the top of the screen. The remaining annular space was backfilled with bentonite and grout.

In order to sample two intervals in deep fill and overburden deposits observed near the Hudson River (in borings at MW-62, -63, and -66), GZA installed two one-inch Schedule 40 PVC wells, or one one-inch and one two-inch well, at these three locations. One of the well screens spanned the tidally influenced shallow water table, and one at the top of rock in a more gravel-rich layer beneath silty, historic, river bottom sediments.

In addition, GZA installed one tracer injection well situated in the overburden above the Unit 1 North Curtain Drain. This well is constructed of two-inch Schedule 40 PVC. The screened interval was backfilled with #2 filter sand to approximately 2 feet above the screen. The remaining annular space was backfilled with bentonite grout. A second tracer injection point was completed adjacent to MW-30's casing.

4.3.3 Wellhead Completion

To protect the monitoring installations against damage and the elements, most installations were finished at the ground surface with an 8-inch or 12-inch flush mount protective casing with a concrete pad. To accommodate the multi-purge, sampling manifold of the Waterloo Systems well installations, the wellheads were completed with a 2 foot by 2 foot by 2 foot well vault. The well vaults were concreted in-place by Entergy subcontractors after the completion of the rock borings. The well vaults are equipped with hinged diamond plate steel lids that are rated for truck wheel loads.

4.3.4 Well Nomenclature

GZA designated names to newly installed monitoring installations[17], typically with the prefix "MW-". Nomenclature of single-interval installations, such as MW-33, were designated a number typically indicative of the order in which locations were selected prior to drilling. Nomenclature of installations containing Waterloo systems or nested piezometers, such as MW-30-69, were designated a number followed by a monitoring depth interval. In Waterloo installations, the depth interval suffix is indicative of the depth to the sampling port from the top of the well casing. In nested piezometers, the monitoring depth interval suffix is indicative of the depth to the bottom of the piezometer from the top of the well riser. These depths are rounded to the nearest foot.

Throughout the course of the investigation, alterations were made to well casings and adjacent ground surfaces due to equipment installation, hydraulic conductivity testing,

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[17] *Monitoring installations* are commonly referred to as *Monitoring wells*, which in this usage, may include multiple, individual well casings. This generic usage is also used herein.

well vault installation, and Site construction activities. In May 2007, GZA reassigned the names of multilevel installations to maintain the above described nomenclature basis as an easily verifiable tool in the field. Changes in installation nomenclature are provided in **Table 4.2**. It should be noted that the provided groundwater and tracer test analytical data, piezometric data, well construction and development logs, transducer installation logs, sampling logs, hydraulic conductivity testing logs, and survey reports dated prior to May 2007 reference the original designated installation nomenclature.

4.3.5 Wellhead Elevation Surveying

As-built surveys of the newly installed monitoring installations were performed in December 2005, March 2006, April 2006, November 2006, January 2007, and May 2007 by Badey and Watson, Inc. **Figure 1.3** reflects the surveyed locations. The survey results are summarized in **Appendix E** and in **Table 4.1**. Note that **Appendix E** survey reports dated prior to May 2007 reference original installation nomenclature. **Table 4.3** includes changes in casing and ground surface elevations and dates of alterations and resurveys throughout the course of the investigation. Elevations are reported with respect to the National Geodetic Vertical Datum of 1929 (NGVD 29)[18], which is also the datum used by the plant.

4.4 HYDRAULIC TESTING

Four types of in situ tests were performed on existing and newly installed monitoring wells to characterize hydrogeologic properties of the bedrock and overburden, and facilitate the selection of well screen and piezometric sampling intervals. These included short duration specific capacity tests, rising head hydraulic conductivity tests, bedrock packer hydraulic conductivity tests, and the Pumping Test. The following sections describe the equipment and procedures used during this testing program.

4.4.1 Short Duration Specific Capacity Tests

A total of eight specific capacity tests and eight extraction tests were performed to assess hydraulic conductivity (K). See **Table 4.4** for a summary of hydraulic conductivity data.

The testing was conducted by pumping water from the well at a constant rate in order to achieve "measurable drawdown" within the well that would stabilize after a relatively short period of time. "Measurable drawdown" was considered between 1.5 and 10 feet for the purposes of this study. Once drawdown apparently stabilized, pumping was allowed to continue at a constant rate for at least thirty additional minutes before pumping ceased.

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[18] The National Geodetic Vertical Datum of 1929 (NGVD 29) is the renamed Sea Level Datum of 1929. The datum was renamed because it is a hybrid model, and *not a pure model of mean sea level*, the geoid, or any other equipotential surface. NGVD29, which is based on "an averaging" of multiple points in the US and Canada, is the vertical "sea level" control datum established for vertical control surveying in the United States of America by the General Adjustment of 1929. The datum is used to measure elevation or altitude above, and depression or depth below, "mean sea level" (MSL). It is noted that there is no single MSL, because it varies from place to place and over time.

If measurable drawdown within the well could not be achieved, and the maximum capacity of the pump was reached, pumping was allowed to continue at a constant rate for approximately thirty minutes, and the pump was turned off. If the characteristics of the monitoring well and immediately surrounding hydrogeology did not allow for a more suitable method of hydraulic testing, the well was characterized as having a K value "greater than" the value estimated at the maximum pumping rate.

If stabilized drawdown within the well could not be achieved, and the water level in the well continued to decline after attempts to minimize pumping rate to the minimum pumping capability of the pump, the pump was turned off. If alternative methods of testing could not be appropriately implemented due to well characteristics, water levels during the recovery period of this test were analyzed and interpreted for K values.

A Grundfos II Readi-Flo submersible pump or peristaltic pump was used for specific capacity testing, and drawdown was measured using an electronic water level meter and/or pressure transducers. Flow rates were either measured using an in-line flow meter, or estimated by measuring the time required to fill a calibrated container. Transducer-logged water level measurements were typically recorded at thirty second or one minute intervals, while manual water level measurements were typically logged every one to five minutes. The entire pumping duration for each test was typically between thirty and ninety minutes.

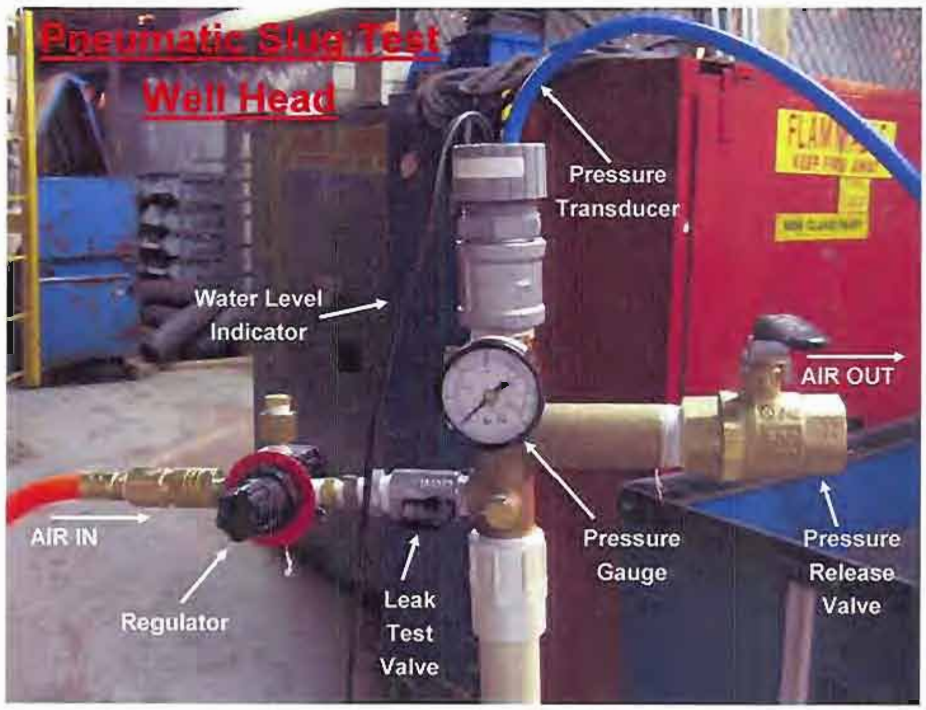
GZA performed specific capacity tests between January 2006 and April 2007. Measurements were also recorded during borehole development. The logs are included in **Appendix F**.

4.4.2 Rising Head Hydraulic Conductivity Tests

A total of forty-three rising head hydraulic conductivity tests were performed at eighteen monitoring wells at the Site. Rising head K tests (slug tests) were performed in MW-36-41, -36-53, -37-57, -41-64, and -42-51 via traditional slug testing. Pneumatic slug tests were performed in monitoring wells MW-53-120, -55-24, -55-24, -55-35, -55-54, -56-85, -57-20, -57-45, -58-65, -59-31, -59-45, -59-68, and -65-80. Hydraulic conductivity (and transmissivity) estimates were then calculated from those results. The calculations for the hydraulic conductivity estimates are provided in **Appendix G**.

At each of the traditional slug tested monitoring wells, the resting (static) water level was measured along with the depth and diameter of the well. A pressure transducer was installed within the screened portion of the tested well to record water level measurements at 10 second intervals. Pressure transducers in immediately adjacent wells also recorded water level measurements at 10 second to one minute intervals. During the first part of the slug test a rod (slug) of approximately 7 feet long was quickly inserted into the tested well below the water table in order to nearly instantaneously displace a volume of water equivalent to the volume of the slug. The raised head of the water column was then dissipated back down to its initial static level. When equilibration at static water level was reached a rising head test was conducted. The slug was quickly withdrawn from the monitoring well, resulting in a nearly instantaneous decline in the water level within the tested well. The lowered head of the water column recovered to its initial static water level.

At each of the pneumatic slug tested wells, static water level was recorded, as well as the depth and diameter of the well. Pressure transducers were installed within the screened portion of the tested well and in adjacent wells to record water level measurements at 1 to 3 second intervals. A pneumatic slug test well head was attached and sealed to the top of the tested well (see enclosed photo below). The well head was then pressurized using compressed air in order to lower the water column to a predetermined depth that was measured using pressure transducers. The water column was not permitted to decline below the top of the well screen. When pressure transducer readings stabilized and the water level in the well was below the water level indicated, the air pressure was instantaneously released through a valve on the pneumatic slug test well head, and the water column was allowed to recover to its initial static water level.



PNUEMATIC SLUG TEST WELL HEAD INSTRUMENTATION

Slug test logs are provided in **Appendix H**. Estimated K values are provided in **Table 4.4**. **Figure 4.1** represents a diagram of the pneumatic slug test well head.

4.4.3 Bedrock Packer Extraction Hydraulic Conductivity Testing

Under the direction of GZA personnel, ADT conducted 186 packer hydraulic conductivity tests between November 2005 and August 2007 in boreholes MW-30, -31, -32, -39, -40, -51, -52, -54, -60, -62, -63, -66 and -67.

PACKER TESTING OF MW-30 WITHIN IP2-SFP EXCAVATION

Bedrock packer hydraulic conductivity testing (packer testing) was performed to estimate the equivalent hydraulic conductivity of the bedrock in the vicinity of the borehole locations. The use of packers permitted the localization of a specific depth interval within a bedrock borehole for sampling and hydraulic conductivity testing. The primary hydraulic conductivity of unfractured marble is insignificant. Bedrock groundwater flow, therefore, is controlled by fractures in the rock formation. However, not all rock fractures are hydraulically active. Accordingly, packer tests were used to assess which rock zones have the ability to transmit measurable quantities of groundwater, and to estimate the equivalent hydraulic conductivities of those fractures.

During packer testing, water samples were collected for Tritium analysis for each tested interval in all boreholes except MW-40. Water samples were also collected for Strontium analysis for every other tested interval in boreholes MW-54, -60, -62, -63, -66, and -67.

Prior to the initiation of packer testing at the Site, the packer assembly was pressure tested. Also, prior to the start of packer testing at each borehole, all downhole equipment was disassembled and steam cleaned. The submersible pump was removed from the packer assembly and decontaminated using a fresh water and Alconox solution. A quality assurance/quality control (QA/QC) sample was collected from this pump after the decontamination process was completed. After reassembly of the packer equipment, packers and air lines were tested for leaks.

Packer tests were performed using an assembly composed of two inflatable bladders, or "packers", with a length of perforated pipe making up the 10-foot test zone between the two packers. A Grundfos Rediflo II submersible pump was placed within this 10-foot-long test zone. Pressure transducers were positioned above, within and below the test zone.

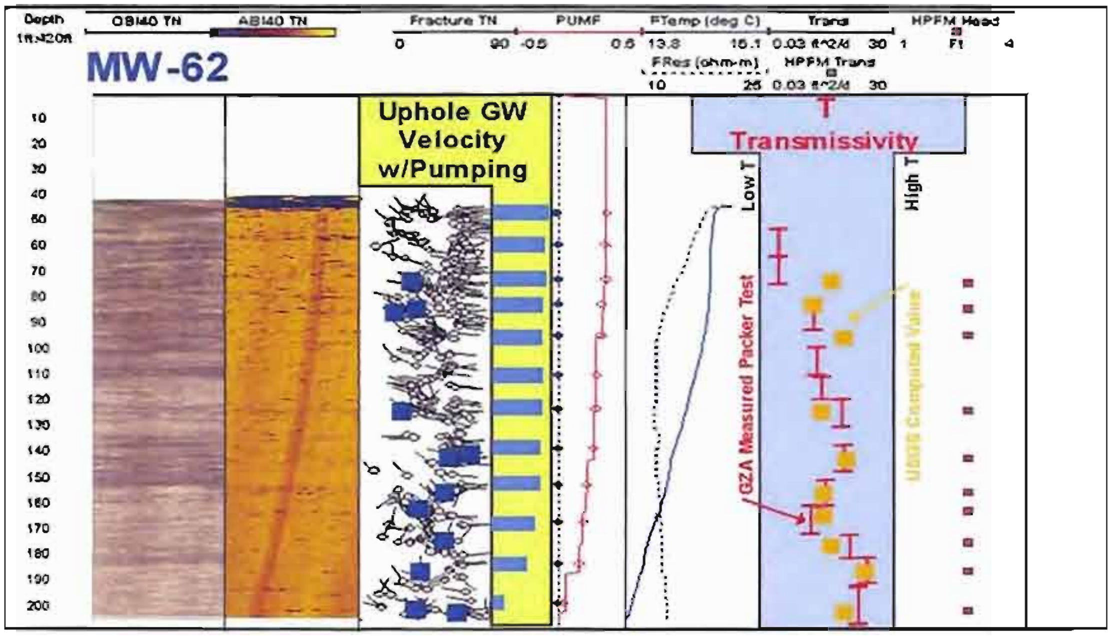
Using a drill rig hoist, the packer assembly was lowered on two-inch-diameter Schedule 80 pipe to the appropriate test depths within each tested borehole. See **Figure 4.2** for a schematic of the packer test assemblage.

Water levels above, within, and below the tested zone were recorded at ten second intervals using pressure transducers. Packers were inflated with 160-195 psi of nitrogen, and water levels were allowed to equilibrate. Once pressures had equilibrated, the pump was turned on and the tested zone was slow purged for at least ten minutes at a rate of 2 to 10 gallons per hour (gph). During this initial purge, a sample was collected for Tritium analysis in boreholes MW-30, MW-31, MW-32, MW-39, MW-51 and MW-52. Immediately following this initial purging period, the pumping rate was increased to a rate of 0.5 to 4 gallons per minute (gpm) in order to achieve drawdown of approximately 10 to 30 feet within the tested zone.

During drawdown, pressure transducer data was observed and compared to assess the potential for cross-zone communication, either through fractures interconnecting around the packer or incomplete seals by the packers. If significant drawdown could not be achieved, a short term sustained yield test was conducted. Once significant drawdown was achieved, or sustained yield was maintained for at least 30 minutes, a sample was collected for Tritium analysis. The pump was turned off, and the water level within the test zone was allowed to recover for either 30 minutes or until 80 percent recovery was achieved. For test zones in which sufficient recovery had been achieved, a final sample was collected for Tritium analysis. This sample was collected from all packer test zones except in borehole MW-40. In some test zones, as noted above, an additional sample was collected for Strontium analysis. After samples were retrieved, the packers were deflated and pressure transducer data was collected.

Packer test intervals and test pressures were measured in the field and recorded by GZA personnel along with all pertinent testing data. Hydraulic conductivity calculations and methodologies are presented in **Appendix G**. Packer test result summary sheets are presented in **Appendix I**. **Table 4.4** summarizes hydraulic conductivity data collected during packer testing.

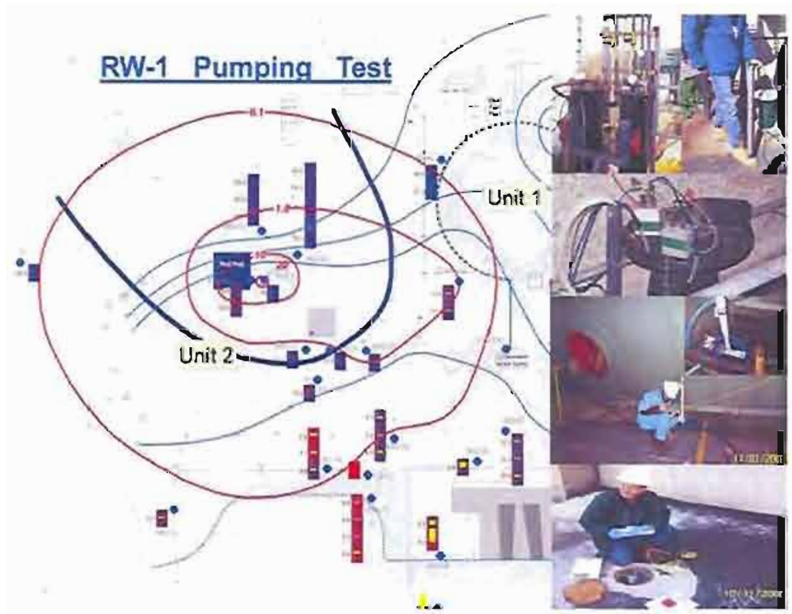
In addition to the analyses referenced above, depth-specific borehole transmissivity values were also computed by the USGS using the heat pulse flow meter data collected during the geophysical logging. These data generally confirmed the packer testing values computed as discussed above (see figure below for an example comparison). In some cases however, these two methods did not correlate well, as reflective of the limitations inherent with each method. For example, the heat pulse flow meter analyses yielded lower transmissivity values where the packer testing transducer data indicated leakage around the packers. In other cases, the heat pulse flow meter analyses proved to be too insensitive to measure lower transmissivity values.



COMPARISON OF PACKER TESTING TO HEAT PULSE FLOW METER ANALYSIS OF TRANSMISSIVITY

4.4.4 Pumping Test

GZA conducted a step drawdown, constant rate drawdown, and aquifer recovery test in recovery well RW-1 near the IP2-SFP as shown on **Figure 1.3**. Collectively, these tests are referred to as the "Pumping Test." The Pumping Test was performed in general accordance with our Standard Operating Procedure (SOP) dated October 11, 2006 and submitted as part of the "Pumping Test Report" dated and submitted to Entergy on December 8, 2006. A schematic of the Pumping Test data, testing and pumping equipment, and data monitoring is provided below.



EQUIPMENT, MONITORING AND DATA FROM PUMPING TEST OF RW-1

Prior to the Pumping Test, GZA installed select instrumentation including flow meters, precision gauges, and valving at the well head to control flow and to collect samples, and transducers in wells and drains to measure water level response to pumping.

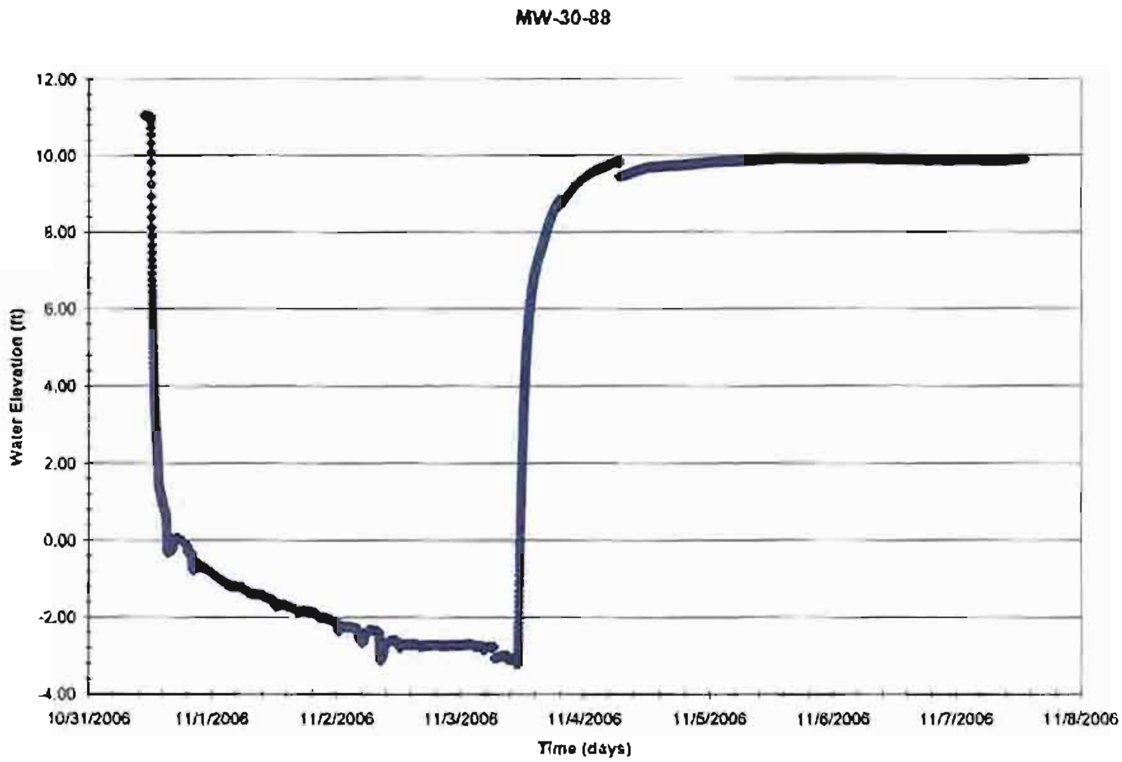
GZA conducted the Pumping Test by extracting groundwater from RW-1 at the following average flow rates:

Test Name	Begin Date	End Date	Pumping Rate at RW-1
Step Drawdown	10/25/2006	10/25/2006	2 gpm for 88 minutes 4 gpm for 77 minutes 5 gpm for 63 minutes 7 gpm for 28 minutes
Constant Rate Drawdown	10/31/2006	11/3/2006	4 gpm for 71 hours
Recovery	11/3/2006	11/6/2006	No pumping

PUMPING TEST SUMMARY TABLE

During the Pumping Test, we monitored and recorded the following:

- Water level elevations with 75 pressure transducers at 44 groundwater monitoring wells at the Site. Water levels in the 15 primary monitoring wells (i.e., I-2, MW-30, -31, -32, -33, -34, -35, -36, -37, -42, -47, -51, -52, -53, and -111) were monitored once per minute. The remaining 29 wells (MW-38, -39, -41, -43, -44, -45, -46, -48, -49, -50, -54, -55, -56, -57, -58, -59, -60, -62, -63, -65, -108, -109, U3-2, U3-3, U3-C1, U3-T1, U3-T2, U3-4D, and U3-4S) were monitored hourly.
- Water quality parameters; we also collected groundwater samples for Tritium and Strontium analysis during the step drawdown and constant rate drawdown test at RW-1.
- Flow rates at the IP1-NCD and IP1-SFDS, and the IP2-Curtain Drain; generally at the frequency and using the methods stated in the SOP.
- Precipitation via data available from the on-Site meteorological tower or via information available at www.wunderground.com for the surrounding area.



EXAMPLE OF TIME VS DRAWDOWN CURVE FOR MW-30

The Pumping Test activities are further detailed in our December 8, 2006 report. The results of the Pumping Test are described in **Section 6.0**.

4.5 WATER SAMPLING

Sampling of on-Site groundwater and surface water sources and off-Site groundwater and surface water sources was conducted during the period of this study. The locations and methods of sampling are described in the following sections. The results of the sampling are discussed in **Section 10.0**.

4.5.1 On-Site Groundwater Sampling

On-Site groundwater sampling commenced in August 2005, upon observation of the moist shrinkage cracks in the IP2-SFP wall. Through May 2007, sampling was conducted primarily by Entergy personnel. During this period, GZA personnel collected groundwater samples only during packer testing and when conducting low flow groundwater sampling at monitoring wells MW-30 and MW-42. After May 2007, GZA personnel conducted all groundwater sampling. Over 700 groundwater samples were collected during the study.

GZA and Entergy personnel collected groundwater samples using traditional purge techniques, modified purge techniques, or low flow sampling techniques. Groundwater samples were collected from specific intervals in monitoring wells MW-30 and the 2-inch diameter well-screened interval of MW-42 using low flow purging and sampling methods described in the USEPA's Low Flow Purging and Sampling Guidance document. These sampling techniques are described in the following sections.

4.5.1.1 Purging

At the early stages of the project, Entergy personnel sampled open borehole wells and nested piezometers by purging the traditional 3 to 5 times the volume of water standing in the well casing[19]. This was accomplished with either a dedicated submersible pump, a peristaltic pump with dedicated tubing, or a Waterra foot-valve pump with dedicated tubing. As the investigation proceeded, GZA became concerned that the standardly-required purge volume could force unrepresentative displacement of contaminants in the low conductivity bedrock through sampling-induced drawdown in the wells. We therefore reduced the purge volume, for wells not low flow-sampled, to 1.5 well volumes for the remainder of the investigation. This modification to the sampling procedures was discussed with the regulators. By May 2007, low flow sampling procedures had been adopted and implemented for all wells.

4.5.1.2 Low Flow Sampling

The low flow sampling method allows collection of groundwater samples representative of ambient flow conditions at discrete sampling zones, while limiting the accumulation of wastewater, mobilization of contaminants, and turbidity of samples by reducing pumping rate and drawdown. GZA collected low flow groundwater samples using peristaltic pumps, Grundfos Readiflo II submersible pumps, and several models of submersible pumps manufactured by Proactiv. Low flow samples were also collected at discrete sampling intervals of deeper boreholes using Solinst Multilevel Waterloo sampling systems. The use of Waterloo systems for low flow sample collection is summarized in the following section. With the exception of wells MW-30 and MW-42, GZA began low flow sampling in May 2007. GZA collected samples from MW-30 and MW-42 using low flow techniques starting in January 2006.

GZA collected low flow samples by slowly pumping from a predetermined well depth while monitoring water quality parameters, including pH, specific conductance, temperature, turbidity, dissolved oxygen, and oxygen reduction potential (ORP). Water quality parameters were monitored using a Horiba U22 water quality meter with an in-line flow-through cell. Pumping rates were typically between 100 and 400 ml per minute, and drawdown within the well was typically limited to between 0.1 and 1.0 foot.

GZA recorded water quality parameters, water level, and flow rate every five to ten minutes during a pre-sampling purge which lasted generally between one half hour and three hours. Samples were collected upon stabilization of water quality parameters listed above. Low flow sampling logs are provided in **Appendix J**. Note that sampling logs dated prior to May 2007 reference original well nomenclature.

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[19] Water quality parameters during well purging were not measured by Entergy personnel as part of their groundwater sampling rounds.

4.5.1.3 Waterloo Low Flow Sampling

Low flow sampling was also conducted in Waterloo installations at MW-30, -31, -32, -39, -40, -51, -52, -54, -60, -62, -63, and -67. Samples were taken from discrete intervals unless the interval was depressurized, in which case 1.5 well volumes were purged prior to sampling.

LOW FLOW SAMPLING OF MW-30

4.5.1.4 Discrete Interval Packer Sampling

During packer testing prior to installation of Waterloo systems, GZA collected groundwater samples representative of several distinct elevations within each borehole. GZA collected water samples for Tritium analysis for each tested interval in all boreholes except MW-40. Water samples were also collected for Strontium analysis in boreholes MW-54, -60, -62, -63, and -66. Sampling procedures were described in **Section 4.4.3.**

4.5.2 On-Site Surface Water Sampling

On January 19, 2007, GZA collected samples from the Discharge Canal and Hudson River to evaluate major cation geochemistry. This sampling was designed to help us assess potential sources of water found within monitoring wells MW-38 and -48. Samples were collected with dedicated high density polyethylene bailers. In addition, Entergy routinely collects composite water samples from the Discharge Canal to evaluate the discharge of radionuclides to the Hudson River. These samples are collected using peristaltic pumps at locations indicated in the Annual Radiological Environmental Operating Report (AREOR).

4.5.3 Off-Site Groundwater Sampling

At the beginning stages of the investigation, prior to a thorough understanding of the hydrogeology of the Site, several off-Site groundwater wells were sampled by Entergy personnel to assess the potential for off-Site contamination. These data are presented in the AREOR and the sampling is conducted under the Radiological Environmental Monitoring Program (REMP). During the course of this study, the normal sampling frequencies were increased to either monthly or quarterly to assess regional background concentrations of contaminants of interest. These sampling points included: four USGS monitoring wells, three LaFarge property wells, and the Fifth Street well in Buchanan. **Figure 4.3** shows the locations of the USGS Wells. **Figure 1.3** portrays the location of the LaFarge wells. Please refer to the AREOR for the location of the Fifth Street well.

USGS Wells - On December 5 and 6, 2006, GZA personnel, accompanied by a New York State Department of Environmental Conservation (NYSDEC) representative, collected groundwater samples from four USGS groundwater monitoring wells to assess background concentrations for Tritium, Strontium and Cesium in the region. The wells were located in Harriman State Park, Rockland County, (RO543); Carmel, New York, Putnam County (P1217); Fort Montgomery, New York, Orange County (local municipal water monitoring well); and Doodletown, New York, Rockland County (RO18). All four monitoring wells were completed in bedrock. The NYSDEC provided GZA with borehole geophysical data. All four wells exhibited upward vertical gradients. GZA selected sample locations based upon the flowmeter data so as to sample the groundwater at a depth just below where it was presumed to be exiting the borehole. The groundwater samples were transported to Entergy under chain of custody procedures. Entergy personnel then shipped the samples to Areva Laboratories in Westboro, Massachusetts for analysis of Tritium, Strontium and Cesium.

LaFarge Wells - GZA personnel supervised the collection of groundwater samples from the Lafarge property immediately South of the Site from groundwater monitoring wells MW-1 through MW-3. Samples were collected by LaFarge's environmental consultant, Groundwater and Environmental Services, Inc., under the oversight of Entergy personnel, GZA and NYSDEC representatives on September 19, 2006. Groundwater samples were collected using a bladder pump following low flow procedures described below. The depths of the wells are shown on **Table 4.1**.

Fifth Street Well - Entergy personnel, accompanied by NRC and NYSDEC personnel, collected samples from the Fifth Street well in Buchanan, New York on November 30, 2005. This well is a former private drinking water well no longer in use.

4.5.4 Off-Site Surface Water Sampling

During the course of this study, off-Site surface water was sampled at the following locations: the Camp Field Reservoir and the New Croton Reservoir, Algonquin Creek, Trap Rock Quarry, the LaFarge property (Gypsum Plant) outfall, and the Hudson River (see **Figure 4.4** for the locations of the Reservoirs). The sampling frequency discussed in the AREOR was increased during the investigation. Detailed sample locations are discussed in the AREOR.

4.6 PIEZOMETRIC LEVELS AND PRESSURE TRANSDUCER DATA

GZA measured piezometric levels at 67 locations at the Site over time (between October 2005 and September 2007) using a system of electronic pressure transducers. These measurements were converted to groundwater elevations (NGVD 29) by referencing the depth of the transducer below the water table at a given time to the elevation of the top of the monitoring well riser. GZA used the resulting data to estimate hydraulic properties of the soil and bedrock, and assess the effects of precipitation, tidal influences, seasonality, and pumping on groundwater flow patterns.

This section describes the methods we used to collect and manage this data. Discussions on the use of the data are presented in **Sections 6.0** and **10.0**.

4.6.1 Transducer Types and Data Retrieval

GZA used two types of transducers, depending on the well type and application. In open wells, GZA installed MiniTroll and LevelTroll transducers, which are vented pneumatic transducers with internal dataloggers. These transducers are manufactured by In-Situ® Inc. In wells equipped with Waterloo systems, GZA installed non-vented vibrating wire transducers manufactured by Geokon® Inc. Each of these transducers was connected to a Geokon datalogger box located within the well vault.

GZA selected and installed pressure transducers within the appropriate operating pressure range required for each well or well interval. **Table 4.5** provides the accuracy of the transducers as reported by In-Situ and Geokon. This table also provides the type of transducer used in each well or well interval.

GZA collected data from In-Situ transducers typically every one to three months, or as needed. We exported data collected from each transducer from data files recognizable only by Win-Situ software into Microsoft® Excel® spreadsheets. Generally, no external data manipulation was required for these data reports. On occasion, adjustments to data were required to correct for daylight savings time, or to correct for measured disturbance of the transducer position within the well.

GZA collected water level data from each Geokon datalogger typically every two weeks to two months, or as needed. After collection, we exported the raw data into Excel spreadsheets and converted reported water levels to water elevations. Because the Geokon transducers are not vented, we adjusted total pressures to account for barometric pressure changes. Into each data report, GZA incorporated: 1) the barometer reading recorded during wellhead zeroing of the respective transducer; and 2) the barometric pressures recorded at or near the Site at the time the total pressures were recorded. Barometric pressures for this project were recorded on an on-going basis on Site using a Geokon transducer exposed to atmosphere. At different times, the barometric pressure transducer was installed several feet above the maximum water table in MW-31, MW-65, and MW-56. For verification, GZA also used barometric pressure data collected by West Point Military Academy, less than ten miles from the Site.

4.6.2 Data Availability and Preservation

A compact disk containing piezometric data collected between October 2005 and September 2007 is provided in **Appendix K**. The data is organized by well number in Excel spreadsheets. Note that piezometric data dated prior to May 2007 reference original well nomenclature.

Graphs of water levels between October 2005 and February 2007 are presented in **Appendix L**. Transducer installation logs are provided in **Appendix M**. As indicated by the legend on the first sheet of this Appendix, colors on these graphs illustrate changes in groundwater temperature. Each graph presents water levels from wells that are grouped together based on proximity to each other and association with selected Site features. Well locations are shown in **Figure 1.3**.

4.7 TRACER TESTING

To further test the Conceptual Site Model and assess groundwater flow paths from the source areas, GZA conducted an organic tracer test consisting of the injection of Fluorescein (a common dye used in anti-freeze) at a tracer introduction point located close to a potential source of Tritium at IP2-FSB. The injection well was installed approximately four feet South of the expansion crack observed in the South wall of the IP2-SFP, adjacent to monitoring well MW-30. The injection well was designed to allow the injection of tracer onto the top of bedrock located at elevation 52 feet. This elevation corresponds to the bottom of the IP2-SFP. Tracer was then gravity fed into the injection well and flushed with water. After injection, routine sampling and monitoring for the presence of tracer in Site wells commenced and continued for 27 weeks[20].

The tracer introduction was made on February 8, 2007. Tap water was introduced into the injection well adjacent to MW-30 beginning at 10:30 hours. By 10:41 hours, 30 gallons of water had been introduced into the injection well to wet the surfaces of the material down gradient from the injection well. The water introduction was then suspended while ten pounds of Fluorescein dye mixture containing approximately 75% dye and 25% diluent, all of which had previously been dissolved in ten gallons of water, was introduced into the injection well. The dye mixture was introduced between 10:42 and 10:50 hours. Tap water introduction was resumed at 10:51 hours and continued until 11:40 hours. A total of 210 gallons of water was used: 30 gallons to wet the surfaces, 10 gallons to dissolve the tracer, and 170 gallons to flush the tracer out of the dry well into the surrounding bedrock fracture system. Water introduction was made at a mean rate of three gallons per minute.

Sampling and monitoring continued through mid-August 2007, which constituted the completion of the test. The well locations monitored during the organic tracer test and the sampling results are presented in **Appendix N**.

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[20] In addition to the routine sampling, specific wells were sampled for a longer period of time as part of short term variability testing (see Section 9.0)

The following sections describe the key elements of the test. The results of the tracer test are discussed in **Section 7.0.**

4.7.1 Injection Well Construction

Following excavation of soil and rock along the southern wall of the IP2-SFP for the construction of a new foundation for a heavier crane, the top of rock was exposed along the South wall of the IP2-SFP at elevation 52 feet. Prior to pouring a mud-mat, construction of the crane foundation and backfilling of the excavation, GZA installed one groundwater monitoring well (MW-30) and one dye injection well. The dye injection well was constructed of one-inch Schedule 40 PVC pipe which terminated at elevation 52 feet. In order to provide a reservoir for the dye to accumulate in prior to seeping into bedrock fractures, a one-foot-thick layer of ¾-inch crushed stone was placed on the top of rock over an area approximately 6 feet by 6 feet square. A mud-mat was poured over the crushed stone layer and across the entire floor of the excavation. The excavation was then backfilled. This injection well design allowed for the dye to be injected on the top of rock and infiltrate into the bedrock in a similar manner as water leaking from the South wall of the IP2-SFP.

4.7.2 Background Sampling

Prior to injection of dye, GZA collected background samples to assess the potential of Fluorescein to be present in the subsurface. Almost all sample locations (which included manholes, surface water bodies, nested wells, Waterloo wells) were sampled for approximately one week periods two to five times prior to dye introduction. This set of data helped in the selection of dye type and quantity, and assured that background levels of Fluorescein were not an obstacle to conducting the groundwater tracing investigation.

4.7.3 Sampling Stations

Sampling stations were selected by GZA for their relevance to the project. Some stations were established as control stations. Control stations were established to detect any fluorescent compounds not introduced as part of this investigation which might enter the study area. Most sampling stations were established to detect dyes introduced during this investigation.

Sampling stations included manholes into the Site drainage system, open waters such as the Discharge Canal and the Hudson River, clusters of nested wells, open borehole wells, and wells with Waterloo packer systems installed. Primary reliance for the detection of dye was placed on activated carbon samplers except at Waterloo locations. One carbon sampler was placed in each well and two were placed in open water locations and in manholes. Open water locations may have strong currents that could damage or wash away a sampler. Placing two samplers at these locations helped ensure that data would be collected for any given time interval and provided duplicate samples for quality assurance. At Waterloo wells, water was the only sampling medium.

Carbon samplers are continuous, accumulative samplers that virtually assure that dye migrating with groundwater is not missed at sampling locations. These samplers, however, provide information on the concentration of dye at a specific time. Because water is an instantaneous sample instead of a continuous sample the Waterloo wells were sampled more frequently.

The sampling schedule was designed to help ensure that the time the tracer arrived was recorded, and that it would be unlikely that a transient event would fail to be detected at any sampling location. The latter point only applies to the Waterloo sampling locations, since carbon packets collect samples continuously. Grab samples of water only represent the conditions at the instant the water is collected.

High frequency (or high intensity) sampling stations were selected based primarily on three criteria:

- The boundaries of the Unit 1 plume. Most wells that are located within the plume were sampled frequently.
- The premise that non-detections of dye could be as important as detections. Therefore, a "halo" of wells expected to have no detectable dye were sampled surrounding the Unit 1 plume so that the boundaries of the tracer plume would be well defined.
- That there was the possibility of poor correspondence between the tracer plume and the Unit 1 plume at some locations, and that the network might have to be adjusted to maintain the halo of non-detection sampling locations. This resulted in frequent review of the sampling network, and sampling stations were moved from the low intensity to high intensity sampling schedule as tracer was detected near the margins of the high intensity sampling network.

4.7.4 Analysis Schedule

Samples were typically shipped from the Site on the sample collection day or the next day to accommodate next day delivery. Primary samples (both carbon and water) were analyzed within five working days after receipt. Water samples analyzed because of tracer detections in the associated carbon samplers were analyzed within five working days following the carbon analyses. Results were communicated to both Ozark Underground Laboratory (OUL) and GZA project management for review of the detections and consideration of whether or not the sampling network should be modified.

4.8 ADDITIONAL GEOPHYSICAL TESTING TO EVALUATE FLOW PATHS

In addition to the downhole geophysical testing described in **Section 4.2.4**, a series of geophysical surveys was conducted to assess the depth to bedrock in certain areas of the Site and to identify the potential presence of preferential groundwater flow paths along utility trenches cut into bedrock. The major findings of the surveys are graphically shown on **Figure 1.3.**

Under the oversight of GZA, AGS conducted surface geophysical surveys to assess depth to bedrock within the IP2-TY, along the North side of IP2-Turbine Generator Building (TB), within the IP3-TY and along the OCA access road on the southern side of the Protected Area. AGS used ground penetrating radar (GPR) and electromagnetic (EM) survey equipment to complete the surveys. The survey reports are attached in **Appendix O.** The results of the surveys indicate that bedrock is fairly shallow beneath the areas investigated, except for the areas along the Hudson River where the depth to bedrock increases.

Specifically, the following work was completed:

- A GPR survey was conducted to assess depth to bedrock and potential utility trenches cut into bedrock in the IP3-TY.
- A GPR survey was conducted to assess the potential for contaminants to enter groundwater through leaking stormwater pipes (E-Series) and flow with groundwater towards the Hudson River within utility trenches cut into rock along the OCA access road on the South side of the Protected Area, and to identify depth to bedrock and any utility trenches cut into rock along this roadway.
- In order to assess the presence of subsurface utility trenches to provide preferential pathways for contaminated groundwater to flow to the North, thus accounting for the impacts to groundwater observed in monitoring well MW-48 and MW-38, AGS performed a geophysical survey consisting of a seismic refraction survey, GPR survey, and an EM survey to provide information on bedrock topography on the southern side of the Site between the Protected Area and the southern warehouse.
- In addition, several utilities were identified using EM survey techniques. However, no information regarding the nature of the backfill along the utilities could be discerned from the geophysical information.

The findings of the geophysical survey work are discussed in **Section 6.0**.

5.0 LABORATORY TESTING

Entergy and GZA arranged for, and managed, the analyses of groundwater samples. Between October 2005 and the end of September 2007, over 700 samples were analyzed for radiological contaminants, and, as part of the tracer test, nearly 4,400 samples were analyzed for Fluorescein. In addition, a limited number of samples were analyzed for selected water quality parameters. This section describes the respective testing programs as well as some of the Quality Assurance/Quality Control (QA/QC) procedures used to assess the validity of the data.

5.1 RADIOLOGICAL

Entergy and GZA personnel both collected groundwater samples for radiological analysis from existing and newly installed wells between October 2005 and September 2007. Groundwater samples were sent by Entergy personnel via chain of custody to outside laboratories for analysis of select parameters including Tritium, Strontium, gamma emitters (including Cesium, and Cobalt), and Nickel[21]. Samples were analyzed at the following laboratories: IPEC, Teledyne Brown Engineering, Inc., located at 2508 Quality Lane, Knoxville, Tennessee; Areva NP, Inc. located at 29 Research Drive, Westboro, Massachusetts; James A Fitzpatrick, NPP Environmental Laboratory, located at 268 Lake Road, Lycoming, New York; and General Engineering Laboratories located at 2040 Savage Road, Charleston, South Carolina. The results of the groundwater analyses are summarized in **Table 5.1**. Note that the sample nomenclature for groundwater analytical data collected after May 2007 are provided in the figures, however, location nomenclature prior to May 2007 may differ[22] due to subsequent casing reference point upgrades.

5.1.1 Hydrogeologic Site Investigation Analytical Data

Groundwater samples were typically analyzed for the following: Tritium by EPA Method 906; Strontium by EPA Method 905; and gamma emitters (including Cesium and Cobalt). In addition, transuranics and Nickel (as well as other "hard to detect" radionuclides) were also analyzed in specific instances, as appropriate.

Quality control criteria utilized during this investigation included the following as appropriate: laboratory blanks; field duplicates; laboratory duplicates; laboratory control samples; matrix spikes and matrix spike duplicates; initial and continuing calibrations; instrument tuning; internal standards; and regulatory split samples.

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[21] Tritium and Strontium were the primary radionuclides focused on during the current work pursuant to source identification, groundwater flow analysis and contaminant plume delineation. Radionuclides other than Tritium and Strontium also exist to a limited extent and are fully addressed within the context of the Unit 2 Tritium and Unit 1 Strontium discussions.

[22] See **Section 4.3.4.** Note, however: 1) High priority and fast track sampling preceded casing elevation surveys and vault installation in several cases, 2) low flow sampling within a well screen resulted in collection of samples at depths differing from the well nomenclature, and 3) reinstallation of Waterloo multilevel wells to upgrade packer assemblies. In addition, sample intervals are designated by depth from top of casing.

An overall evaluation of the data indicates that the sample handling, shipment and analytical procedures have been complied with, and the analytical results should be useable. However, during one time period (August and September 2006), Strontium analytical results from Teledyne Brown Engineering, Inc. were as much as an order of magnitude different than split samples analyzed by the NRC and the NYSDOH. (Following verification of this information, the laboratory was dropped from the investigation program.) Therefore, that sample set was not utilized as part of the investigation.

Data Collection and Tracking

The data collection and data tracking phase included the following:

- Preparing all sample bottle labels and chain-of-custody forms;
- Documenting all required data in field log books and field logs;
- Performing data entry of the sampling information into Entergy's database system; and
- Quality assurance/quality control reviews of all data entry.

Laboratory Analysis

The laboratory analysis phase included the following:

- Regular communication between the laboratory and the project laboratory data manager;
- Reviewing the laboratory's sample receipt acknowledgement form;
- Documenting the project's progress in Entergy's database system; and
- Laboratory preparation of the Electronic Data Deliverable (EDD).

Data Loading

The data loading phase included the following:

- Loading all EDDs into the database;
- Resolving any data loading issues;
- Creating a post-load report for content review; and
- Notifying the project team when EDDs were available.

Data Visualization and Analysis

The data visualization and analysis phase included the initial data review by the project team and the production of data queries and draft reports to interpret the data. This phase was accomplished through the use of query tools and preformatted reports in the database.

5.2 ORGANIC TRACER

Sampling for the tracer was based on both activated carbon samplers and on grab water samples. All analyses were conducted using a Shimadzu RF5301 fluorescence spectrophotometer operated under a synchronous scan protocol. Details of the analytical approach are presented in the Ozark Underground Laboratory (OUL) procedures and criteria document **(Appendix P)**.

5.3 WATER QUALITY PARAMETERS

Groundwater samples were collected from monitoring wells MW-38, MW-48-23, and MW-48-38 and also from the Discharge Canal and Hudson River. The groundwater was collected as a grab sample using low flow sampling techniques. The surface water samples from the top of the water column were collected using bailers. The samples were collected at high and low tides. Groundwater samples were also collected at mid tide[23]. The samples were sent under chain-of-custody procedures to Life Science Laboratories, Inc., Brittonfield Parkway, Suite 200, East Syracuse, NY 13057. The samples were analyzed for Bicarbonate Alkalinity (as $CaCO_3$) under EPA Method M2320; Iron, Magnesium, Sodium, and Calcium under EPA Method 6010; and Sulfate and Chloride under EPA Method E300.

[23] Sample nomenclature was as follows: Monitoring Location Name-Depth Interval (if applicable), Tide Interval (H=High, M=Mid, L=Low) and replicate number (if applicable).

6.0 HYDROGEOLOGIC SETTING

This section describes the hydrogeologic setting at IPEC. Our description is based on a literature search and the findings of our field investigation program. The hydrogeology is described in reference to the two components of an unconfined aquifer found at IPEC; overburden and bedrock. Both the overburden (in select areas) and bedrock are groundwater-bearing zones which are monitored at the Site. Refer to **Section 4.0** for a summary of the groundwater monitoring system.

6.1 REGIONAL SETTING

The surface topography in the region of the Site slopes downward relatively steeply towards the Hudson River and is characterized by ground surface elevations ranging between approximately 10 and approximately 140 feet above the National Geodetic Vertical Datum of 1929 (NGVD 29). Refer to **Figures 1.3** and **3.2** for Site and regional topographical maps.

The Hudson River is a tidally influenced estuary in the vicinity of the Site, generally experiencing two high tides and two low tides daily. Near high tide, the river experiences a flood current running North. Near low tide, the river experiences an ebb current flowing South. Surface water elevations of the Hudson River as measured at Peekskill, NY, approximately two miles North of the Site, from October 20, 2005 through May 8, 2006 have ranged from -1.31 feet to 3.26 feet NGVD 29. On-Site measurements indicate that the Hudson River elevations vary between -1.1 feet to 3.8 feet NGVD 29.

Other surface water features include the cooling water Discharge Canal with a mean surface water elevation of approximately 1.7 feet above the Hudson River. The Discharge Canal is shown on **Figure 1.3**. The Discharge Canal conveys up to 1.76 million gallons per minute (MGM) from Units 2 and 3, discharging to the Hudson River. As shown on cross-sections A-A' and B-B' on **Figure 1.3**, the walls of the canal are constructed of low structural concrete. However, the current condition and thickness of the canal bottom is variable and appears to range from a 0.5-foot-thick mud slab in the IP2 area (based on construction drawings) to a bedrock bottom in the IP1 area.

Stormwater at developed portions of the region and Site is directed towards and collected in catch basins and discharged to surface water bodies. Stormwater discharges from the Site are routed to the cooling water Discharge Canal[24], the Hudson River, or the groundwater regime through leaks from the storm system.

6.2 GROUNDWATER RECHARGE

Groundwater recharge at and near the Site is limited to precipitation. That is, there is no significant artificial recharge or irrigation in the area. Precipitation in the vicinity of the

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[24] There are stormwater outfalls that discharge directly to the Hudson River.

Site is approximately 36 inches per year[25]. Recognizing that a portion of precipitation is lost to evaporation, transpiration, and run-off, direct recharge to an aquifer was estimated. Large scale modeling performed by the USGS for Westchester County, NY[26], suggests that groundwater recharge to glacial till-covered bedrock hills, typical of the conditions near Indian Point, ranges from 3.6 to 7.5 inches per year with an average of 5.5 inches per year. Our experience in a similar hydrogeologic setting[27] found higher natural recharge rates, averaging approximately 10 inches per year. Considering all available information, we believe recharge at the Site is between 1/10 and 1/3 of precipitation. Based on our evaluation, we estimate recharge on and up-gradient of the Site is approximately 10 inches/year[28]. Note that for the purposes of this study (as opposed to water supply evaluations), it is conservative to use high estimates for recharge.

6.3 GROUNDWATER DISCHARGE

Groundwater flows from areas of higher heads to areas of lower heads along the path of least resistance. At the Site, discharge from the groundwater occurs into the Discharge Canal, the Hudson River, and to system underdrains. As evidenced by Site groundwater contours, groundwater discharge is not uniform along the river or to the Discharge Canal. That is, the aquifer in areas of the Site with higher transmissivities (lower resistance to flow) will discharge more water than other areas. Similarly, the water table fluctuates seasonally (due to long term changes in average recharge rates) and locally during rainfall events and periods of snow melt. Consequently, groundwater discharge is not constant in time. Additionally, changes in the river elevation cause additional short term variations in discharge rates.

The Hudson River is the regional sink in the area. As such, groundwater from the upland areas to either side of the river valley flow towards and discharge to the river under ambient conditions, see **Figure 6.10**. Groundwater from IPEC does not flow under the river to the other side (e.g., to Rockland County) under ambient conditions. Further, because of the hydraulic properties of the bedrock, as well as the size of the Hudson River in this area, there is no reason to believe that pumping or injection (non-ambient conditions) could induce such flows.

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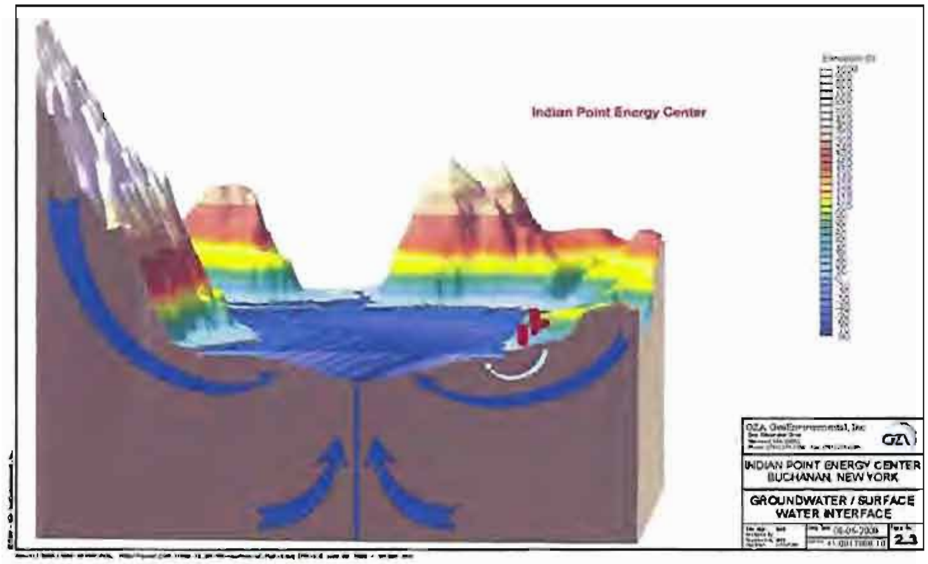
[25] This precipitation value is a 10 year average of data available from the on-Site meteorological station.

[26] USGS. Water Use, Ground-Water Recharge and Availability, and Quality of Water in the Greenwich Area, Fairfield County, Connecticut and Westchester County, New York, 2000-2002.

[27] Calibrated Groundwater Model, Central Landfill Super Fund Site, Johnston Rhode Island, June 2006

[28] Areal Recharge varies temporarily and spatially. The average of 10 inches per year is an estimated watershed-wide, long term average. The development at the Site induces additional runoff. We believe that this potential decrease in areal recharge is offset by recharge from exfiltration of leaky stormwater systems. As discussed in **Section 6.7**, this appears to be the case.



GROUNDWATER FLOW BELOW AND INTO HUDSON RIVER

Foundation drains at three structures (see **Section 6.7**) intercept groundwater (see **Figure 1.3**). This water is conveyed, via gravity flow and/or pumping, to the Discharge Canal, creating local depression in the water table and a flattening of hydraulic gradients downgradient of the structure. With these conditions noted, over a period of months the rate of groundwater discharge to the river at IPEC is continuous and fairly constant. Discussions on the rate of discharge are provided in **Section 6.7**.

6.4 GEOLOGY

This section describes the geology of the Site and region. It is based upon a literature search and the results of our investigations. **Figure 6.2** portrays the regional bedrock geology. The narrative is organized to convey the role of geologic and tectonic processes in creating the mechanisms by which groundwater flows through the Site[29]. Findings support our Conceptual Site Model (CSM) and indicate that the bedrock at the Site is characterized by sufficiently interconnected small bedrock fractures to allow the hydrogeologic system to function and be modeled as a non-homogeneous, anisotropic, porous media.

6.4.1 Overburden Geology

The Lower Hudson Valley has been subjected to repeated glacial advance and retreat, creating a typical glacial morphology of main and tributary valleys and bedrock ledges. The glaciers have controlled the deposition of unconsolidated deposits in the region, although these are absent locally due to erosion and excavation. Glacial till lies directly on the bedrock surface and is generally less than 10 feet thick, although it is locally thicker against steep North-facing bedrock slopes. The till is typically unstratified and

[29] The Inwood Marble, which predominates at the Site, is a crystalline metamorphic rock type. As such, it has a very low primary porosity (i.e., water does not flow through the intact rock itself, but is confined to the fractures in the rock.

poorly sorted. Locally, it consists of a silty, fine- to medium-grained, brown, sandy matrix containing fine gravel to boulder-size bedrock fragments. Fluvial and lacustrine glacial deposits occur in valley bottoms and valley walls. The glacio-fluvial deposits are typically medium to coarse sand and gravel with minor silt. The lacustrine deposits are finely laminated and varved clays fining upwards to fine- to medium-grained sand, and the fluvial/deltaic sediments are mixtures of coarser sands and gravels and finer sands to clays. Recent deposits are essentially flood plain and marsh deposits along the Hudson River, its tributaries, and small enclosed drainage basins.

Overburden geology at the Site is limited to a layer ranging from ground surface to between 3.5 and 59 feet below ground surface (bgs), with thicknesses generally increasing towards the Hudson River. Overburden materials are dominated by anthropogenic fill (borings MW-41, -49, -52, as well as the upper 20 feet of -39, -48, -61, -62, -63, -66 and 67). Soil-based fill materials at the Site consist primarily of silty clay, sand and gravel mixtures (i.e., regraded/transported on-site glacial till) or gravel/cobble/boulder-size blast rock. In areas adjacent to structures excavated into bedrock, the fill occurs as concrete, compacted granular soils, and blast rock fill. Native materials occur as open areas of glacial till overlying bedrock, or silty clays, organic silt and clay, and sandy material overlain by granular fill. A 20- to 50-foot-thick sequence of river sediments (organic silts) is found along the Hudson River above bedrock in borings MW-38, -48, -61, -62, -63, -66 and 67 The approximate location of natural materials is shown on **Figure 6.3**.

6.4.2 Bedrock Geology

The geology of the Site has been investigated and reported by Dames & Moore (1975) prior to this program. **Figures 6.2** and **6.4** show the bedrock geology of the region and the Site, respectively. The current investigations have added substantial detail to this assessment which shows that the bedrock beneath the Site is considerably fractured and contains sufficient interconnectivity to support groundwater flow, at the scale of the Site, as flow through a non-homogeneous, anisotropic, porous media.

The Site is located in a complex of Cambro-Ordovician rocks represented by the Manhattan Formation and Inwood Marble Formation in angular unconformity. The Site lies predominantly upon the Inwood Marble Formation as an angular unconformity with the Manhattan Formation. The oldest rock is the Inwood Formation, which was derived from deposition of carbonate materials in a shallow inland sea during the Cambrian through the early Ordovician period. The Manhattan Formation is interpreted to post-date the Middle Ordovician regional unconformity with the Inwood Marble and represents sediments derived from continental or volcanic island materials in deeper waters.

During the Ordovician period, an island arc system consisting of a series of volcanic islands appeared off the coast of what is currently North America as a subduction zone developed in response to oceanic crust colliding with continental crust. The presence of the volcanic island arc system resulted in interlayering of volcanic material with the sedimentary rocks of the Inwood Marble and Manhattan Formations. As continued subduction occurred and continental land mass began to collide with continental North America during the Taconic and Acadian Orogenies, the rocks of the Inwood Marble

Formation and the Manhattan Formation underwent substantial metamorphism and deformation.

The Inwood Marble is a relatively pure carbonate rock of dolomitic and/or calcic mineralogy with silica rich zones. The rock tends to be coarsely sacherroidal with remnant foliation and intercalated mica schist. The color and crystalline texture vary from place to place due to the various levels of metamorphism; the color is typically white to blue grey. The metamorphic grade is locally elevated due to minor intrusions. The common minerals are calcite, dolomite, muscovite, quartz, pyrite and microcline. The Manhattan Formation is represented on the Site by two distinct members. The lower member is an assemblage of schist, schistose gneiss and amphibolites intercalated with marble, white quartzite and fine-grained metapelite. The marble bearing lower member of the Manhattan Formation likely represents transition from a shallow carbonate sea to deeper water sedimentation and maybe the equivalent to the Balmville Limestone which occurs in Dutchess County[30]. The middle member is garnet rich mica schist. The upper member consists of biotite-muscovite mica schist with quartz-feldspar laminae.

The original sediments have undergone repeated intense phases of burial, metamorphism, uplift, folding and faulting due to: three phases of continental collision (the Taconic, Acadian, and Alleghanian); continental rifting as the present Atlantic Ocean began to form in the Mesozoic; erosion/uplift; and recent glacial rebound. All of these processes have resulted in the presence of fractures that affect the hydraulic properties of the material. The main deformational events are represented by multiple superimposed textures and structures including faults, healed breccias, crenulations, foliation slips, micro-faults, and continuous/truncated joints/fractures. The first phase of fold deformation (F_1) was essentially ductile and produced isoclinal folds contemporaneous with the most intense metamorphism. It was at this time that the dominant foliation likely developed along original bedding planes. The cooling period following this phase marks the onset of regional brittle faulting and development of fractures along the bedding planes. The second phase of folding (F_2) is characterized by flexural slip, indicative of brittle conditions, producing distinct fault and fracture orientations: a conjugate system normal to the foliation; West-Northwest and North-South conjugate strike-slip faults; Northwest faults and fractures parallel to the direction of extension; and thrust and extension fractures parallel to the foliation.

The Cortlandt Complex (a large igneous intrusion located East of the Site) was intruded during the F_2 phase. The post-Cortlandt dislocations were associated with a third phase of folding (F_3) causing a mutual rotation of the structural elements producing a complex of conjugate features with a wide range of orientations as described by Dames & Moore and found during our study. On the Site, the regional features are represented by North-Northeast and North-Northwest trending faults in cross-cutting relationships, representing a conjugate system with a North-South regional compression direction. The final tectonic event was associated with a shear system oriented North-East, reactivating movement along Northeast-trending faults and minor North-Northeast to North-Northwest-trending faults. In addition to these major events, there has been minor

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[30] In Vermont, this unit is equivalent to the Whipple Marble.

normal movement on North-South and Northwest-trending faults associated with continental rifting during the Mesozoic Era.

Finally, post-deformational uplift and glacial rebound have resulted in a series of fractures related to expansion, after the rock mass/ice load was removed during erosion and glacial retreat. These manifest themselves as semi-sinuous or undulating horizontal relief fractures.

6.4.3 Groundwater in Bedrock

In metamorphic bedrock such as the marble present at the Site, groundwater occurs and migrates in open spaces such as fractures. These void spaces are termed secondary porosity. The primary porosity consists of void spaces within the rock matrix itself. The Inwood Marble has a very low primary porosity which does not contribute to the flow or storage of significant volumes of water. Therefore, the presence of fractures and faults ultimately determines the hydraulic conductivity of the bedrock mass. The fracture aperture spacing and the degree of fracture interconnectivity are dominant variables in how groundwater flows through the fractured bedrock environment. Groundwater flows from areas of higher hydraulic head to areas of lower hydraulic head along fractures providing the least resistance. If the structure of the rock is dominated by fractures and foliations of a single orientation, then groundwater flow will be along this orientation towards areas of lower hydraulic head. Also, if fractures are separated by large distances and not interconnected, groundwater will flow in a relatively limited number of fractures and flow will be governed by the orientation of local structures within the rock. This may result in groundwater flow occurring along paths that may not be reflected in topography. However, if there are abundant sets of fractures of differing orientations relatively close together and interconnected, groundwater flow will typically mimic topography.

GZA found no evidences of solution features (i.e., cavities, voids). Such features (if present) can control the direction of groundwater flow. Carbonate rocks have relatively high solubility under certain ambient surface conditions. This can result in solution cavities and caves known as karst systems. In these situations, groundwater can flow predominantly along open cavities and result in preferential pathways. Our assessment of over 3,200 linear feet of rock core and 2,950 linear feet of borehole geophysical logs found no evidence of any large scale solution features. Minor, discontinuous vugs (small unfilled cavities) and voids were observed primarily along partially healed fractures with euhedral calcite crystals growing into fractures. This evidence suggests that prior to denudation, resulting in exposure of the rocks to the current elevations; hydrothermal fluids were percolating through open fractures. Mineralization occurred along the fracture planes resulting in a significant number of healed fractures observed in the rock. In some cases, the fractures were partially healed, resulting in the occurrence of vugs in some of the more brecciated zones. The presence of calcite deposition in fractures supports our observations that solution features are not prevalent at the Site. That is, open fractures are due to tectonic forces, that carbonate is precipitating within the fractures, and no large solution cavity process is occurring.

Since earlier conceptual models for the Site hypothesized that groundwater flow would be to the South-Southeast along the original F1 foliation and fracture sets, we performed a detailed structural analysis of the bedrock to assess whether groundwater flow would be dominated by discrete fracture flow or would behave more in accordance with flow through porous media. This analysis had implications relative to on-Site contaminant migration and the potential for off-Site migration via dominant fracture sets.

6.4.4 Regional Scale Geostructure

GZA assessed regional fracture patterns presented in the Dames & Moore (1975) report as a photo lineament analysis (**Figure 6.5**). On the regional scale of the lineament analysis, there are three sets of intersecting fracture orientations. The major strike orientations within a 15 mile radius of the Site indicated a Northeast, North, and East-West trend. A review of the major tributaries to the Hudson River indicates the drainage pattern is predominantly aligned with similar orientations and generally structurally controlled.

6.4.5 Site Scale Geostructure

On a Site scale, GZA projected the fracture plane orientations calculated from the borehole geophysical data onto one elevation (elevation 10 feet) to create a Site lineament analysis (**Figure 6.6**). Assessment of the more permeable fractures on this projection showed that fractures were oriented consistent with the regional assessment (Northeast, North and East-West), and that fracture orientations intersect one another. In addition, our Site scale lineament analysis showed a number of Northwest orientated fractures located between Unit 1 and Unit 2 in the area where the Unit 1 and Unit 2 plumes commingle. Evaluation of the preconstruction bedrock topography also indicated that this was a low point in the bedrock surface. Low points in marble bedrock surfaces are usually associated with areas of higher fracture density or faulting as these would be areas more prone to weathering, erosion and glacial gouging. This presents further evidence for a zone of higher transmissivity.

Based upon the regional and Site scale lineament analyses, it was apparent that the multiple fracture orientations result in intersections of fracture planes. However, more detailed analysis was required. Therefore, GZA assessed the individual rock cores and fracture orientations calculated from the borehole geophysical analysis.

6.4.6 Borehole Scale Geostructure

Twenty-three of the forty-seven boreholes were evaluated using acoustical televiewer (ATV) and optical televiewer (OTV) borehole logging techniques by Geophysical Applications, Inc. The ATV data establishes naturally occurring joint/fracture dip angles and planer dip directions for planer features intersecting a borehole.

The apparent joint/fracture orientations and depths were input into a stereographic framework using DIPS software developed by RocScience, Inc. of Toronto, Canada, after correction from magnetic North to true North. The stereographic projections are a southern hemispheric view and are equal-angle based. The program presents the joint/fracture dip and dip direction in a tabular format with customizing options, and allows joint/fracture set selection to establish groups of domains and families of geostructural data.

The 4,623 data points from the 23 boreholes were input into the DIPS program. The polar projections for all the boreholes are presented as **Figure 6.7**. In our opinion, these data show three dominant, apparent, conjugate sets of fractures striking to the Northeast-Southwest, East-West, and North-South. The majority of the dip angles range consistently between 30 and 70 degrees for each major orientation. In addition, there are many horizontal and vertical fractures. The orientations of the fractures, the conjugate sets of fractures, and the presence of vertical and horizontal fractures all support a high degree of interconnectivity.

The database also contains columns showing the depth of the individual joint/fractures and apparent vertical continuous spacing[31]. In each borehole, three average values of apparent vertical joint set spacing for depths between 0-30 feet, 30-100 feet, and depths greater than 100 feet were calculated and summarized in the following table. No significant differences in joint spacing with depth were found.

AVERAGE APPARENT JOINT SPACING, FT							
	Depth Below top of the rock				Depth Below top of the rock		
Borehole	0~30ft	30ft~100ft	>100ft	Borehole	0~30ft	30ft~100ft	>100ft
MW-30	0.53	0.64	--	MW-55	0.48	0.47	--
MW-31	1.46	0.63	--	MW-56	--	0.32	--
MW-32	--	0.36	0.39	MW-57	0.55	0.30	--
MW-34	0.72	--	--	MW-58	0.32	0.66	--
MW-35	0.80	--	--	MW-59	0.35	0.41	--
MW-39	--	0.66	0.67	MW-60	1.38	0.83	0.59
MW-40	0.37	1.11	1.69	MW-62	--	0.49	0.64
MW-51	0.37	0.88	0.84	MW-63	--	0.35	0.44
MW-52	0.45	0.58	0.89	MW-65	--	1.26	--
MW-53	--	0.71	--	MW-66	--	0.75	0.59
MW-54	0.47	0.58	0.39	MW-67	0.47	0.59	0.54
				RW-1	--	2.22	1.71

AVERAGE APPARENT JOINT SPACING

Joint spacing is a significant parameter in assessing flow in a fractured rock and assessing the validity of using an equivalent porous media flow model. The spacing of joints was determined by direct measurement from rock core samples or from ATV data in 22 boreholes, and is presented in a database (**Appendix Q**). These data indicate an apparent joint/fracture spacing between 0.3 and 2.2 feet, with an average of 0.7 feet.

Based upon the assessment described above, the data suggest that the bedrock aquifer can be visualized as a series of polygonal blocks separated by interconnected fractures. This geometry is graphically portrayed by a series of seven apparent fracture

[31] Apparent vertical spacing is the distance between joint/fractures along the vertical line of the borehole.

profiles designated A-A' through G-G' presented on **Figure 6.9**; profile locations are presented in **Figure 6.8**. The profiles show the orientation and potential connectivity of the geostructure if the ATV borehole measured planes extended for 1,000 feet (500 feet on either side of the borehole). The joint/fracture lines represent the trace of the plane projected onto a vertical profile. Additional illustrations of the fracture orientations in three dimensions are presented in **Section 6.4.8**.

6.4.7 Geologic Faults

The groundwater flow pattern and thus contaminant transport can be further influenced by the presence of faults. These faults can either act as barriers or conduits to flow depending on the presence of clay-rich fault gouge. Rock core samples revealed significant clay fault gouge zones that generally ranged between 0.2 and 0.7 vertical feet thick at borehole locations MW-31, -50, -54, -60, and -61. These zones were encountered at depths ranging between 39 and 200 feet below existing grades. The dip angles were measured by the ATV methods and ranged between 49 and 82 degrees at locations MW-31, MW-54, and MW-60, with dip directions toward the East (MW-54) and the Southeast (MW-31 and MW-60). No ATV measurements were conducted at MW-50 or MW-61. At MW-61, no core was recovered between 156 feet bgs and 221 feet bgs. Collection of split spoon samples in this interval verified the presence of a clay-filled fault gouge. This boring likely intersected a steeply dipping North-South trending fault. The presence of this fault is consistent with faults previously mapped by Dames & Moore (1975). The near vertical orientation of the fault is further supported by observations of bedrock core from locations MW-66, advanced within 8 feet of MW-61. No fault gouge was observed in this boring. A fracture zone was noted between 136 and 145 feet bgs and is characterized by low RQDs, however, this fracture zone did not exhibit clay filled fault gouge and was more consistent with tightly spaced fractures.

Because the fault extends to the top of the bedrock, the question arises as to why we did not observe the fault zone above 156 feet bgs at MW-61. This is due to the geometry of the fault. The fault zone is sub-vertical, i.e. less than 90 degrees, but also may vary in orientation with depth. As the boring was advanced deeper into the bedrock, it intersected the fault zone at 156 feet bgs. The boring continued within the fault, in a near vertical portion of the fault, to the termination of the boring.

Furthermore, the rock core samples revealed several fracture zones ranging between approximately 0.5 feet and 110 feet thick. Significant zones of poor to no recovery are evident at MW-50, MW-61 and MW-66: boring MW-50 and MW-54 were aligned along or near the trace of historic faults mapped by Dames & Moore (1975). MW-49 and MW-61, may be aligned along the extension of a historic fault mapped by Dames & Moore (1975). The poor recovery observed at MW-50 and MW-61 is indicative of clay gouge that was washed out during the drilling process (which is consistent with, but not fully verified by, the split spoon samples containing clay, recovered in these borings). We further note the presence of this fault zone does not appear to materially alter groundwater flow directions or contaminant migration towards the Hudson River.

Figure 6.4 portrays faults mapped on the Site by Dames & Moore (1975). There are three major groups of faults with associated fractures identified at and in the vicinity of the Site. These groups have azimuths of approximately 45, 75, and 290 degrees. The East to N75E faults consist of conjugate faults where the sinistral set strikes West to N70W dipping southward, and the dextral set strikes East to N75E dipping southward. These faults are most often offset or truncated by younger faults. West striking faults in the Inwood Formation are typically characterized by breccias which have been healed by a re-crystallized calcite cement.

An additional fault or fracture zone appears (not shown on **Figure 6.4**) to extend from the Hudson River Southwest between Units 1 and 2, as expressed by fracture orientations and a low in the preconstruction bedrock contours. This appears be a zone of higher transmissivity as indicated by inflections in groundwater contours, tidal response measurements, and the shape of the contaminant plume.

6.4.8 Bedrock Structure Visualization

In order to aid in the visualization of the role bedrock structure plays on groundwater flow as well as show the apparent interconnectivity at the Site, GZA imported data collected throughout the various phases of investigation into a 3-dimensional visualization model. The Environmental Visualization Software (EVS) software suite, created by CTech Development Corporation, was the primary software application used for the development of this model. This software package provides real-time model rendering, animation/flyover capabilities, database and GIS interface utilities, and numerous image output options. EVS also provides the ability to interpolate variably spaced datasets via kriging, an established geostatistical technique. The EVS kriging process selects an optimal semi-variogram model for each kriged dataset in order to estimate unknown values, and provides statistical confidence for estimated values. The results of these analyses can then be rendered across three dimensions (x, y and z) to provide a spatially referenced visualization model.

GZA incorporated the borehole geophysical data provided by GA, the packer testing results, and the USGS evaluation of the HPFM data into the 3-dimensional visualization model. Our goal was to illustrate transmissive fracture locations. For many of the zones identified as transmissive, several fractures likely contribute to the estimated transmissivity. In these cases, a percentage of the estimated zone transmissivity was allocated to each contributing fracture based on the HPFM results and ATV/OTV logs. In addition, multiple fractures in close proximity and exhibiting similar planar characteristics were combined to present a single planar feature to avoid redundancy in the model. The fracture data set was imported into the 3-dimensional visualization model intact.

Figures 6.10 through **6.14** present the locations of transmissive fractures within each boring. Fractures are represented as disks with 50 foot radii. A single disk represents the strike direction and dip angle of a transmissive fracture feature. Fracture disks are also color coded to reflect the assigned transmissivity value. Boring designations and locations highlighted in yellow indicate the borings for which geophysical and transmissivity information was available. Boring designations and locations highlighted in white are lacking geophysical data; therefore, fractures are not presented. The transmissive fracture data set was divided into low transmissive (0.02 - 10 ft^2/day, **Figure 6.10**), moderate transmissive (10 – 50 ft^2/day, **Figure 6.11**) and high transmissive (50 – 250 ft^2/day, **Figure 6.12**) subsets. While there are limited geophysical data for borings located to the South and East of the Site, the available data do indicate that there appears to be a zone composed of more transmissive fractures within the center of the Site. This observation coincides with a low in the bedrock as elucidated by preconstruction bedrock contours (**Figure 6.4**). This historic depression may be the result of weathered or fractured bedrock being susceptible to glacial advance and retreat, indicating the potential for a fault to be present in this area. This is consistent with the observation of a lineament West of Unit 2 toward the Hudson River discussed above.

Figure 6.13 represents the same fracture data set, but with the fracture disk radius extended to 250 feet. A horizontal cutting plane has been extended across the Site at elevation 10 feet, identifying the strike direction of each fracture as it intersects the plane. For a selected diameter of disk, the width of the strike line has significance. A shallow dipping disk would have more contact with the horizontal cutting plane than a steeply dipping disk. Accordingly, a wider strike line indicates a fracture strike direction with a shallower dip angle. The East-West lineament is clearly visible in this figure, aligned approximately from Unit 2 toward the Hudson River, and comprised of moderate and high transmissive fractures. **Figure 6.14** represents the same horizontal slice concept; however, the slice plane is now placed at elevation -100 feet. There are no high transmissive fractures intersected at this elevation, indicating high transmissive fractures are more predominant at shallow depths. This is consistent with **Figure 6.13**, the Conceptual Site Model, hydraulic conductivity tests and previous reports (Tectonics, 2004). Because we observed no decrease in fracture spacing with depth (see **Section 6.4.6**), this suggests the hydraulic aperture of fractures decreases with depth.

While there are some localized trends in fracture strike direction, there is an abundance of intersecting fractures on a Site-wide scale occurring at all elevations. In addition, the fracture disk component of the 3-dimensional visualization model has been reviewed to identify potential fracture connections on a borehole-to-borehole scale. No significant interconnections were identified. These observations suggest that bedrock is highly fragmented on a Site-wide scale, high transmissive fractures are not continuous across IPEC, and groundwater flow through the Site may be modeled as flow through a non-homogeneous, anisotropic, porous media.

6.4.9 Bedrock Surface Elevations and Preferential Groundwater Flow Pathways

The results of the surface geophysical surveys are portrayed on **Figure 1.3**. The geophysical survey identified apparent bedrock at depths of between 2 and 18 feet below ground surface (bgs) within the IP2-TY. A depression in the bedrock surface exists in the vicinity of monitoring well MW-111. Bedrock in the depression was found at a depth of 16 to 18 feet bgs. Along the North side of the IP2-TB, apparent depth to bedrock was approximately 8 to 12 feet bgs and only intermittent groundwater associated with rainfall events has been encountered. This is likely the depth bedrock was cut in order to accommodate the service water lines. No discrete utility trenches were observed in the bedrock. Based upon the results of the geophysical survey it is more likely that bedrock was cut to a depth to accommodate deep subsurface utilities and potentially dewatering, rather than install utilities in individual trenches. On the eastern, western and southern sides of the Transformer yard, rock was encountered between 2 feet and 7 feet bgs. No groundwater was encountered in the overburden in these areas. However, groundwater was encountered in the backfill found along the western wall of the Discharge Canal, which forms the eastern boundary of the IP2-TY.

Within the IP3-TY, the approximate depth to bedrock ranged between 7.5 and 10.5 feet bgs. Generally the northern and southern ends of the survey area had the deepest and shallowest depths to bedrock, respectively. Again, the surveys did not exhibit evidence of individual utility trenches cut into bedrock. No groundwater was observed in overburden within borings advanced within the IP3-TY.

To assess the potential for contaminants to enter groundwater through leaking stormwater pipes (E-Series) and flow with groundwater towards the Hudson River within utility trenches cut into rock along the OCA access road on the South side of the Protected Area, the depth to bedrock and utility trenches cut into rock along this roadway was evaluated. The approximate depth to bedrock ranged between 8 and 16 feet bgs. Bedrock reflectors appeared to be less defined in this survey area compared to other areas at the Site. Many potential utilities were observed in the survey area, however it appears that one large bedrock trench was excavated to accommodate the utilities as well as the roadway. The bedrock appeared to be deeper near the "delta gate" along the East side of the survey area, reaching an apparent depth of 16 feet bgs. Further to the West the apparent bedrock surface was observed at a depth of approximately 8 feet bgs.

Seismic data collected around the warehouse on the South side of the Protected Area provided good subsurface information to a depth of approximately 50 feet bgs. In general, the apparent bedrock surface was found at depths of approximately ground surface on the East side of the survey area and sloped down to depths greater than 45 feet to the West. Near MW-48, the bedrock was located at 25 feet bgs. Topography of the bedrock interface ranged from flat to highly variable over relatively short distances and there were a few locations where the bedrock interface "disappeared" or was located greater than 40 to 45 feet bgs. Over most of the area, the bedrock interface was more gradual and slightly undulating along the profile lines. In general, the depth to bedrock was greater then 20 feet across most of the survey area, indicating that subsurface utilities would not be cut into bedrock trenches.

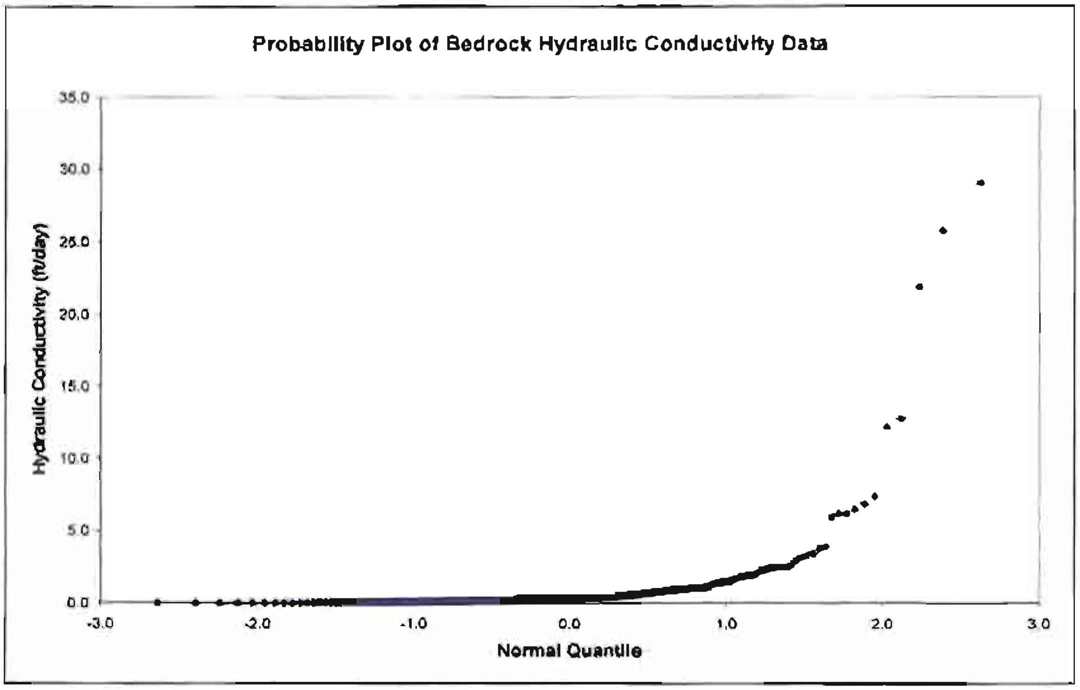
6.5 AQUIFER PROPERTIES

Our investigations demonstrate that, for the purposes of evaluating groundwater flux, bedrock beneath the Site can be modeled as flow in porous media. Following are the hydraulic properties we assigned to our equivalent conceptual porous media model.

6.5.1 Hydraulic Conductivity

Transmissivity and hydraulic conductivity[32] data were collected as part of the hydrogeologic investigation in both the overburden and bedrock. The geometric mean of hydraulic conductivity in the overburden zone is 12.6 ft/day and the geometric mean in the bedrock is 0.27 ft/day. As indicated below, calculated hydraulic conductivities within the bedrock were found to be log-normally distributed.

GZA used probability graphs to evaluate the statistical distribution of the bedrock hydraulic conductivity data. As shown on the following two graphs, the log-transformed data better approximates a straight line. This indicates the log-transformed hydraulic conductivities are approximately normal and the hydraulic conductivity values are log-normal. This indicates that the geometric mean is a good approximation.



STATISTICAL ANALYSIS OF HYDRAULIC CONDUCTIVITY MAGNITUDE

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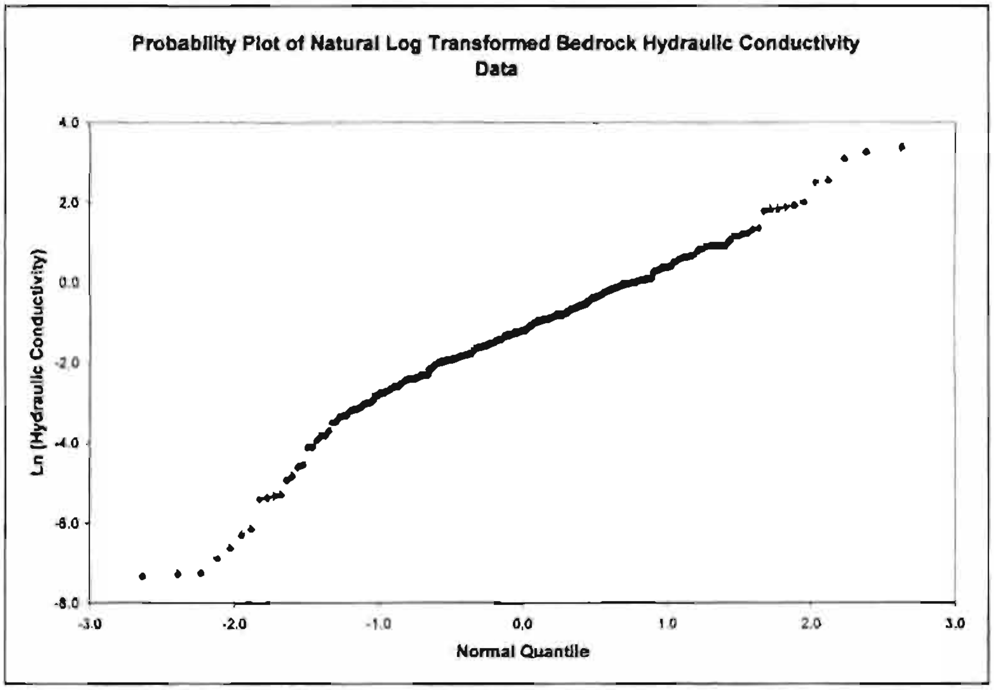
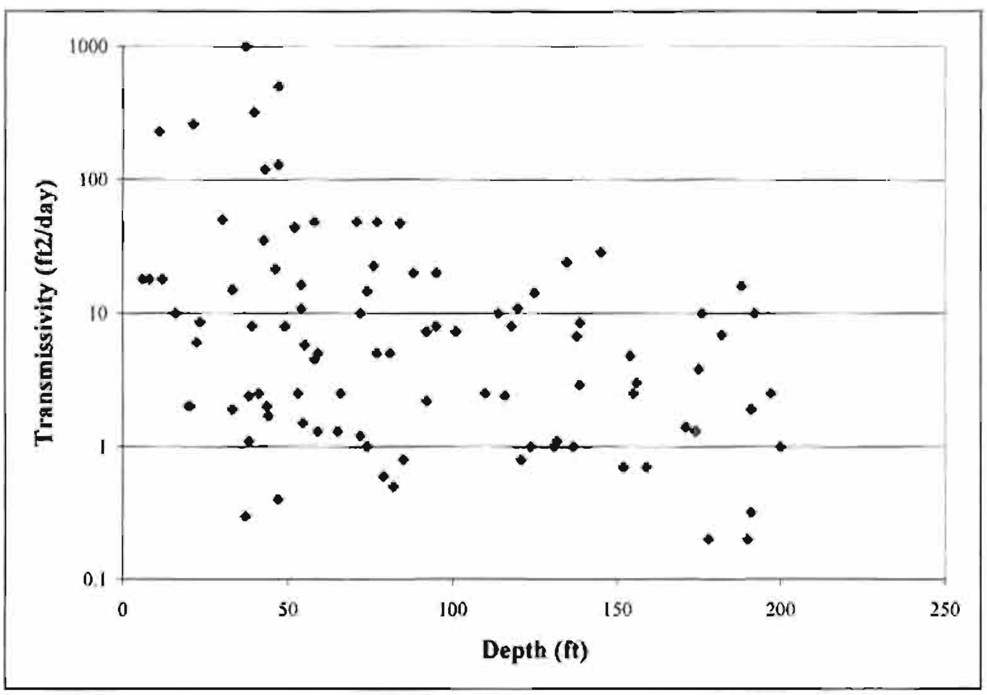
[32] Transmissivity, as used here, is the property measured in the field and is the product of an equivalent hydraulic conductivity (K) and the test interval.



STATISTICAL ANALYSIS OF HYDRAULIC CONDUCTIVITY MAGNITUDE (NATURAL LOG TRANSFORMED)

As shown below, GZA also developed a graph of depth versus transmissivity of bedrock. In viewing that graph, note that all USGS[33] measured transmissivities of greater than 100 ft^2/day were found at depths of less than approximately 50 feet bgs.



TRANSMISSIVITY VS DEPTH

[33] Transmissivities shown were computed by the USGS from their heat pulse flow meter data which were in agreement with our packer test data.

It should be noted that the hydraulic conductivity values are based on aquifer tests conducted at specific locations and limited hydraulic loading, and are therefore only representative of the aquifer immediately adjacent to the subject borehole.

GZA also conducted a Pumping Test which imposed a larger hydraulic stress over a larger portion of the aquifer. We believe this test provides us with the most reliable estimate of transmissivity of the bedrock in the area of the Pump Test. However, the area of influence of the Pump Test did not encompass the zone of higher hydraulic conductivity within the fracture zone between Units 1 and 2. Depending on the methods used to evaluate the Pumping Test data, we estimate bedrock transmissivity values generally in the range of 30 ft^2/day to 50 ft^2/day[34]. This suggests an average hydraulic conductivity of between 0.2 and 0.4 feet/day.

To further evaluate the vertical distribution of the hydraulic conductivity, we computed the geometric mean of measured values in the upper 40 feet of the aquifer and the geometric mean of all values measured below that depth. This calculation resulted in values of 0.4 feet per day for the upper forty feet and 0.2 feet per day for the deeper aquifer.

6.5.2 Effective Porosity

Evaluation of Pumping Test data also allows calculation of storativity. Our Pumping Test results show the storativity of the bedrock aquifer is 0.0003. (Note: overburden wells were not present within the cone of depression and, therefore, storativity for the overburden could not be evaluated.) Because the bedrock aquifer is unconfined and the primary porosity of the marble is, essentially, zero, the effective porosity of the bedrock can be as small as the storativity. However, due to dead-end fractures, the effective porosity is likely to be higher.

To evaluate the reasonableness of estimated properties, we used the cubic equation, as shown below, to estimate the hydraulic aperture and storativity of the fracture system:

$$Q = \frac{\rho_w g b^2}{12\mu}(bw)\frac{\partial h}{\partial l}$$

Where:

Q = volumetric flow (ft^3)
ρ_w = density of water (62.4 lb/ft^3)
g = gravitational constant (32.2 ft/s^2)
b = aperture opening (ft)

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[34] The Pumping Test indicated the transmissivity of the rock was fairly isotropic, and only limited horizontal anisotropy was observed during the Pump Tests (e.g., in the drawdown observations at monitoring well MW 53-120). At the scale of the Pumping Test we believe there are sufficient heterogeneities that the aquifer can be considered to be a non-homogeneous isotropic porous media.

μ = dynamic viscosity of water (0.0006733 lb/ft*s)

w = fracture width perpendicular to the flow direction (ft)

$\frac{\partial h}{\partial l}$ = groundwater gradient

From this, the concept of an equivalent hydraulic conductivity has been developed[35]:

$$K = \frac{\rho_w g n b^3}{12\mu}$$

Where:

Variables are as previously defined, and;

n = number of open features per unit distance across the rock face

Using a fracture spacing of one foot and an equivalent bulk hydraulic conductivity of 0.27 feet per day (9×10^{-5} cm/sec), this calculation indicates a hydraulic aperture of approximately 75 microns, and a theoretical minimum porosity of 2.4×10^{-4}. The calculated porosity is in good agreement with estimates of storativity developed from Pumping Test data (**Section 4.4.4**) and tidal responses (**Section 6.6**).

In summary, the measured effective porosity of the bedrock aquifer is approximately 0.0003.

6.6 TIDAL INFLUENCES

As discussed previously, the Hudson River, adjacent to the Site, rises and falls in response to ocean tides. Based on our measurements, this tidal variation (the numerical difference between low water and subsequent high water elevations) in 2006 ranged from approximately 1.4 feet to 4.3 feet, and averaged approximately 2.7 feet. This variation occurred between approximately elevation -1.5 feet to 3.7 feet NGVD 29 (i.e., the low tide elevations were typically above elevation -1.5 feet and the high tide elevations were typically below elevation 3.7 feet). These data are in good agreement with published information (see **Section 6.1**).

This natural variation produced measured effects that helped us better understand hydrogeologic information obtained at the Site. One such effect is water level changes in monitoring wells at the Site. The observed changes demonstrate that the bedrock aquifer is significantly fractured, and provided additional insight into aquifer properties.

Discharge of heated cooling water, in conjunction with tidal influences, produced a second effect: temporal temperature changes in groundwater in wells located near the Discharge

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[35] Snow, D.T. 1968. Rock Fracture Spacings, Openings, and Porosities. Journal of Soil Mechanics.. Found. Div. Proc. Am. Soc. Civil Engrs., v. 94, p. 73-91.

Canal. We used that information to help explain water quality data collected from two specific wells (MW-38 and MW-48, originally proposed as southern boundary monitoring wells), which did not initially conform with our Conceptual Site Model (see **Section 6.6.2** below). These two effects are described in the following sections.

6.6.1 Groundwater Levels

The tidal-induced variations in surface water levels near the edge of the Site's aquifer (in the river and intake structures and Discharge Canal[36]) induced pressure changes in groundwater that were observed in monitoring wells at the IPEC. As a general statement, these responses (as anticipated) varied over time as sinusoidal-like curves that decreased in amplitude and exhibited greater lag time with increased distances from the river/Discharge Canal[37].

At the time of our tidal response study, there were 87 transducers installed in 49 monitoring wells. As shown on the following graph, we observed measurable hydraulic responses to tidal variations at 43 of these transducer locations. In viewing that graph, note distances are measured from the edge of the Hudson River. We chose this as the boundary because data suggests the river has more influence on piezometric levels in the bedrock aquifer than do the intake structures and Discharge Canal. We further note that: 1) 41 of the 44 pressure transducers within 400 feet of the Hudson responded to tidal variations; 2) at greater distances, tidal responses may have occurred but were too small to be recorded because of the accuracy of the transducers; and 3) the tidal response in wells located in the higher hydraulic conductivity area between Units 1 and 2 was more pronounced than in other areas. Cumulatively, these data demonstrate:

- The aquifer is in strong hydraulic communication with the Hudson River; and
- The bedrock aquifer is well-fractured.

[36] The elevation of the water in the Discharge Canal rises and falls with the river elevation, but is maintained approximately 20 inches above the river level.
[37] Observed variations from this trend, in our opinion, are consistent with anticipated heterogeneities in an equivalent porous media model.