APPENDIX C

GROUNDWATER UPWELLING EVALUATION

Groundwater Upwelling Velocities in Remediation Areas, Onondaga Lake Bottom Subsites

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Executive Summary

This report describes the results of extensive field and analytical studies that have quantified the discharge of groundwater to the areas in Onondaga Lake where a sediment cap will be placed as part of the remedial activities undertaken to meet the requirements of the Record of Decision for the Onondaga Lake Bottom Subsite. The current rates of groundwater discharge in Remediation Areas A and E and the northern section of Remediation Area C, which are similar to discharge rates expected after placement of the cap, have been delineated based on the analysis of chloride depth profiles at more than 250 locations within and in the vicinity of these Remediation Areas. In Remediation Area B, Remediation Area D, and the southern section of Remediation Area C, the rates of groundwater discharge after placement of the cap will be significantly lower than current rates as the result of the construction and operation of a hydraulic containment system along the shoreline. Groundwater discharge rates after placement of the cap in these remediation areas were calculated based on groundwater flow rates upward through the underlying regional confining unit (the silt and clay unit).

This report describes a number of methods that were implemented in the field to estimate groundwater discharge rates, which are commonly referred to as upwelling velocities. The evaluation of upward groundwater velocity through the sediment based on the change in chloride concentrations with depth in sediment pore water was determined to be the best method for quantifying current upwelling velocities in the Remediation Areas. This report describes the theoretical bases for the use of this method to estimate upwelling velocities and describes the extensive data collected on chloride concentrations in sediments to accurately delineate the current distribution of upwelling velocities within the Remediation Areas.

The upwelling velocities within the Remediation Areas are low. The median upwelling velocities in Remediation Areas A, B, C and E are significantly less than 2 cm/year, though upwelling velocities greater than 32 cm/year were observed in some locations. In Remediation Area D and the southern section of Remediation Area C, calculated upwelling velocities with the cap in place are less than 2 cm/year, and in the eastern portion of Remediation Area D calculated upwelling velocity with the cap in place are less than 1 cm/year. In Remediation Area B, with operation of the anticipated hydraulic containment system, calculated upwelling velocities are also less than 2 cm/year.

The data and evaluations described in this report provide an excellent foundation for the design of the remedy for Onondaga Lake. The upwelling velocities that are described in this report will be utilized in the chemical isolation model for purposes of cap design.

REPORT

Section 1
Introduction

This technical report describes groundwater discharge to the areas in Onondaga Lake where a sediment cap will be placed as part of the remedial activities undertaken to meet the requirements of the Record of Decision for the Onondaga Lake Bottom Subsite. The areas where a sediment cap will be constructed have been geographically grouped into five sub-areas termed Remediation Areas A through E. The locations of the Remediation Areas, which have a total area of about 400 acres, are shown on Figure 1.

Groundwater discharge to Onondaga Lake has been evaluated in detail because groundwater flux through lake sediments can remobilize and transport contaminants in the sediments into the upper layers of the cap. As a result, understanding the groundwater discharge that will occur through the sediment cap after placement is essential for predicting the long-term performance of the sediment cap. In the analytical and numerical models developed to simulate the performance of the sediment cap (e.g., see Appendix B), the parameter describing the rate of groundwater discharge is referred to as the “Darcy velocity”. The Darcy velocity is the rate at which groundwater moves upward through the sediment cap. The Darcy velocity is frequently called the “upwelling velocity”. The upwelling velocities that are described in this report have been used as inputs to the chemical isolation model used for cap design (see Appendix B).

In Remediation Areas A and E it is anticipated that groundwater discharge through the cap will be similar to that which is occurring today. As a result, evaluations of groundwater discharge following construction of the cap have focused on understanding and quantifying existing rates of groundwater discharge. Onshore from Remediation Area D and the southern section of Remediation Area C, a hydraulic containment system is currently being installed along the shoreline that will reduce the groundwater discharge in these areas to negligible levels. A hydraulic containment system is also anticipated along the shoreline adjacent to Remediation Area B as a component of the remedial action for Wastebeds 1-8 (Figure 1).

In Remediation Area B, Remediation Area D, and the southern portion of Remediation Area C evaluations of groundwater discharge following construction of the cap have focused on understanding that component of groundwater discharge that will not be captured by the hydraulic containment systems and continue to discharge through the cap following completion of the remedy. The existing rates of groundwater discharge in these remediation areas provide almost no information on the amount of groundwater discharge that will occur following construction of the hydraulic containment system. Therefore, numerical and analytical techniques have been used to quantify the groundwater discharge rates after construction of the hydraulic containment system and the sediment cap in Remediation Area B, Remediation Area D and the southern section of Remediation Area C.

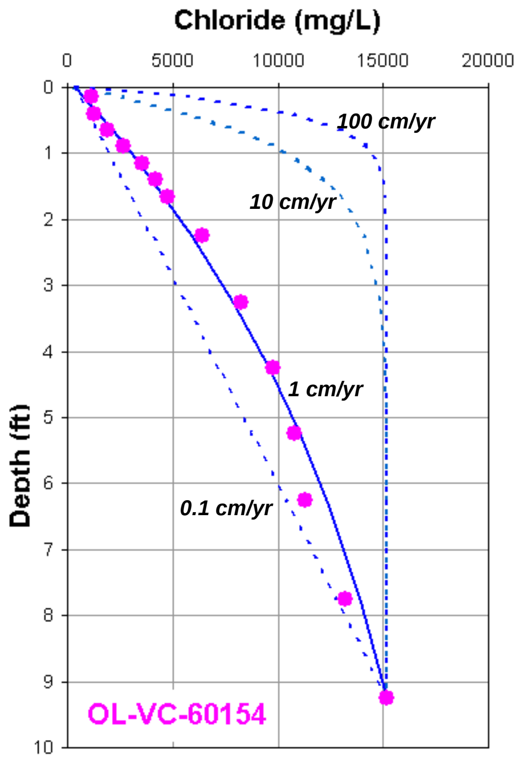
A detailed description of groundwater flow to Onondaga Lake is contained in Appendix D: Part A to the Onondaga Lake Feasibility Study (FS) titled "Groundwater Flow to Onondaga Lake" (Parsons 2004). In addition, following publication of the FS, the United States Geological Survey (USGS) published an analysis of groundwater flow in the unconsolidated sediments underlying Onondaga Lake and the contiguous glacial valleys (Yager and others 2007). The major findings of these studies are summarized in this report and the reader is referred to these previous studies for more detailed information.

The analyses of groundwater discharge described in Appendix D of the FS indicated that in areas offshore of where a hydraulic containment system would be constructed upwelling velocities would be less than 2 cm/year with the containment system in operation. Upwelling velocities in Remediation Areas A and E, where a hydraulic containment system would not be constructed, were estimated during the FS to be higher in near shore areas. Upwelling velocities in Remediation Area A ranged from 300 cm/year within 20 feet of the shoreline to less than 2 cm/year beyond 700 feet from the shoreline, and upwelling velocities in Remediation Area E ranged from 70 cm/year near the shoreline to less than 2 cm/year beyond 300 feet from the shoreline.

This report primarily focuses on the studies and investigations that have been conducted since the FS was completed to better quantify groundwater discharge to the five remediation areas. Seepage meters and chloride-depth profiles of the sediments were the field methods employed in the Pre-Design Investigations (PDI) to quantify groundwater discharge rates. These methods and the results of these methods are described in this report as well as other methods that were considered to quantify groundwater discharge rates. In addition, as part of the Pre-Design Investigations, a large number of borings have been advanced into the sediments beneath the Remediation Areas. The data from these borings have provided a much better understanding of the characteristics of the sediments and the thickness and continuity of the major stratigraphic units. This information has allowed the development of a better understanding of groundwater flow within the sediments.

The chloride-depth profile method was judged to be the most reliable and accurate method for quantifying the relatively low groundwater discharge rates through the sediments in the Remediation Areas. This method relies on the observation that the pore waters in the sediments beneath Onondaga Lake have significantly higher chloride concentrations than the lake water as the result of natural brines beneath the lake and migration of brines from the wastebeds along the shoreline of Onondaga Lake. As a result, there is a significant chloride concentration gradient from the sediments to the lake. The change in chloride concentration with depth below the lake/sediment interface provides information on the rate of upward groundwater flow through the sediment.

The chloride-depth profile below the sediment-water interface if there is no upward groundwater flow through the sediment is linear as a result of diffusion. If there is upward groundwater flow, the chloride depth profile is convex, with the convexity a function of the



magnitude of the groundwater flow, as shown on the figure below. Analysis of the convexity of the profile is the method that was used to quantify groundwater upwelling velocities. This method is useful for analyzing upwelling velocities that are less than about 50 cm/year because at greater upwelling velocities, the chloride concentration does not change significantly with depth.

The figure to the right shows a plot of chloride concentrations in pore water versus depth at a boring located in Remediation Area E (OL-VC-60154) to illustrate the large changes in chloride concentrations that occur with depth below the sediment-water interface. The measured chloride data are plotted as large dots and chloride concentrations increase from about 359 mg/L at the sediment-water interface to over 15,000 mg/L at a depth of about 9 feet below the sediment-water interface. The measured chloride data follow a convex profile indicating a relatively small upwelling velocity. Also shown on the figure are the expected chloride depth profiles for upwelling velocities of 0.1 cm/year, 1 cm/year, 10 cm/year and 100 cm/year. These expected chloride depth profiles illustrate the significant effect that changes in upwelling velocities have on the shape of the chloride depth profile. For example, the chloride depth profile with an upwelling velocity of 1 cm/year is significantly different than that with an upwelling velocity of 10 cm/year. The measured chloride data shown on the figure follow a trend similar to that expected with an upwelling velocity of about 1 cm/year.

Section 2 of this report describes groundwater conditions in the Remediation Areas, Section 3 describes measurements of Upwelling Velocities, Section 4 presents the upwelling velocities, and compares methods for estimating upwelling velocities, Section 5 describes analyses of upward groundwater flow through the silt and clay unit, and Section 6 describes an evaluation of uncertainty in calculated upwelling velocities.

Section 2
Groundwater Conditions in Remediation Areas

Geologic Setting

Onondaga Lake overlies a deep, northwest-trending glacial trough in the Vernon Shale, the bedrock formation beneath and in the vicinity of the lake. A schematic block diagram of the southeastern end of the lake, which illustrates the trough, is shown on Figure 2. The trough averages about 300 feet deep along the axis of the lake and is filled primarily with unconsolidated, fine-grained sediments, although a coarse grained unit typically occurs overlying till near the base of the unconsolidated sediments. The thickness of the unconsolidated sediments decreases rapidly away from Onondaga Lake, except in the valleys of the main tributaries, which are also underlain by unconsolidated sediments. The stratigraphic sequences observed in most borings advanced beneath the lake and adjacent upland areas are similar:

- Surficial sediments typically described as silt with fine sand and fill material;
- Gray clayey marl, gray-brown clayey silty marl (marl unit);
- Brown-gray clay, gray-brown silt and clay (silt and clay unit);
- Gray-brown silt with sand layers (fine sand and silt unit);
- Sand sometimes with gravel (sand and gravel unit);
- Red till, dense clay and silt with sand and gravel (till unit); and
- Green, red and gray shale (bedrock).

The silt and clay unit is an important confining unit or aquitard that impedes upward groundwater flow to the lake. This unit has vertical hydraulic conductivity of about 10^{-7} cm/sec. This unit has been interpreted to be continuous beneath the entire lake, consistent with the interpretation in the USGS report by Yager and others (2007). A thickness map of this unit based on interpretation of boring logs is shown on Figure 3.

Hydrogeologic cross sections through Remediation Areas A, D and E are shown on Figures 4 to 6 and locations of these sections are shown on Figure 1. These cross sections, at a minimum, depict the silt and clay unit and overlying sediments. Where information is available in the vicinity of these cross sections on the geologic units below the silt and clay unit, this information is also shown. The sections are annotated with notes from the boring logs regarding lithologic observations within each of the geologic units. In general the marl is described as silt and/or silt and clay though in some logs the marl was noted as consisting of gravel and/or sand sized sediments. In Remediation Area D, relatively thick deposits of Solvay waste and other materials contained within the In-Lake Waste Deposits overlie the marl unit (Figure 5). Additional hydrogeologic cross sections are contained in Attachment I.

Onondaga Lake and Groundwater Flow

Onondaga Lake, oriented along a northwest-southeast axis, is approximately 4.5 miles long and 1 mile wide. The lake has a mean depth of 36 feet and a maximum depth of 65 feet which occurs in the southern part of the lake. The average lake level during the past 20 years was 362.9 feet above mean sea level (AMSL),[1] based on records from the USGS gage on Onondaga Lake. The surface area of the lake at this elevation is approximately 4.5 square miles, and the volume is approximately 34,600 million gallons. Surface water inflows and outflows from the lake average about 470 cubic feet per second based on average flows between 1998 and 2002 (Onondaga County 2003). The groundwater component of the lake water budget is small, estimated to be less than 0.5 percent of surface water inflows (Parsons 2004). Precipitation on the lake and evaporation from the lake are approximately equal; therefore, the net of precipitation and evaporation is small. The average residence time of water in the lake is approximately 100 days.

Regional groundwater flow in both the bedrock and the unconsolidated sediments is towards the valleys of the major tributaries of the lake. Groundwater discharge areas include seven major tributaries: Ninemile Creek, Geddes Brook, Harbor Brook, Bloody Brook, Onondaga Creek, Saw Mill Creek, and Ley Creek. Groundwater flow towards and into the lake originates primarily as precipitation that infiltrates into the unconsolidated sediments bordering the lake. Because the saturated unconsolidated sediments are restricted to a relatively narrow band on either side of the lake, the total recharge area is relatively small, and as a result, recharge to and discharge from the unconsolidated sediments is relatively small. Most of the groundwater in the unconsolidated sediments that flows toward the lake discharges to the tributaries and to drains along the shoreline, with the remainder discharging in near-shore areas of the lake. This occurs, in part, because of the thickening wedge of fine-grained, low-permeability materials beneath the lake and because of dense sodium-chloride brines in the unconsolidated sediments beneath the lake.

Most of the groundwater discharge that occurs to the lake is the result of groundwater flow through the marl and overlying units from the upland areas. These units are typically fine grained, though there are some sand stringers or lenses, as shown on the hydrogeologic cross sections. As a result, groundwater flow rates through these units are not large and most of the groundwater discharge occurs near shore in the littoral zone.

In addition, some groundwater discharge to the lake occurs as the result of upward groundwater flow through the silt and clay unit from the deeper permeable units. The sand and gravel unit and the overlying fine sand and silt unit are the primary deeper permeable units. These units are primarily recharged where they subcrop around the perimeter of the lake. Groundwater levels in the sand and gravel along the lakeshore are typically well above the lake

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[1] Vertical datum referenced to the North American Vertical Datum of 1988 (NAVD 88).

level indicating the potential for upward groundwater flow. The vertical hydraulic conductivity of the silt and clay unit is estimated to be 10^{-7} cm/sec or less and thus the total upward groundwater flow through this unit is very small. The potential upward groundwater flow through the silt and clay unit is described in detail in Section 5.0.

The presence of natural sodium-chloride brines in the unconsolidated sediments beneath the lake complicates the understanding of local groundwater flow conditions. These brines are believed to have originated primarily from the dissolution of soluble minerals in the unconsolidated glacial sediments in the Onondaga Trough that originated from bedrock scour caused by glacial advance and retreat. Yager and others (2007) stated: *"The halite brine in the Onondaga Trough probably formed through dissolution of halite and gypsum beds that were exposed in the Syracuse Formation through erosion by glacial ice."* In the past, discharge of brines at salt springs was reported to have occurred around much of the shoreline of the southern basin of the lake (USGS 2000). These discharges likely occurred in areas where the silt and clay unit thinned or disappeared along the shoreline. The natural discharge of brines has ceased due to extraction of brines from wells along the shoreline. From 1797 to 1917, over 11.5 million tons of finished salt were produced from the springs and wells along the southern shoreline of the lake (USGS 2000). This represents the salt content from the constant production of 500 gallons per minute (gpm) of brine with a chloride concentration of 60,000 mg/L over this period. The production of these brines most likely decreased groundwater pressures in the more permeable zones beneath the lake.

In addition to the natural sodium-chloride brines, there are natural mixed cation brines in the bedrock. These brines formed by the dissolution of evaporate beds within the Vernon Shale and overlying bedrock units. These brines are enriched in calcium, magnesium, and bromide relative to the sodium-chloride brines. In addition to the natural brines, some brines in groundwater result from seepage from the wastebeds. These brines are comprised primarily of sodium, calcium, and chloride. The wastebed brines typically have sodium to calcium ratios that are less than 1, whereas the natural sodium-chloride brines have sodium to calcium ratios that are greater than 10. The mixed cation brines typically have sodium to calcium ratios in the range of 1.4 to 4. The mixing of relatively fresh groundwater, natural sodium-chloride brines, natural mixed cation brines, and brines from the wastebeds have created a wide variety of groundwater quality types in the vicinity of Onondaga Lake. The distribution of groundwater quality provides information on groundwater migration and origin.

Hydraulic Barrier System

A hydraulic containment system along the shoreline adjacent to Remediation Area D and the southern section of Remediation Area C is an integral part of the lake remedy. This hydraulic containment system consists of four primary elements: 1) an impermeable barrier or wall seated in the upper portion of the silt and clay unit; 2) a gravel filled drain, completed to an elevation that is several feet below the elevation of the lowest recorded lake level, with a collection pipe embedded within, 3) wick drains within the lower portion of the fill and within the marl unit, 4) pumps to maintain the water level in the drain below lake level, and 5) a water treatment facility. The hydraulic containment system is designed to capture the shallow groundwater flowing towards the lake in the materials above the silt and clay unit. In addition, the drains will capture some flow from the underlying units by increasing hydraulic gradients across the confining unit. A schematic of the hydraulic barrier system is shown on Figure 7

A 2,850 foot section of the hydraulic containment system has already been completed adjacent to the southern section of Remediation Area C and part of Remediation Area D (Willis/Semet IRM Barrier Wall). The impermeable barrier in this area consists of a sealed joint sheet pile wall. The water level in the drain of the completed portion of the system currently is maintained at a level that is 0.5 feet lower than lake level. The final section of the 1.5-mile long hydraulic containment system, which is to be built landward of Remediation Area D, is scheduled for construction to begin in 2010.

A hydraulic containment system is also anticipated along the shoreline adjacent to Remediation Area B as a component of the remedial action for Wastebeds 1-8. This hydraulic containment system is anticipated to capture all shallow groundwater flowing towards the lake and will extend northward from Ditch A for approximately 6,000 feet (Figure 1).

Groundwater Flow Model

A groundwater flow model has been developed to quantify the rates and direction of groundwater flow in the unconsolidated materials and in the upper bedrock in the vicinity of Onondaga Lake and to quantify groundwater discharge in the vicinity of Onondaga Lake. Version 1.0 of the groundwater model is described in Appendix D to the FS (Parsons 2004). The model domain encompassed an area of approximately 13 square miles surrounding the southwest shoreline of Onondaga Lake. Since the FS was completed, the model domain has been expanded to include all of Onondaga Lake and additional Honeywell properties south of the lake. Revisions have been made to the model since the original version and it is currently being updated with new data. This revised model, referred to as model Version 3.0, is anticipated to be completed and approved by the NYSDEC in the spring of 2010.

Section 3
Measurements of Upwelling Velocities

Three types of field methods were implemented in an attempt to quantify groundwater discharge rates to the Remediation Areas in Onondaga Lake; 1) a piezometer-based method to measure hydraulic heads in the sediment pore waters, 2) seepage meters to directly measure groundwater discharge, and 3) measurement of chloride concentrations with depth below the sediment-water interface to estimate groundwater flow rates through the sediments. The piezometer-based method consisted of a network of piezometers with recording devices installed within the lake sediments in late 2002 and monitored through July 2003 as part of a study known as the Groundwater Upwelling Investigation (Parsons 2003). The intent of this method was to measure upward hydraulic gradients within the lake sediments and to covert the hydraulic gradients to upwelling velocities using estimates of the vertical hydraulic conductivity of the sediments. Two seepage meter studies were conducted to evaluate the use of this method, which directly measures groundwater discharge. An initial study was conducted with six meters in 2005 and a second study was conducted with thirteen seepage meters in 2007. Several field methods were also evaluated to measure and/or estimate sediment chloride concentrations; measurement of sediment conductivity using a direct push conductivity probe, Vibracore sampling with centrifuging of sediment samples to obtain sufficient pore water for analysis of chloride, and in-situ peepers. Each of the field methods implemented in an attempt to quantify groundwater discharge rates is described below.

In addition to the quantitative methods implemented in the field, an additional method was used to qualitatively screen the lake bottom for locations with potentially anomalous groundwater discharge rates such as subaqueous springs and seeps. This method consisted of towing a conductivity and temperature sensor near the lake bottom and analyzing the data for anomalous temperature and conductivity readings that might potentially indicate areas of elevated groundwater discharge. Two surveys were conducted: one in 2005 and a second in 2007. This qualitative investigation of groundwater discharge is described below followed by a discussion of the quantitative methods.

A number of other techniques for estimating groundwater fluxes were considered but rejected as not feasible for use in Onondaga Lake. An excellent review of field techniques for estimating water fluxes between groundwater and surface water has been published by the USGS (Rosenberry and LaBaugh 2008). A technique frequently used for quantitatively estimating groundwater fluxes is temperature. The seminal paper regarding this issue is Bredehoeft and Papadopulos (1965) *"Rates of vertical groundwater movement estimated from earth's thermal profile"*. Temperature techniques for estimating groundwater velocities, as noted by Sayles and Jenkins (1982), work best for upwelling velocities of greater than 50 cm/year. A recently developed technique for using temperature to quantify groundwater discharge is based on collecting time-series data at various depths below the sediment-water interface and evaluating how the temperature signal is attenuated with depth. A description of this method is contained in Keery and others (2006). An evaluation of this method indicated that resolution of this method was on the order of 200 cm/year. Recent advances in fiber-optic temperature sensing have indicated the potential of this technique to accurately define temperatures at the sediment water interface but the technique does not yet lend itself to the quantitative estimation of upwelling velocities (Day-Lewis and others 2006).

Temperature and Conductivity Survey

Two temperature and conductivity surveys were conducted in the lake in an attempt to identify areas of groundwater discharge. These surveys were designed to qualitatively identify areas of groundwater discharge, but not to quantify the rate of groundwater discharge. The areas of potential groundwater discharge identified by these methods were then investigated by other methods in an attempt to quantify the discharge rates.

The first survey was conducted on September 7 and 8, 2005 using a Hanna S6T2 temperature and conductivity meter that was towed near the lake bottom from a slowly moving boat. Measurements were conducted in transects along the shoreline east of Ninemile Creek and conducted along the northern portion of the shoreline in Remediation Area E. The measurements along the shoreline east of Ninemile Creek did not identify potential groundwater discharge areas, as neither temperature nor conductivity changed significantly across the survey transects. In Remediation Area E, one potential upwelling location, which was identified by an approximately 1.5 degree F decrease in temperature and an increase in conductivity, was observed. A seepage meter was located at the observed temperature and conductivity anomaly (meter 60052 as described below).

A second and much more comprehensive temperature and conductivity survey was conducted from April 24 to 26, 2007 in Remediation Areas A and E. For these surveys, a YSI 6600 series multi-parameter Sonde was used to measure water temperature, specific conductance, salinity, dissolved oxygen, turbidity, and sensor depth. The sensor was mounted in a custom built steel cage and towed with a 15-foot Jon boat as close to the bottom as possible. As an initial calibration step, the unit was tested on a known brine spring in Onondaga Creek to ensure it would identify a large anomaly in the groundwater discharging through the sediments. This screening step was successful in identifying the location of a large spring in lower Onondaga Creek. The survey was conducted by running transects approximately 25 feet apart along the shoreline from water depths of about two feet to six feet. Figures displaying the temperature and conductivity data collected during this survey are contained in Attachment II. For the most part, the temperature and conductivity patterns are consistent and uniform with very few anomalies suggesting potential groundwater discharge. One distinct anomaly of higher conductivity was observed along the shoreline east of the mouth of Ninemile Creek and a seepage meter cluster was located in this area (Seepage Meter Cluster 4-2 as described below).

Another conductivity anomaly was observed adjacent to the shoreline east of Harbor Brook and a seepage meter cluster was located in this area (Cluster 7-1 as described below).

Groundwater Upwelling Investigation – 2003

A groundwater upwelling study was conducted in Remediation Area A near the mouth of Ninemile Creek and in Remediation Areas C and D in 2002 and 2003 (Parsons 2003). The study consisted of vibrating wire piezometers emplaced in pairs at depths of 4.0 and 14.5 feet below the sediment-water interface at three or four locations along each of six transects oriented approximately perpendicular to the shoreline. The locations of the piezometers are shown on Figure 8. Hydraulic pressures were recorded every twelve hours at these locations from December 27, 2002 through August 1, 2003. An attempt was made to estimate vertical hydraulic conductivity at each piezometer location from a slug test conducted within a solid steel casing driven to a depth of 4.5 feet. These tests, because of the strongly stratified nature of the sediments and the limited open area at the base of the steel casing, greatly overestimated the actual vertical hydraulic conductivity of the sediment.

The data from the one transect with three sets of piezometers in Remediation Area A are the only results from the upwelling investigation that are relevant to understanding upwelling velocities following placement of a sediment cap (a hydraulic containment system will be constructed at the other transect locations). The piezometer pairs in the transect in Remediation Area A were located 25 feet, 538 feet and 1,011 feet from the shoreline. The sediments along this transect are primarily silts with some sands and clays (refer to hydrogeologic cross-section shown on Figure 4; cross-section trace is shown in Figure 1).

The average upward hydraulic gradient, during the period investigated, calculated as the pressure head difference between the piezometers at a depth of 14.5 feet and the one at a depth of 4.0 feet ranged between 0.01 and 0.026 feet per foot at the three piezometer pairs (Attachment III). The estimated vertical hydraulic conductivity of the sediments between a depth of 4.0 feet and 14.5 feet is approximately 10^{-5} cm/sec. Based on this estimate of the hydraulic conductivity, the upwelling velocity along the transect ranges from about 3 to 8 cm/year. There is a large error associated with the hydraulic conductivity estimate and therefore there is significant uncertainty regarding the estimated upwelling velocity using this method.

The piezometer-based method was determined not to be a reliable method for estimating groundwater discharge rates to the lake. There were two main reasons why it was judged to be unreliable: 1) there are no dependable methods for accurately and precisely estimating effective vertical hydraulic conductivity of the sediments, and 2) it is difficult to obtain reliable estimates of pore water pressures from the vibrating wire piezometers for reasons that could not be fully explained. It is hypothesized that the accumulation of biogenically generated gas in the sand packed interval in which the piezometers were placed led to anomalous pressure measurements.

Seepage Meter Investigations

Two seepage meter investigations were conducted during pre-design investigations for the Lake. One was conducted with six seepage meters as part of the Phase I Pre-Design Investigations in 2005 and the second was conducted with 13 seepage meters as part of the Phase III Pre-Design Investigations in 2007. The seepage meters used in this study were an adaptation of the type of seepage meter described by Lee (1977).[2] A useful review of seepage meters is contained in Rosenberry (2005). These two seepage meter investigations are described below.

<u>Seepage Meters – Phase I Investigation</u>

The seepage meters used in the Phase I Investigation were constructed with two-foot diameter PVC housing and an interior acrylic dome. Each meter consisted of two sections: a lower section that was installed into the sediment, and an upper section that housed the dome and a thin-walled Teflon sample bag. The two sections joined at a sealed male-to-female fitting to ensure that there was no leakage. The seepage meters were installed as a two-step process. First, the lower section of the seepage meter was slowly pushed 12 to 18 inches into the lakebed. After a stabilization period of at least 24 hours, the top and bottom sections of the meter were attached with a gasket to create a water-tight seal and bolted together using threaded steel rods. Finally, the four-liter measurement bags were prefilled with 60 ml of water and attached to the seepage meters.

Three seepage meters were installed in Remediation Area A and three were installed in Remediation Area E at the locations shown on Figures 9 and 11. One of the meters installed in Remediation Area A was located adjacent to a piezometer pair installed as part of the Upwelling Investigation described above. The meters in Remediation Area A were installed between 325 feet and 820 feet from shore, and the meters in Remediation Area E were installed between 200 feet and 430 feet from shore based on access and water depth constraints. The meters were monitored approximately weekly from September 16 through November 15, 2005.

There was significant variability in the weekly measurements of upwelling velocities at each of the meters, even though the piezometers indicated that hydraulic gradients were relatively constant during the period of the study. An analysis of the data that were collected indicates that the volume of water collected in the seepage meter bags was influenced by multiple factors in addition to the ambient flux of groundwater through the sediments. As a result, the groundwater flux through the sediments could not accurately be estimated directly from the water that accumulated in the seepage meter collection bags. Initially following seepage meter installation, gas production from decaying vegetation appears to have significantly

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[2] The use of seepage meters to investigate groundwater discharge to lakes in central New York is discussed in Schneider and others (2004) and Sebestyen and others (2001).

influenced the rate of water accumulation, and as a result, data from the early period are not useful for estimating groundwater fluxes through the sediments. Settlement of the seepage meters was also a major factor influencing the rate of water accumulation. In Onondaga Lake where high winds and resulting waves impart forces on the meters, settlement is a major concern. A very small amount of settlement results in a relatively large volume of water accumulation in the collection bags relative to the amount of water accumulation from the ambient seepage flux. The measured weekly upwelling velocities at the six seepage meters are shown on figures in Attachment IV.

Lake levels were relatively stable and gas production, at five of the six meters, was relatively constant during the period October 27 to November 15, 2005. Therefore, the amount of water that accumulated in the collection bags during this period can be attributed both to settlement (in part caused by wind and wave action) and ambient groundwater flux. Based on data from this period, the median combined settlement-induced flux and groundwater flux at each of the meters, with the exception of 60053 (SM-6) where gas production varied significantly during this period, are the following:

40013 (SM-1) – 19 cm/year,
40014 (SM-2) – 4 cm/year,
40015 (SM-3) – 44 cm/year,
60051 (SM-4) – 9 cm/year and
60052 (SM-5) – 10 cm/year.

These fluxes represent an upper bound estimate of the groundwater flux as it is likely that the settlement induced flux was significant but insufficient reference data were available to determine the exact amount of settlement.

<u>Seepage Meters – Phase III Investigation</u>

The seepage meters used in the Phase I Investigation were redesigned for the Phase III Investigation based on issues identified with the original meters during the Phase I Investigation. The meters were redesigned to reduce impacts of waves (e.g., wavebreaks, stabilization poles, etc.) and to reduce settlement. In addition, large volume bags were used for sample collection and control bags were used at each meter to assess outside factors influencing water accumulation in the bags. The control bags were based on the design described in Cable and others (2004). In addition, wave height was monitored to account for any influences caused by wave action, centimeter scale measurements of meter elevations were made to assess settlement, and water levels were monitored in the lake and in on-shore monitoring wells to assess changes in horizontal gradients towards the lake during the investigation. A photograph of a redesigned seepage meter is shown in Attachment IV.

Seepage meters were installed at five locations during the Phase III Investigation; three in Remediation Area A, and two in Remediation Area E. Multiple meters were used at each location to assess the reproducibility of results. At three of the locations, three seepage meters were installed in close proximity to each other. At the other two locations, two meters were installed in close proximity to each other. The seepage meters were located as follows:

- Cluster 4-1 was located near the shoreline approximately 900 feet east of Ninemile Creek to evaluate a temperature and conductivity anomaly at this location. These meters are labeled 40097, 40098, and 40122 on Figure 9.
- Cluster 4-2 was located about 1,300 feet east of Ninemile Creek to evaluate a temperature and conductivity anomaly at this location. These meters are labeled 40095 and 40096 on Figure 9.
- Cluster 4-3 was located approximately 1,600 feet east of Ninemile Creek to evaluate potential groundwater discharge from the distal end of a buried former channel of Ninemile Creek. These meters are labeled 40099, 40100, and 40101 on Figure 9.
- Cluster 7-1 was located approximately 350 feet east of Harbor Brook to evaluate a conductivity anomaly at this location. These meters are labeled 70067, 70068 and 70069 on Figure 11; and
- Cluster 7-2 was located approximately 1,000 feet east of Harbor Brook. These meters are labeled 70065 and 70066 in Figure 11.

The seepage meters were monitored approximately weekly from June through August, 2007. The measured upwelling velocities at each of the seepage meter clusters are shown on figures in Attachment IV.

The results of the Phase III seepage meter study indicated that seepage meters are not a reliable method for measuring small upwelling velocities in Onondaga Lake. The results indicated that seepage meters do not consistently provide a reliable estimate of the “true” upwelling velocity. This conclusion is based on the following observations:

- The seepage meter data from the near-shore portion of Remediation Area A indicate negligible groundwater discharge whereas other lines of evidence (pore water chloride profiles and groundwater modeling) indicate that quantifiable groundwater discharge is occurring.
- The upwelling velocities at seepage meter pairs and triplicates showed little correlation between/among meters.
- The upwelling velocities calculated from the control bags were of the same order of magnitude as the rates calculated from the meters. In addition, upwelling velocities calculated from the control bags do not correlate temporally among locations.

Overall, the lack of reproducibility between/among meters at the five cluster locations indicated that the seepage meters were not a reliable method for estimating upwelling velocities of the magnitude that occur in Onondaga Lake.

Chloride-Depth Profiles

Effler and others (1990) noted that chloride concentrations in the shallow sediments beneath Onondaga Lake increased nearly linearly with depth. They noted that this indicated a diffusive flux of chloride to the lake from a deep source of chloride. The source of chloride is now understood to be halite brines within the glacial deposits that fill the Onondaga Trough and brines from seepage from the wastebeds. TAMS (2002) noted that the chloride gradients beneath Onondaga Lake were not truly linear and that the deviation from linearity could be used to estimate the upwelling velocity.

The use of chemical concentration gradients in sediments to investigate upwelling velocities was first reported in the literature in 1982 when two studies were published that quantified upwelling velocities in the Pacific Ocean. One study used calcium and magnesium ion gradients to quantify upwelling velocities in the range of 1 cm/year to 20 cm/year near the Galapagos Islands, and the other study in the equatorial East Pacific Ocean quantified upwelling velocities of about 20 cm/year using calcium ion gradients and the ratio of helium-4 to helium-2 (Maris and Bender, 1982; Sayles and Jenkins 1982). Additional studies that have described the use of chemical concentration gradients in sediments to estimate upwelling velocities include Berg and others (1998), Maris and others (1984), and Anati (1994). All of these studies have indicated that the use of chemical concentration gradients is a useful method for quantifying upwelling velocities that are less than approximately 50 cm/year. Groundwater flow rates through lake sediments were evaluated using tritium and chloride concentration depth profiles in sediments by Cornett and others (1989).

The section below describes the theoretical basis for the use of chemical concentration gradients in sediments to estimate upwelling velocities, the field methods that were investigated for measuring and/or estimating chloride concentrations in pore water, and the method of data evaluation.

<u>Description of Method</u>

At steady state conditions, the governing equation for vertical migration of chloride by advection with groundwater and diffusion is:

$$0 = -v\frac{\partial c}{\partial x} + D\frac{\partial^2 c}{\partial x^2} \qquad \text{for} \quad 0 \le x \le L \qquad (1)$$

with the following boundary conditions:

$$c(x,0) = c_o; \quad c(0,t) = c_o; \quad \text{and} \quad c(L,t) = c_L$$

where: c = chloride concentration,
c_o = chloride concentration at upper boundary;
c_L = chloride concentration at lower boundary;
L = length of domain;
v = seepage velocity (Darcy velocity divided by porosity);
D = sum of diffusion and dispersion coefficients

An analytical solution to this equation developed by Al-Niami and Rushton (1977) was used to solve Equation 1 and was implemented in a Microsoft Excel spreadsheet to analyze the chloride depth profiles. The upwelling velocity was calculated by solving Equation 1 in an iterative manner until there was a good correspondence between the calculated and the measured chloride depth profile.

In evaluating chloride-depth profiles using Equation 1, it is important to note that the steepest concentration gradients occur near the sediment-water interface. As a result, calculated upwelling velocities are most sensitive to the chloride data collected near the interface. In applying Equation 1 to the evaluation of upwelling velocities for purposes of this report, a preference was given to using only data from the upper five feet to estimate the upwelling velocity as deviations from linearity, if there were any, were most pronounced in this depth range. All profiles, though, were analyzed using data from the upper five feet as well as data from the entire depth profile, which typically consisted of data to a nominal depth of about 9 feet below the interface.

Model Parameters

The use of Equation 1 to analyze steady-state concentration profiles requires the definition of the parameter D, which is the sum of the diffusion and dispersive coefficients. The parameter D is defined as:

$$D = \omega D^* + \alpha_L v \quad (2)$$

where: D^* is the diffusion coefficient, ω is coefficient related to tortuosity and α_L is dispersion length.

The coefficient related to tortuosity is defined based on Boudreau (1996) as:

$$\omega = n/(1 - \ln(n^2)) \quad (3)$$

where: n is the porosity.

These parameters are a function of two characteristics of the sediment media, porosity and dispersion length; and a function of the diffusion coefficient of chloride in pore water. For purposes of the analysis of the chloride depth profiles from sediments of Onondaga Lake, the following values for these characteristics were used:

A porosity value of 0.65 was used for evaluation of chloride depth profiles from Remediation Area C, a value of 0.75 was used for Remediation Area A, and a value of 0.70 was used for Remediation Area E. Sediment porosity was measured at multiple depths at 64 Vibracore locations; the average porosity at these 64 locations is shown on Figure 12. The available porosity data are listed in Attachment V.

The dispersion length was calculated using equation (26) in Neuman (1990), which was developed to calculate the scale dependence of the dispersion length. This equation is: $\alpha_L = 0.0169L^{1.53}$, where L is length of the flow field in meters (note that equation requires that L be in units of meters). For a flow field length of 5 feet the calculated dispersion length is about 0.1 feet. The use of this method to estimate the dispersion length and alternative methods for estimating the dispersion length is discussed in detail in Attachment XI.

The effective diffusion coefficient for chloride was specified as 1.235 cm^2/day based on Felmy and Weare (1991) for a brine at 11° C.

An assumption implicit in the use of Equation 1 to estimate upwelling velocities is that the chloride concentrations in the sediments are at steady state; that is concentrations are not changing with time. A series of evaluations were conducted to determine the time required to reach steady state in shallow sediments after the sediments were disturbed. The calculations indicate that steady state is typically reached within a few decades. These calculations are described in Attachment VIII. In addition, it is assumed that chloride is neither being produced by dissolution nor lost by precipitation or sorption within the sediments. This is a valid assumption in most of the Remediation Areas but in some locations, particularly in areas with In-Lake Waste Deposits, it appears that this assumption may not be valid. As a result, this method was not used to evaluate upwelling velocities in areas known to contain In-Lake Waste Deposits.

Measurement of Sediment Chloride Concentrations

The initial method used to measure sediment chloride concentrations was to collect cores using the Vibracore method, section the cores into 1.0 foot intervals, centrifuge the cores, and then analyze the pore water for chloride and specific conductance. After evaluation of the data from the Phase I Pre-Design Investigation, it was determined that data at closer intervals was required for accurate analysis of the chloride-depth profiles and in Phase II the cores were sectioned into 0.5-foot intervals. In Phase III, the upper two feet of cores were sectioned into 0.2 foot intervals, but the pore water centrifuged from these small sections was only sufficient for analysis of chloride and specific conductance. All other pore water samples from Phase III were analyzed for common anions and cations, including chloride, and specific conductance. The cation-anion balance and the correlation between specific conductance and chloride were used to evaluate data quality.

In Phase II, the use of diffusion samplers (peepers) also was investigated for obtaining estimates of chloride concentrations in pore water. Fourteen extended peepers were installed at the five seepage meter clusters to approximate depths of eight to nine feet. The stainless steel peepers consist of a series of cells spaced at 0.5 foot intervals that are filled with deionized water and covered with a membrane. Ions in the sediment pore water diffuse across the membrane and the peeper is kept in place ideally until equilibrium is reached between the cell and the pore water. The peepers in the Phase II investigation were left in place for approximately one week prior to retrieval. Pore water samples were collected from locations adjacent to each of the peepers and the concentrations measured in the pore water were compared to those determined from the peepers. In almost all cases, the measured chloride concentrations in the pore water were higher than the chloride concentrations in the peepers. This is consistent with the results of the laboratory study conducted by Jackson and Anderson (2007) that indicated that chloride equilibrium requires much longer deployment time than one week. Diffusion samplers were also installed in each of the five seepage meters cluster in the Phase III investigations. These samplers were left in place for approximately three to five weeks and in general the chloride concentrations determined from these diffusion samplers were also lower than those measured in pore water. The chloride depth profiles determined from the diffusion samplers in Phase III are shown along with the chloride depth profile from a nearby vibracore location in Attachment XII.

Because it is labor intensive to collect and centrifuge core samples for pore water analyses or to utilize extended peepers, alternative techniques were investigated for rapidly estimating sediment pore water chloride concentrations. The most promising technique identified was the measurement of sediment conductivity with a probe advanced into the sediment and subsequent conversion of conductivity to equivalent chloride concentrations. The main technical weakness of this technique is that sediment conductivity is not the same as pore water conductivity as a conductivity probe in contact with sediment measures a response that is both a function of the sediment matrix and the characteristics of the pore water. In the investigations it was determined that there was a relatively good correlation between sediment conductivity and pore water conductivity.

A Geoprobe SC4000 soil conductivity probe was used for measuring sediment conductivity. The probe uses a four-pole Wenner-type array; current is passed through the outer contacts of this array and voltage is measured on the inner two contacts. Conductivity measurements were made at 0.05 foot intervals as the probe was advanced as well as temperature and the rate of probe advance. Most probes were advanced to a depth of approximately ten feet.

The conductivity data were converted to equivalent chloride concentrations using a conversion factor. A conversion factor of 0.89 was used to convert from conductivity in uS/cm^2 to mg/L chloride in Remediation Areas A, B and C and a factor of 0.80 was used in Remediation Areas D and E. These factors were developed from comparisons of pore water chloride and sediment conductivity data collected in close proximity to each other. The calculated upwelling velocities are not sensitive to the conversion factor as the conversion factor merely scales the chloride depth profile and does not affect the convexity of the profile. Attachment VI contains plots of chloride concentrations and conductivity versus depth for 31 locations where both pore water and sediment conductivity data were collected. In general, the shapes of the depth profiles are similar for both the pore water data and the sediment conductivity data.

There are inherent strengths and weaknesses with both methods used to construct chloride depth profiles. The chloride-depth profiles constructed from chemical analyses of pore water provide a more accurate estimate of actual changes in chemical concentrations with depth because the parameter of interest, chloride, is measured directly. The main weakness with the chloride-depth profiles developed from pore water is related to the fact that the measured concentrations represent an average concentration over the section of core analyzed. As a result, it is not possible to accurately define the chloride-depth profile very near the sediment-water interface where the chloride concentrations change rapidly with depth. The sediment-conductivity data collected with the Geoprobe conductivity probe, on the other hand, are an approximate analog for chloride concentrations in pore water, but because the probe does not measure pore water properties alone, variations in conductivity measurements with depth are also related to changes in the physical/chemical properties of the sediment. This method, though, allows variations in conductivity near the sediment water interface to be determined very precisely. Recognizing the strengths and limitations of the two methods leads to the conclusion that both methods can be used to provide reliable estimates of upwelling velocity.

Field Investigations

Chloride-depth profiles were constructed and used to estimate upwelling velocities at 287 locations within and in the vicinity of the Remediation Areas[3]. At 87 locations chloride-depth profiles were developed from analyses of pore water collected from cores during the Phase II, Phase III and Phase V Investigations, and at 229 locations chloride-depth profiles were developed from sediment conductivity data collected in the Phase III and Phase IV Investigation in 2007 and 2008[4]. Pore water data from 72 locations sampled as part of the Lake RI and 10 locations as part of the Phase I Preliminary Design Investigation were not used for estimating upwelling velocities because of a limited number of depth-discrete samples collected at each location. In addition, sediment conductivity data collected as part of the DNAPL Investigation (Parsons 2006) near the Causeway and in Phase II were not used for estimating upwelling velocities because of a lack of standardization in collection of the data. The table on the following page lists all of the investigations in which pore water and sediment conductivity data were collected, the number of locations at which data were collected, and comments regarding data collection.

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[3] Upwelling velocities were estimated from the analysis of 376 chloride-depth profiles collected at the 287 locations; 87 profiles developed from pore water data and 289 profiles developed from sediment conductivity data. At eight additional locations, the data collected were not analyzable.

[4] At 31 locations chloride-depth profiles were developed from both pore water data and sediment conductivity data.

Type	Study Phase	Date	Locations	Comments
Pore Water	RI	1992	72	Borings were advanced throughout the lake to a nominal depth of 3 feet and generally 3 to 5 subsamples from each boring analyzed for chloride. These data were not used to calculate upwelling velocities because of limited depth-discrete data.
	Phase 1 PDI	2005	10	Sediment samples collected at nominal depths of 1, 3, and 5 feet and pore water collected by centrifuging the samples. These data were not used to calculate upwelling velocities because of limited depth-discrete data.
	Phase II PDI	2006	13	Sediment samples collected at one foot depth intervals to ten feet and pore water collected by centrifuging the samples.
	Phase III PDI	2007	21	Sediment samples collected at one foot depth intervals to ten feet and pore water collected by centrifuging the samples. Collocated with seepage meters and Geoprobes.
	Phase III PDI Addendum 5	Dec 2007	30	Pore water collected by centrifuging sediments from approximate intervals of 0.0-0.3 feet, 0.3-0.5 feet, 0.5-0.8 feet, 0.8-1.0 feet, 1.0-1.3 feet, 1.3-1.5 feet, 1.5-1.8 feet, 2-2.5 feet, 3-3.5 feet, 4-4.5 feet, 5-5.5 feet, 6-6.5 feet, 7-7.5 feet, 8-8.5 feet, and 9-9.5 feet.
	Phase V	2009	23	Pore water collected by centrifuging sediments from intervals of 0-0.25 feet, 0.25-0.5 feet, 0.5-0.75 feet, 0.75-1.0 feet, 1.0-1.25 feet, 1.25-1.50 feet, 1.50-1.75 feet, 2.0-2.5 feet, 3.0-3.5 feet, 4.0-4.5 feet, 5.0-5.5 feet, 6.0-6.5 feet, 7.5-8.0 feet and 9.0-9.50 feet.
Sediment Conductivity	DNAPL Investigation	2006	20	Advanced along the causeway in SMU2 to a nominal depth of 45 feet using a Geoprobe fitted with a MIPs and conductivity detector. These data were not used to estimate upwelling velocities.
	Phase II PDI	2006	68	Advanced using Geoprobe method to nominal depth of ten feet. These data were not used to estimate upwelling velocities.
	Phase III PDI	2007	39	Advanced using Geoprobe method to nominal depth of ten feet in proximity to five seepage meters in SMU4 and SMU7.
	Phase III PDI Addendum 5	2007	82	Advanced using Geoprobe method to nominal depth of ten feet.
	Phase IV PDI	2008	124	Advanced using Geoprobe method to nominal depth of ten feet.

Sediment conductivity data and pore water data could not be collected in some areas because of the presence of a Solvay crust and/or obstructions in the water. Locations with crust and/or obstructions in the vicinity of Remediation Areas B and C are shown on Figure 10. In addition, the crust in the In-Lake Waste Deposits in Remediation Area D also prevented the collection of sediment conductivity and pore water data.

Initial Data Evaluations

The following steps were completed initially to evaluate the data that had been collected:

1. Anion-cation balances were calculated for the pore water analyses; the balances are listed in Attachment V. In a number of instances, the error in the anion-cation balance was greater than twenty percent. Based on an evaluation of chloride concentrations and specific conductance, it was determined that the error was generally attributable to an under reporting of cation concentrations. Plots were completed of conductivity versus chloride for data from each Vibracore location to identify chloride data that were outliers. These plots are contained in Attachment V.

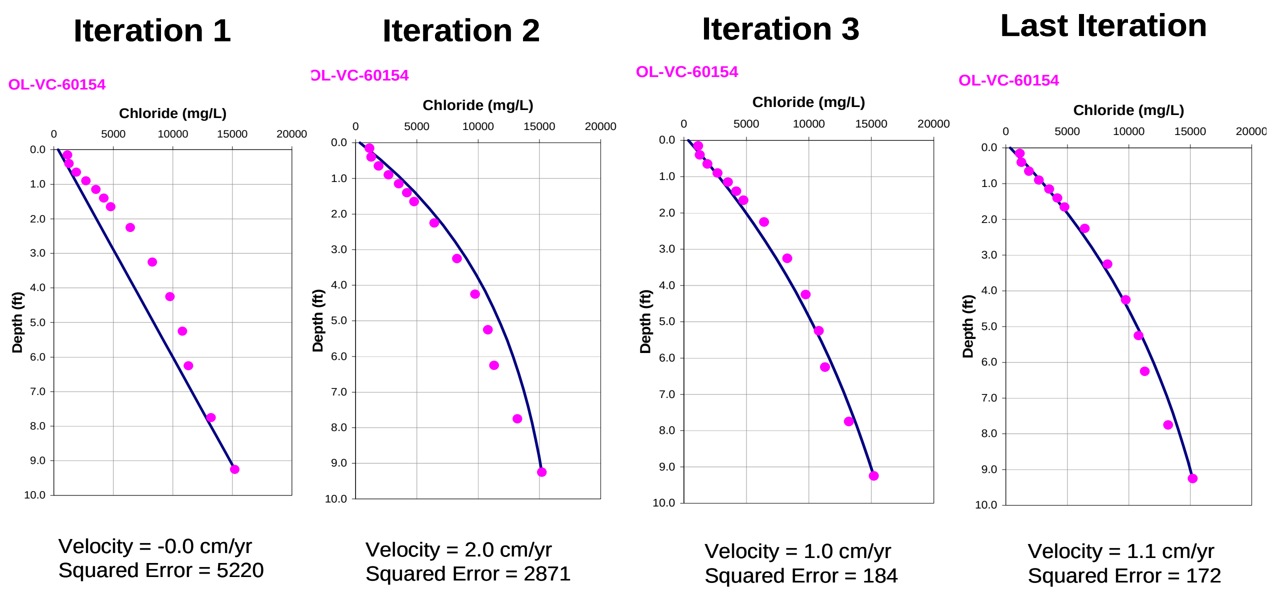
2. Plots of conductivity versus depth and chloride versus depth were developed for each location with co-located Geoprobe and Vibracore data, and a relationship was developed between the conductivity values from the Geoprobe and the chloride concentrations from pore water collected from the cores. These plots are contained in Attachment VI for thirty one locations with Geoprobe and Vibracore data. A linear factor relating the chloride concentration to conductivity was calculated using the Solver routine in Excel in which the sum of the squared difference between calculated chloride concentrations and observed chloride concentrations were minimized. The calculated factors for each of the thirty-one locations are listed in Attachment VI.

3. Plots of porosity versus depth were prepared for each of the Vibracore locations. These plots are contained in Attachment V. An average porosity was calculated for each location and the average porosity values at each of the Vibracore locations are shown on Figure 12.

4. Plots of sodium and sodium-calcium ratio versus depth were prepared for each of the Vibracore locations. These plots are contained in Attachment V.

Section 4
Upwelling Velocities Calculated from Chloride-Depth Profiles

The chloride-depth profiles developed from pore water data and sediment conductivity data collected in the littoral zone in, and in the vicinity of the Remediation Areas were analyzed using the procedures described in the previous section. Plots of the chloride-depth profiles are contained in Attachment VII. In total, as a result of duplicate and triplicate data collected at some locations, 376 chloride-depth profiles were developed for 287 locations. The analysis consisted of iteratively solving Equation 1, described in Section 3, using various values of the upwelling velocity until a "best fit" between the calculated and the measured chloride depth profile was obtained. The "best fit" was, in the ideal case, defined as a solution in which the sum of the squared differences between the measured and calculated chloride values was minimized. An example of the iterative process is illustrated below for the analysis of the pore water chloride data from location OL-VC-60154. An initial estimate of the upwelling velocity is 0.0 cm/year, which produces a sum of the squared differences between the calculated and measured values (squared error) of 5220. A second estimate of the upwelling velocity of 2.0 cm/year[5] produces a



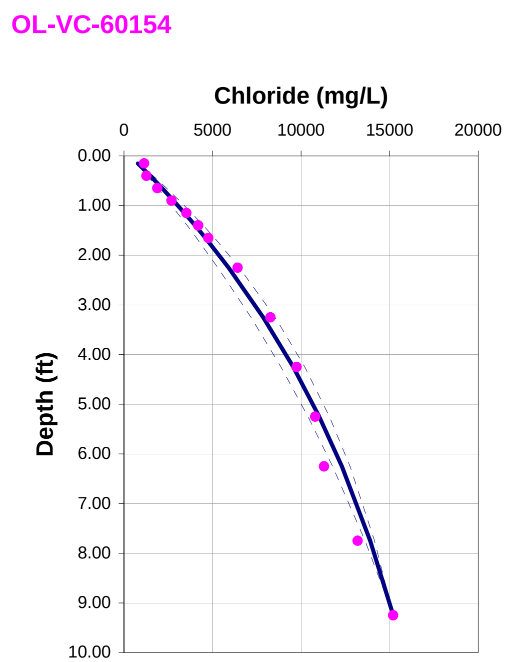
5 In this text a positive upwelling velocity indicates groundwater flow towards the sediment-water interface. This direction is opposite the standard groundwater convention in which a "positive" velocity indicates downward flow. In Attachment VII, the standard groundwater convention was used; thus for location OL-VC-60154 the "best fit" velocity is listed as "-1.0" rather than "1.0" as described above.

squared error of 2871, a third estimate of the upwelling velocity of 1.0 cm/year produces a squared error of 184 cm/year, and finally after many iterations a final solution of 1.1 cm/year is calculated with a squared error of 172.

The iterative solutions were calculated with the Solver routine in Excel[6] which is designed to find the solution that minimizes the squared error. In this example, relatively small changes in the upwelling velocity produces large changes in the squared error; for example changing the velocity from 2 cm/year to 1 cm/year reduces the squared error from 2871 to 184. This sensitivity of the squared error to the velocity in this example indicates that the upwelling velocity can be accurately quantified from the measured data[7].

In practice, the solution that minimized the squared error was not always the "best fit" solution as in some cases this solution was biased by scatter in the data. When the solution obtained by minimizing the squared error did not, in the professional judgment of the analyst, provide an acceptable fit to the measured data, this solution was manually adjusted to obtain a better fit to the measured data. In manually adjusting the solution, data collected near the sediment-water interface were weighted more than data from deeper depths.

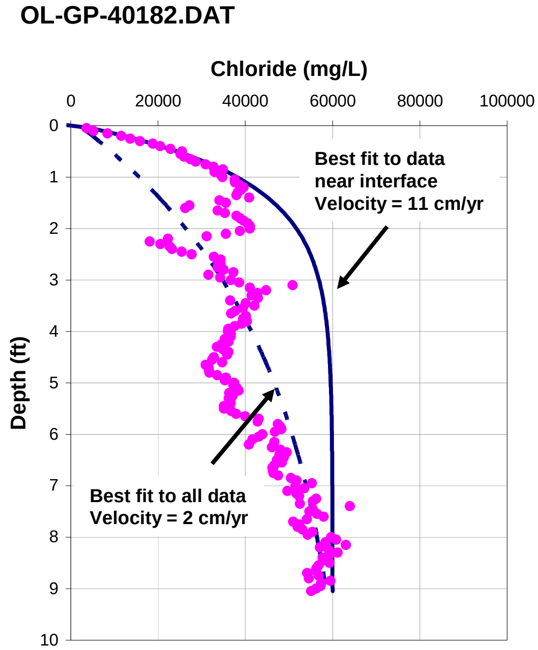
The upwelling velocities that were calculated for each of the chloride-depth profiles are listed on Table 1 and are shown on Figures 13 through 15 for Remediation Areas A, B, C and E, respectively[8]. The "best fit" solutions to Equation 1 for each of the chloride-depth profiles that were analyzed are shown on the plots in Attachment VII along with the parameter values used in solving Equation 1. An example plot for pore water data from OL-VC-60154 is shown to the right. The solid line indicates the "best fit" solution with a velocity of 1.1 cm/year, and the dashed lines indicate solutions for velocities of 1.1 ± 30% cm/year. A rigorous quantitative evaluation of the uncertainty associated with the "best fit" solution is described in Section 6.



[6] Microsoft Office Excel 2003 was used for these analyses.

[7] This example over simplifies the analysis of the data from OL-VC-60154 since in determining the "best fit" solution both the velocity and the concentration at the lower boundary were adjusted in the iteration process.

[8] On the figures, the upwelling velocities are rounded to the nearest integer; thus a velocity of 0.4 cm/year is shown on the figures as 0 cm/year.



In analyzing the chloride-depth profiles, a "best fit" solution was calculated based on an analysis of data from the sediments within five feet of the sediment-water interface and a "best fit" solution was calculated based on data from within the upper ten feet of the sediment-water interface. "Best fit" solutions were calculated using the two data sets to check the consistency of the calculated upwelling velocity and these results are shown on the plots in Attachment VII. In most cases, similar upwelling velocities were calculated using data from the upper five feet and data from the upper ten feet. In general for purposes of evaluating the spatial distribution of upwelling velocities, the higher of the estimates was used and this value is listed on Table 1 and posted on Figures 13 through 15[9].

At some locations, the measured chloride-depth profile did not define a smooth change in chloride concentrations with depth. As a result, the correspondence between the "best-fit" solution to Equation 1 and the measured data is poor. An example of a chloride-depth profile where the "best-fit" solution poorly matches the observed data is at location OL-GP-40182; the data from this location is shown on the figure above. A "best-fit" solution to the entire data set and a "best-fit" solution to the data near the interface for this location are also shown on the figure above. The upwelling velocity corresponding to the "best-fit" solution to the data near the interface is about 11 cm/year and the velocity corresponding to the "best-fit" solution to the entire data set is about 2 cm/year.

The calculated chloride-depth profiles of the "best-fit" solutions increase monotonically with depth whereas the data from OL-GP-40182 display significant scatter between a depth of about 1 foot and 5 feet below the sediment-water interface that is inconsistent with the calculated "best-fit" profiles. The deviation between the form of the measured data and the underlying model could be caused by a number of factors, but insufficient information is available to identify the main factors. It is suspected that a major factor is a poor correspondence between the sediment conductivity reading and the conductivity of the pore water due to variations in

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[9] An exception was when the data from the upper five feet did not correspond to the "best-fit" depth profile as well as data from the upper ten feet (or vice versa); in these cases, the "best-fit" solution that better fits the data is the value listed on Table 1 and posted on Figures 13 through 15, an a comment is included in Table 1 and Table VII-1.

lithology with depth and variations in the contact between the probe and the sediment with depth. The sediment-conductivity data from near the sediment-water interface are judged to be more representative of actual conditions because the data provide a smooth chloride-depth profile that is consistent with the analytical model at this sampling location. Therefore, the "best-fit" solution to the data near the sediment-water interface provides a better estimate of actual upwelling velocity than the "best-fit" solution to the entire data set from the upper nine feet of sediment; therefore, the upwelling velocity is about 11 cm/year at OL-GP-40182.

Table 1 includes notes indicating the quality of the upwelling analysis, which is a qualitative assessment of how well the measured data matched the chloride-depth profiles calculated using Equation 1. The quality of the upwelling analysis for about 80 percent of the chloride-depth profiles based on pore water data and for about 60 percent of the chloride-depth profiles based on sediment-conductivity data are judged to be "good". For these chloride-depth profiles the chloride concentrations generally increase monotonically with depth with little scatter and there is a good correspondence between the observed and calculated chloride-depth profiles. For these analyses, there is a high degree of confidence in the calculated upwelling velocities. On the other hand, the quality of the upwelling analysis for about 7 percent of the chloride-depth profiles based on pore water data and about 16 percent of the chloride-depth profiles based on sediment conductivity data are described as "poor". In general, these analyses are judged to be "poor" because the observed chloride concentrations do not increase monotonically with depth as illustrated above for location OL-GP-40182. For these analyses there is significant uncertainty associated with the calculated upwelling velocity. On Figures 13 through 15, the posted upwelling velocities at all locations where the analysis was judged to be "poor" are shown with a very light, or grayed-out font to emphasize the uncertainty associated with these upwelling estimates.

At some locations, the calculated upwelling velocity based on the "best-fit" solution exceeded a seepage velocity (as defined in Equation 1) of 50 cm/year which was judged to be the upper bound velocity that could be estimated by this method. For these locations Table 1 notes that the velocity is greater than the Darcy velocity that corresponds to a seepage velocity of 50 cm/year[10].

Calculated upwelling velocities in Remediation Areas A, C and E are overall low, with the exception of near shore areas in Remediation Area A where upwelling velocities exceed 37 cm/year. The median upwelling velocity in these three Remediation Areas based on the data collected are less than 2 cm/year. Summary statistics based on all the calculated upwelling velocities from the three Remediation Areas are listed below:

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[10] The upwelling velocities listed on Table 1 are Darcy velocities. The Darcy velocity by definition is equal to the seepage velocity multiplied by the porosity. Since the porosity is always less than one, the Darcy velocity is always less than the seepage velocity.

		Number of Locations	Median Darcy Velocity (cm/year)	Standard[11] Deviation (cm/year)
Remediation Area A	All data	84	1.6	10
	Pore water data	24	3.8	13
	Sediment Conductivity Data	60	1.2	9.1
Remediation Area B	Pore water data	4	1.8	1.5
Remediation Area C	All data	62	1.1	7.9
	Pore water data	9	1.8	3.6
	Sediment Conductivity Data	53	1.0	8.4
Remediation Area E	All data	174	1.7	3.3
	Pore water data	30	0.9	3.0
	Sediment Conductivity Data	144	1.8	3.4

Cumulative frequency plots for the upwelling velocity estimates from pore water and sediment conductivity data from all locations in Remediation Areas A, C and E are shown on the top of the next page. Separate plots are shown for estimates of upwelling velocities from pore water data and estimates from sediment conductivity data.

These plots provide a visual depiction of the range of upwelling velocities in Remediation Areas A, C and E and show that at well over fifty percent of the sample locations the upwelling velocities are less than 2 cm/year (except for pore water data from Remediation Area A). In addition, the plots show that the cumulative frequency curves based on sediment conductivity data and pore water data are similar. Differences between the cumulative frequency curves for the two methods are in part explained by the much larger number of locations with sediment conductivity data.

Based on the distribution of upwelling data and the proposed approach for capping and dredging in the remediation areas, additional data will be collected using a Vibracore during future phases of the PDI. These data will be used to address data gaps and refine the input parameters for the cap design.

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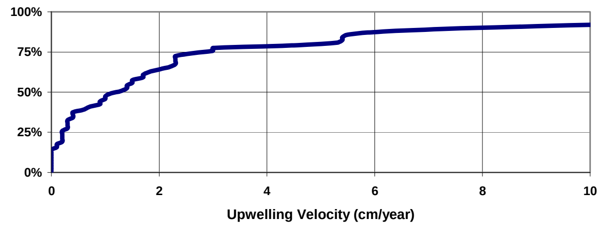
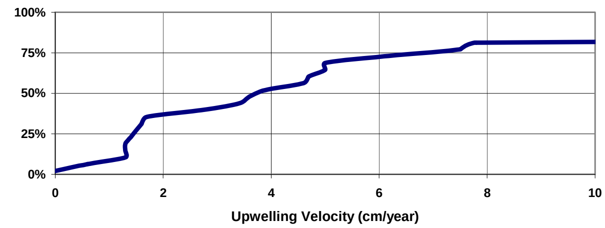
[11] In calculating the standard deviation, when the seepage velocity exceeded 50 cm/year, a Darcy velocity corresponding to a seepage velocity of 50 cm/year was used in the calculation.

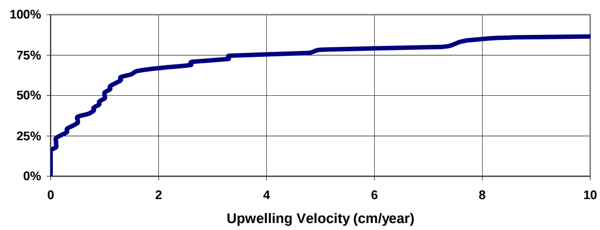
Remediation Area A -- Sediment Conductivity Data



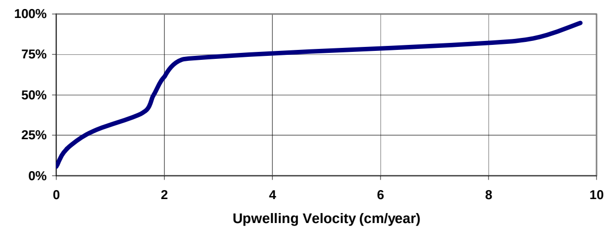
Remediation Area A -- Pore Water Data



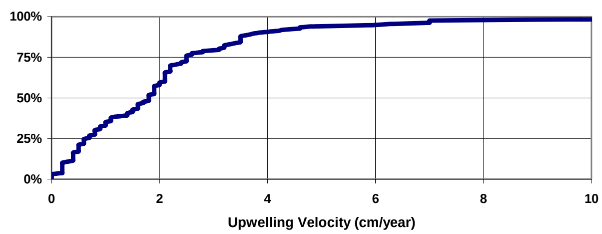
Remediation Area C -- Sediment Conductivity Data



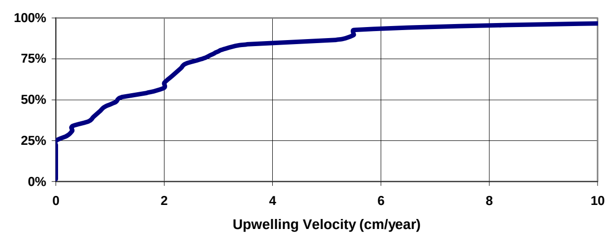
Remediation Area C -- Pore Water Data



Remediation Area E-- Sediment Conductivity Data



Remediation Area E -- Pore Water Data

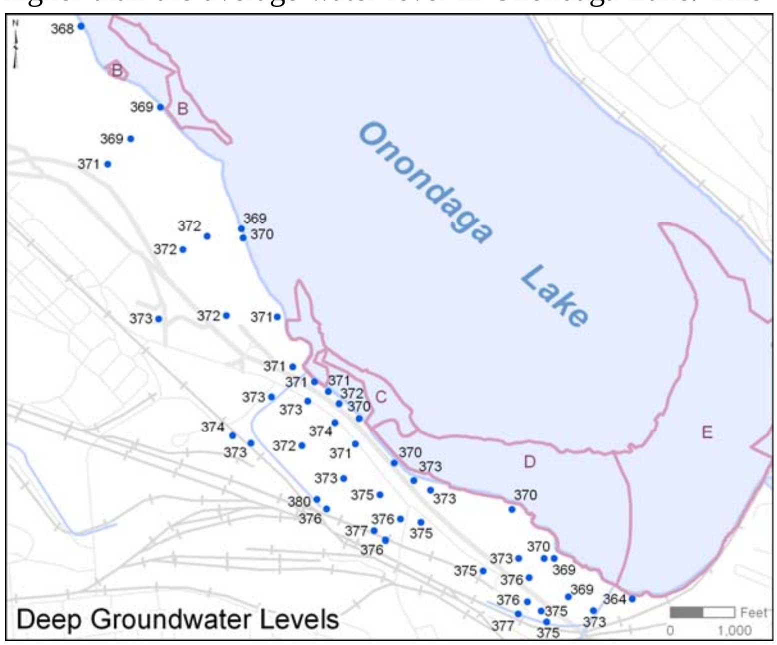


Section 5
Analysis of Upward Groundwater Flow through Silt and Clay Unit

Groundwater discharge in Remediation Area D and the southern section of Remediation Area C will be significantly less than current rates following construction and operation of the hydraulic containment system described in the Record of Decision. In addition, a hydraulic containment system anticipated as a component of the remedial action for Wastebeds 1-8 would reduce groundwater discharge to Remediation Area B to less than 2 cm/yr. In areas offshore of the hydraulic containment systems, groundwater discharge will potentially come from two sources; recharge in the area between the lake shore and the hydraulic barrier and upward groundwater flow through the silt and clay layer. The engineered design for the restoration of wetlands outboard of the barrier wall will prevent, to the extent practicable, groundwater recharge along the transitional slope from the wall to the wetlands by placing a low permeability material in this area. As a result, the only significant potential source of groundwater discharge is upward migration of groundwater through the silt and clay layer.

Remediation Area D and Southern Section of Remediation Area C

Groundwater levels, and hydraulic heads, in the permeable units below the silt and clay unit in Remediation Areas B, C and D are higher than the average water level in Onondaga Lake. This creates the potential for upward groundwater flow from the deeper units to the lake. Some of the monitoring wells completed in the sand and gravel unit along the shoreline, adjacent to Remediation Area C and D, flow at the surface, which illustrates realization of this potential. The water levels in the sand and gravel in onshore wells in the vicinity of Remediation Area B, C, and D are shown on the figure to the right (elevations are in feet AMSL)[12]. Water levels in the wells in the vicinity of the lakeshore range from 364 to 374 feet AMSL. The



[12] Water level data represent best estimate of average water levels in the deep zone (O'Brien & Gere 2009)

average lake level is about 363 feet AMSL; therefore, the water level differences between the sand and gravel zone and the lake range from about 1 foot to 11 feet, with the smallest differences occurring in the southeast corner of the lake near the mouth of Harbor Brook. Along much of the shoreline, the water level difference between the sand and gravel zone and the lake is about 7 feet. The potential for upward flow from the deep units is proportional to the water level difference. Therefore, the potential for upward flow is smaller in the southeast corner of the lake. The magnitude of the upward flow is also related to the thickness and permeability of the silt and clay unit and differences in groundwater density between the sand and gravel zone and the lake.

Several lines of evidence have been used to estimate the upward groundwater flow through the silt and clay unit, and all of these lines of evidence indicate the rate of groundwater flow is very small. From a large-scale perspective, the presence of halite brines in the unconsolidated units beneath the lake provides very strong evidence that the rate of upward groundwater flow through the sediments is very small. The existence of the brine in the sand and gravel aquifer is consistent with only the diffusive flux of chloride across the silt and clay unit as discussed in Appendix D of the Lake FS and in the USGS report by Yager and others (2007). If upward flow of any appreciable magnitude was occurring across the silt and clay unit, the halite brine in the deep zone, which originated about 16,000 years ago during the end of the last period of glaciation, would have dissipated long ago.

Water-quality data collected from a deep boring (OL-STA-30033) advanced to bedrock in the lake in Remediation Area B also provide qualitative information on the negligible rate of upward groundwater flow through the silt and clay unit. In this boring, pore water samples were collected as the boring was advanced. Pore water samples collected within the silt and clay unit have the characteristics of the natural halite brine and water samples in the underlying more permeable units have the characteristics of Solvay leachate. This change in water quality with depth is the result of lateral movement of Solvay leachate in the more permeable units from the nearby wastebed. Prior to operation of the wastebeds, water quality in the silt and clay unit and the underlying permeable unit most likely had the characteristics of halite brines similar to what is observed elsewhere in the lake. During or following operation of the wastebeds, Solvay leachate migrated within the more permeable units away from the wastebeds displacing the natural halite brine. This migration likely occurred prior to 1950 as dating of the groundwater in the more permeable units along the lakeshore with the tritium method indicates a groundwater age of more than 60 years. The Solvay leachate does not appear to have migrated upward into the silt and clay unit as the natural halite brine in this unit has not been displaced, indicating that the rate of upward groundwater flow is very small. At an upward groundwater velocity of 2 cm/year, over a period of 60 years, the Solvay leachate would have migrated about 10 feet into the silt and clay unit[13]. The fact that the Solvay leachate has apparently not migrated into the silt

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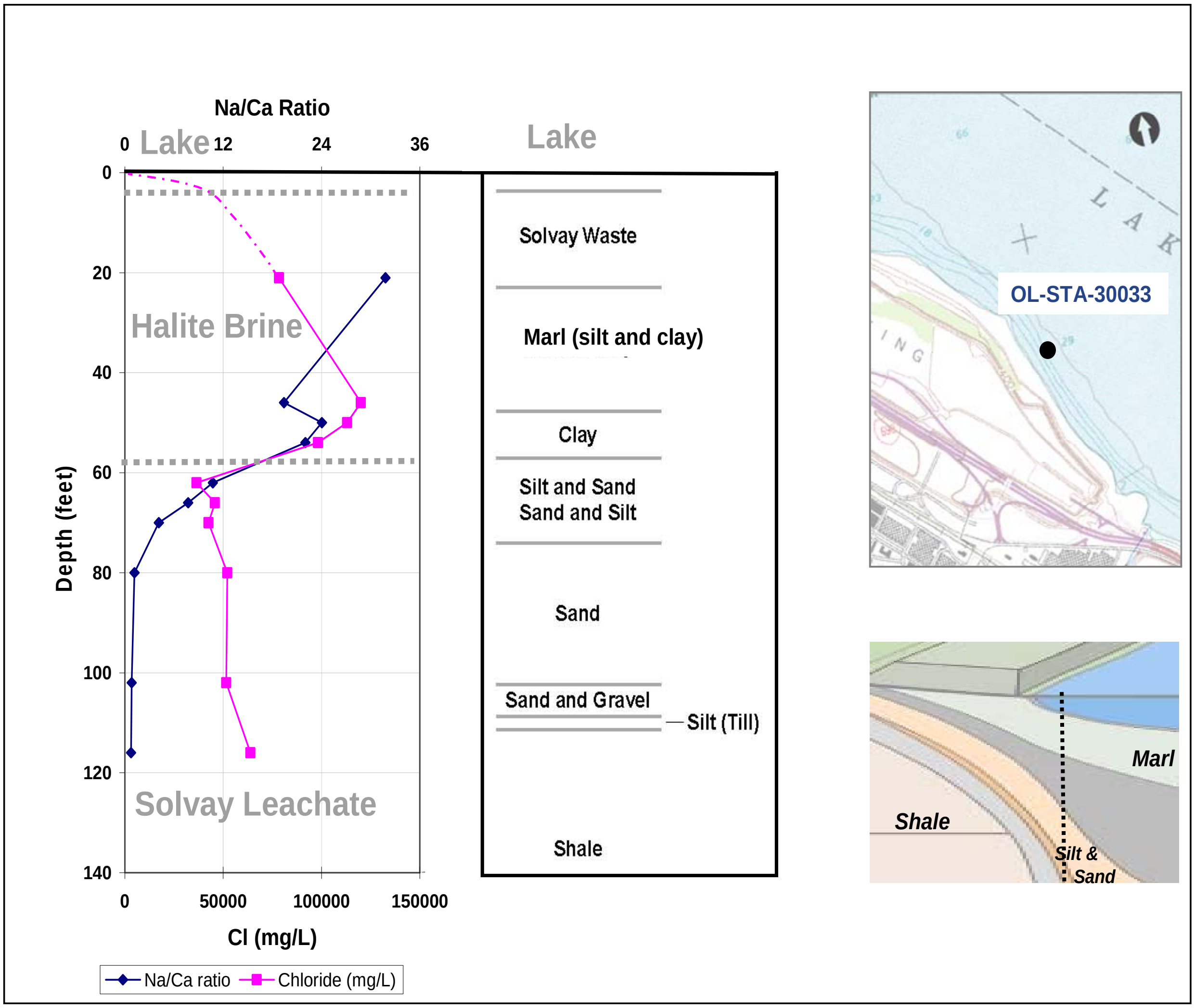
[13] This distance is based on an upwelling velocity of 2 cm/year, an effective porosity of 0.4, and a 60 year migration time frame.



and clay unit suggests that the upward groundwater flow rate through the silt and clay unit is significantly less than 2 cm/year in Remediation Area B. A plot of water-quality data variations with depth in the deep boring advanced in the lake offshore of Remediation Area B (OL-STA-30033) is shown above along with a geologic log, location map and a schematic cross section with well location.

An estimate of groundwater flow across the silt and clay unit was also made using chloride concentration gradients in an analogous manner to that used to estimate upwelling velocities near the sediment-water interface. Pore water samples were collected in three borings in SMU2[14] from the upper eight feet of the silt and clay unit and analyzed for chloride

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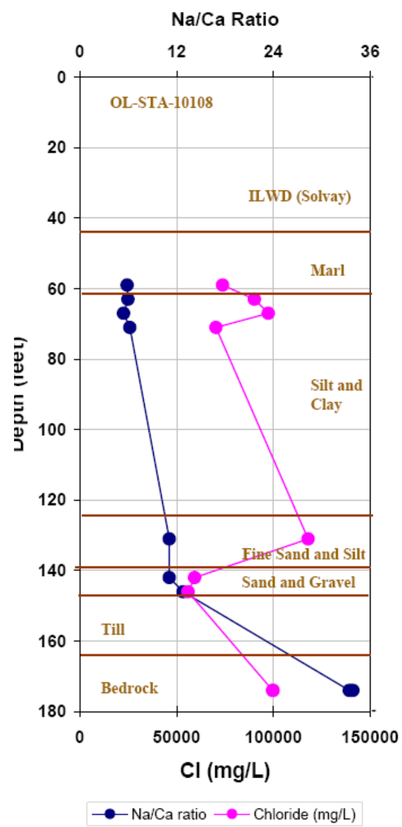
[14] Borings OL-STA-20042, OL-STA-20053, OL-STA-20058 advanced in May 2006.

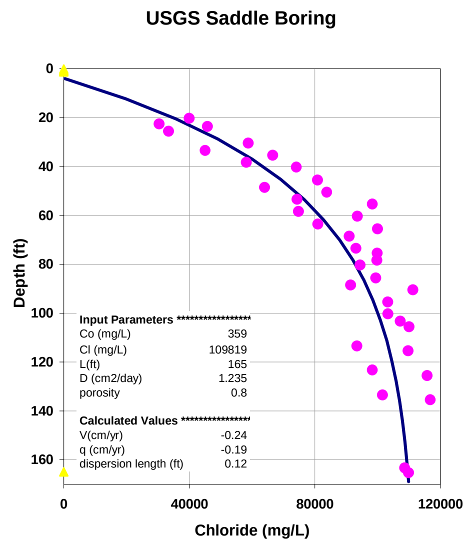
concentrations in the pore water to provide information to quantify the upward groundwater flow through this unit. The pore water chloride data from these borings were interpreted using Equation 1 to quantify groundwater velocity through the silt and clay unit. The calculated velocity through the silt and clay unit at all three borings was less than 0.5 cm/year. The estimate though has significant uncertainty because the chloride concentration gradient within the silt and clay unit is small due to the fact that this unit is located tens of feet below the sediment-water interface. The results of these evaluations are contained in Attachment X.

A deep boring was advanced in Remediation Area D, approximately 2,000 feet offshore, into bedrock which was encountered at a depth of 169 feet below the sediment-water interface. In this boring, unlike the boring in Remediation Area B, all the pore water had the characteristics of a natural sodium-chloride brine. The chloride-depth profile from this boring could not be analyzed to determine upwelling velocities because chloride concentrations in the sand and gravel unit were lower than in the overlying fine sand and silt and the underlying bedrock, likely reflecting changes in water quality induced by historic brine production[15]. A plot of chloride concentrations with depth in this boring, as well as sodium to calcium ratios, are shown on the figure to the right.



The USGS advanced a boring to a depth of 181 feet near the center of the lake in the profundal zone beyond Remediation Area A. Sediment samples were collected as the boring was advanced and subsequently centrifuged in the laboratory to obtain pore water samples. These samples were analyzed for a number of analytes including calcium, sodium and chloride. The chloride-depth data have been analyzed using the techniques described above to estimate the upwelling velocity. The calculated upwelling velocity is 0.24 cm/year as shown on the plot below.

[15] The USGS (2000) reported that 11.5 million tons of salt were removed from brines produced from the groundwater system at Onondaga Lake from 1797 to 1917. This represents the salt content from the constant production of 500 gallons per minute of brine with a chloride concentration of 60,000 mg/L over this period. Most of this production occurred from the permeable sand and gravel unit. This production lowered groundwater levels throughout the connected portion of the sand and gravel unit and induced the migration of fresher groundwater from the landward margins of the sand and gravel unit.



The silt and clay unit typically is described in the field as brown to dark gray clay with some silt with medium to high plasticity. The effective vertical hydraulic conductivity of the silt and clay unit was specified in the modeling analyses conducted by the USGS (Yager and others 2007) to be 10^{-7} cm/sec ($9x10^{-5}$ m/day). In the Groundwater Flow Model described in Section 2, the vertical hydraulic conductivity of the silt and clay unit was estimated in the initial model calibration process to be slightly higher, about $2x10^{-7}$ cm/sec. The model also calibrates with lower values of vertical hydraulic conductivity for this unit but not with higher values. These estimates of the hydraulic conductivity are consistent with the characteristics of the silt and clay unit.

The thickness of the silt and clay unit beneath the lake is variable, ranging from about 10 feet to over 80 feet in the Remediation Areas. A map of the thicknesses of the silt and clay unit beneath much of Onondaga Lake is shown on Figure 3 and a detailed map showing the thickness in Remediation Area D is shown on Figure 16. On these figures the locations of all borings that were advanced into the silt and clay unit and the thicknesses of the silt and clay unit penetrated by the borings are shown. Most borings were not advanced completely through the silt and clay unit, and for these borings the value posted on the map is a minimum estimate of the thickness of the unit. In much of the eastern part of Remediation Area D and in adjacent Remediation Area E, the silt and clay unit is over 80 feet thick. The unit is thinnest along the shoreline in the western portion of Remediation Area D, but the unit thickens rapidly away from the shoreline.

The rate of upward groundwater flow through the silt and clay unit can be estimated with Darcy's law $v = ki$ where v is the upwelling velocity, k is the vertical hydraulic conductivity, and i is the hydraulic gradient. This equation is valid if the density of the groundwater on either side of the silt and clay unit is approximately the same, which is generally the case as brines occur both in the marl overlying the silt and clay unit and in the underlying fine sand and silt unit and the sand and gravel unit. If the density is not the same, the velocity can be estimated with the following equation:

$$v = -k\left(\frac{\partial h_f}{\partial z} + \left(\frac{\rho - \rho_f}{\rho_f}\right)\right) \qquad (4)$$

where: h_f is equivalent fresh-water head, ρ is average density between two locations where head is measured, and ρ_f is freshwater density (Parsons 2004, Appendix D: Part A).

The large variations in the thickness of the silt and clay unit results in differences in the upward groundwater flow in Remediation Area D with the larger upward groundwater flows occurring near the shoreline where the silt and clay unit is the thinnest. The silt and clay unit beneath the lake at Remediation Area D appears to be the thinnest adjacent to the East Flume. A boring was advanced and monitoring wells were installed on the spit of land beneath the East Flume and the lake to determine the characteristics of the silt and clay unit and groundwater conditions in this area (boring HB-SB-213 and monitoring wells HB-MW-213D, HB-MW-213I and HB-MW-213S). Monitoring wells HB-MW-213I and HB-MW-213D are screened in the marl above the silt and clay unit and in the sand and silt unit below the silt and clay unit, respectively. Based on the water level difference between these two wells, the thickness of the silt and clay unit and the higher of the two estimates of the vertical hydraulic conductivity described above, the upward groundwater velocity is less than 2 cm/year[16].

Evaluations of potential upwelling velocities were conducted considering the water level differences measured at the various monitoring locations along the shoreline in Remediation Area D and the density variations in groundwater. These evaluations indicate that upwelling velocities will be less than 2 cm/year adjacent to the shoreline where the silt and clay unit is thinnest, to less than 1 cm/year where the silt and clay unit is greater than 22 feet thick, to less than 0.5 cm/year where the silt and clay unit is greater than 44 feet thick[17]. The calculated upwelling velocities at selected monitoring locations, based on water levels in deep and intermediate well pairs, are listed on Table 4.

The groundwater model, described in the Lake FS, is an analytical tool that combines in a rigorous mathematical framework all of the important factors that affect the rate of vertical groundwater movement through the sediments beneath Onondaga Lake. The groundwater model incorporates information on the variations in thickness of each of the geologic units including the silt and clay unit, variations in hydraulic properties, and variations in density of groundwater within the subsurface. In addition, the groundwater model can explicitly represent the effects of operation of the hydraulic containment system on vertical groundwater flow through the silt and clay unit. As noted above, the groundwater model was used to estimate upwelling velocities for the Lake FS, and the results of the evaluations were that upwelling velocities in Remediation Area D following installation and operation of the hydraulic containment system would be less than 2 cm/year. The numerical methods used to calculate flow in the groundwater model have precision limitations due to the nature of the algorithms used in the model, and our evaluations indicated that the precision of the calculations of upwelling velocities generated a maximum

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[16] The upward groundwater velocity is calculated based on a vertical hydraulic conductivity of $1x10^{-7}$ cm/sec, a water level difference across the silt and clay unit of 4.92 feet based on water levels collected on November 3, 2008 (O'Brien & Gere 2009) and a silt and clay unit thickness of 8 feet. The hydraulic gradient is calculated as the water-level difference divided by the silt and clay thickness. The densities of groundwater at HB-MW-213I and HB-MW-213D are similar as measured total dissolved solids concentrations were 48,900 mg/L and 47,000 mg/L, respectively in November 2008.

[17] These estimates were calculated using a water-level difference across the silt and clay unit of 7 feet and vertical hydraulic conductivities for the silt and clay unit in the range of $1x10^{-7}$ cm/year.

value of 2 cm/year. Therefore, with the numerical model it was determined that upwelling velocities of less than 2 cm/year could not meaningfully be calculated with the numerical model alone. The one-dimensional analyses of groundwater flow through the silt and clay unit described above; however, does provide additional justification for the use of 2 cm/year as a maximum upwelling velocity within Remediation Area D with the shallow hydraulic containment system in operation.

The presence of upward hydraulic gradients from the deep groundwater zones to Onondaga Lake indicates that there is the potential for upward groundwater flow from the deep zones to Onondaga Lake. The hydraulic containment system that will be operated along the lakeshore at Remediation Area D and portions of Remediation Area C will capture shallow groundwater flowing towards the lake but will have a negligible effect on the potential upward flowing groundwater from the deeper groundwater zones to the lake. The evaluations described above indicate that the upwelling velocities with the hydraulic containment system in operation will be less than 2 cm/year. Upwelling velocities may approach 2 cm/year along the shoreline in the western portion of Remediation Area D where the silt and clay unit is the thinnest but upwelling velocities may be much less than 2 cm/year in Remediation Area D where the silt and clay unit is much thicker.

Based on the multiple lines of evidence described above, estimates of the upwelling rates in Remediation Area D with operation of the hydraulic containment system in operation have been developed. These estimates are based on the assumption that groundwater discharge in the Remediation Area D with operation of the hydraulic containment system will be the result only of upward groundwater flow through the silt and clay unit. The rate of groundwater flow through the silt and clay unit is a function of the hydraulic gradient across this unit, the thickness of the unit and the effective vertical permeability of this unit. A contour map of equal upwelling velocities within Remediation Area D has been developed based on estimates of groundwater gradient, and thickness and vertical permeability for the silt and clay unit. This contour map is shown on Figure 17. Upwelling velocities in much of Remediation Area D are less than 1 cm/year.

Remediation Area B

A hydraulic containment system is anticipated along the shoreline of Wastebeds 1-8 that will extend northward from Ditch A for about 6,000 feet. Operation of this hydraulic containment system will capture shallow groundwater flowing towards the lake. With operation of this system, upwelling velocities in Remediation Area B will be the result of only upward migration of groundwater through the silt and clay layer, which will be less than 2 cm/yr.

In Remediation Area B the thickness of the silt and clay unit ranges from about 20 to 80 feet (Figure 18). Water levels in the sand and gravel zone along the shoreline adjacent to Remediation Area B are in the range of 368 to 369 feet AMSL indicating a water-level difference between the sand and gravel zone and the lake of approximately 5 to 6 feet. Potential upwelling velocities in Remediation Area B were calculated using a similar procedure to that described above for Remediation Area D[18]. The calculated upwelling velocities through the silt and clay unit and through the marl and cap into the lake are less than 2 cm/year.

Northern Section of Remediation Area C

Currently, a hydraulic containment system is not anticipated to extend along the shoreline adjacent to the northern section of Remediation Area C (Figure 1). In the area between the anticipated Wastebeds 1-8 hydraulic containment system and the Willis/Semet hydraulic containment system, shallow groundwater would continue to discharge to the lake near the shoreline. As a result, groundwater upwelling velocities after remediation are anticipated to be similar to current upwelling velocities as shown on Figure 14a in the central portion of the northern section of Remediation Area C. In those portions of Remediation Area C that are offshore from the hydraulic containment systems, operation of the hydraulic containment systems will result in a reduction of upwelling velocities from current rates to less than 2 cm/yr.

At three locations within the northern section of Remediation Area C calculated upwelling velocities are greater than 30 cm/year as shown on Figure 14a (locations OL-GP-30071, OL-GP-30075 and OL-GP-30076). There is a low degree of confidence in these results though, because at each of the locations the conductivity probe was advanced multiple times and widely different results were obtained from each advancement. For example, at location OL-GP-30075 the conductivity probe was advanced four times in close proximity to each other and the resulting chloride-depth profiles were very different with calculating upwelling velocities ranging from 4.5 cm/year to >32.5 cm/year. Likewise at the other two locations, calculated upwelling velocities for the multiple probe advancements ranged from less than 4 cm/year to greater than 30 cm/year. Vibracores will be advanced in this area during future design investigations to obtain pore water data to better define the chloride-depth profile and provide a more reliable estimate of the upwelling velocities in this area.

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[18] Upwelling velocities were calculated using Equation 2 in Attachment D.1 to the Onondaga Lake FS (Parsons 2004).

Section 6
Evaluation of Uncertainty in Calculated Upwelling Velocities

Upwelling velocities in certain Remediation Areas of the Lake have been calculated with the chloride-depth profile method, which was determined to be the best method for quantifying the upwelling velocities. In evaluating the chloride-depth profiles, the best estimates of aquifer and chemical parameters have been utilized in the analyses. This section briefly discusses the uncertainty associated with the input parameters, the uncertainty associated with reproducibility of results from co-located borings, and the uncertainty associated with the use of a "best fit" solution to Equation 1 to estimate the upwelling velocity.

Sensitivity to Model Parameters

The sensitivity of calculated upwelling velocities to dispersion length, porosity and chloride factor was evaluated. Sensitivity analyses were conducted using the data from Geoprobe location GP-40168 and Vibracore locations VC-40091, VC-40092 and VC-70058. The estimated upwelling velocities at these locations ranged from 5.7 to 10.3 cm/year. The sensitivity analyses consisted of the following four evaluations:

1. Increasing the dispersion length from 0.1 feet to 0.8 feet;
2. Decreasing the porosity to the lowest porosity value measured in the vicinity of the location;
3. Increasing the factor that converts conductivity to chloride from 0.8 to 1.0 (only for sediment conductivity data); and
4. Decreasing the factor that converts conductivity to chloride from 0.8 to 0.64 (only for sediment conductivity data).

The results of these sensitivity evaluations indicate the calculated upwelling velocities are sensitive to porosity and dispersion length, but not very sensitive to the chloride adjustment factor. The results of the sensitivity evaluations for porosity and dispersion length that were conducted for the chloride-depth profiles from GP-40168, VC-40091, VC-40092, and VC-70058 are contained in Attachment XI.

Reproducibility of Results

The reproducibility of calculated upwelling velocities was evaluated by comparing the upwelling velocities calculated from sediment conductivity data with those calculated from the Vibracore data at each of the thirty locations with both types of data and by comparing calculated upwelling velocities from multiple sediment-conductivity borings advanced in close proximity to one another. Overall the calculated velocities from co-located Vibracore and sediment-conductivity borings compare well. The results of these evaluations are listed on Table 2 and plots of these data are contained in Attachment IX.

At 47 locations, multiple sets of sediment conductivity data were collected. The upwelling velocities at locations with multiple sets of conductivity data are listed on Table 3. At most locations, the upwelling velocities calculated from each set of data are similar.

The reproducibility of calculated upwelling velocity was also assessed by comparing sediment conductivity data taken in different seasons at the same location. Chloride profiles based on sediment conductivity were obtained during spring and fall seasons at several locations (OL-GP-40183, OL-GP-40184, OL-GP-40185, OL-GP-40186, and OL-GP-70107). The upwelling velocities determined in different seasons for these locations are comparable, except in cases where the data are difficult to analyze due to exceeding the maximum measurement capability of the probe (OL-GP-70107). Distinct seasonal trends could not be reliably identified. At four locations, profiles were obtained during the summer months in both 2007 and 2008 (OL-GP-40074, OL-GP-40010, OL-GP-70053, and OL-GP-70054). The upwelling velocity determinations were comparable, except in cases where the data were difficult to analyze due to the measured values exceeding the maximum measurement capability of the probe.

Model Fit

The uncertainty of the upwelling velocities calculated with a "best fit" solution to Equation 1 was evaluated by calculation of a confidence interval (CI) for the calculated velocity. This uncertainty is primarily related to scatter in the chloride or conductivity depth profile data. The confidence interval is calculated as:

$$b \pm f \cdot s_b \qquad (5)$$

where b is the calibrated parameter value, f is the confidence interval factor (for a 90% CI, f=1.645), and s_b is the standard deviation of the estimated parameter value. The standard deviation of a parameter value is a function of the perturbation sensitivities and the observation variances (*Aster et al. 2005*, *Doherty 2008*):

$$s_b^2 = \sigma^2 \left(\underline{X}^T \underline{X} \right)^{-1} \qquad (6)$$

where X is a matrix of the sensitivities of observations to parameters (calculated using forward difference perturbations) and σ^2 is an *m*-vector containing the observation variance calculated according to (*Doherty 2008*):

$$\sigma^2 = \frac{\Phi}{m-n} \qquad (7)$$

where Φ is the residual sum of squares, *m* is the number of observations, and *n* is the number of parameters.

Because there is only 1 parameter, the sensitivity matrix $\underline{X}$ has *m* rows and only 1 column, making it a vector. As such, calculation of $\underline{X}^T\underline{X}$ is simply:

$$\sum_{i=1}^{m} x_i^2 \qquad (8)$$

where x_i is the *i*th row in the sensitivity vector.

The calculated confidence intervals for each of the upwelling velocities are listed on Table 1. At most locations, the confidence interval is relatively small.

This formal analysis of uncertainty is based on the assumption that the boundary conditions for Equation 1 are fixed. In practice though, there is some uncertainty relative to the lower boundary condition. For the analyses that were judged to be "good" as listed on Table 1, the uncertainty related to the lower boundary condition is small, but for analyses judged as "fair" or "poor", there may be additional uncertainty related to the magnitude of the lower boundary condition.

Another measure of model fit is the correspondence between the upwelling velocities calculated based on "best-fit" solution to the upper five feet of data and the upwelling velocities based on "best-fit" solution to the upper ten feet of data. For locations where the upwelling results from the two sets of analyses are similar, this is an indication that the uncertainty associated with the upwelling estimate is low; whereas, when the two estimates differ significantly it indicates uncertainty regarding the estimated upwelling velocity. The upwelling velocities estimated from the upper five feet of data and the upper ten feet of data are listed in Attachment VII.

Summary

The evaluations of the uncertainties in the upwelling velocities quantified with the chloride-depth profile method have indicated a high degree of confidence in the calculated upwelling velocities, but as with all evaluations based on field data, there is some uncertainty associated with individual evaluations of upwelling velocities. In this investigation, upwelling velocities were determined at a total of 287 locations and the spatial consistency of results, as shown on Figures 13, 14 and 15, increased the confidence associated with estimates at individual locations.

Section 7
Conclusions

This report describes the results of extensive field and analytical studies that have quantified the discharge of groundwater to the areas in Onondaga Lake where a sediment cap will be placed as part of the remedial activities undertaken to meet the requirements of the Record of Decision for the Onondaga Lake Bottom Subsite. The current rates of groundwater discharge in Remediation Areas A and E and the northern section of Remediation Area C, which are similar to discharge rates expected after placement of the cap, have been delineated based on the analysis of chloride depth profiles at more than 250 locations within and in the vicinity of these Remediation Areas. In Remediation Area B, D, and the southern section of Remediation Area C, the rates of groundwater discharge after placement of the cap will be significantly lower than current rates as the result of the construction and operation of a hydraulic containment system along the shoreline. Groundwater discharge rates in Remediation Area B, D and the southern section of Area C after placement of the cap were calculated based on groundwater flow rates upward through the underlying regional confining unit (the silt and clay unit).

This report describes a number of methods that were implemented in the field to estimate groundwater discharge rates, which are commonly referred to as upwelling velocities. The evaluation of upward groundwater velocity through the sediment based on the change in chloride concentrations with depth in sediment pore water was determined to be the best method for estimating current upwelling velocities in the Remediation Areas. This report describes the theoretical bases for the use of this method to estimate upwelling velocities and describes the extensive data collected on chloride concentrations in sediments to accurately delineate the current distribution of upwelling velocities within the Remediation Areas.

The upwelling velocities within the Remediation Areas are low. The median upwelling velocities currently in Remediation Areas A, B, C and E are less than 2 cm/year, though upwelling velocities greater than 32 cm/year were determined in some locations. In Remediation Area D and the southern section of Area C, calculated upwelling velocities with the hydraulic containment system in place are less than 2 cm/year, and in the eastern portion of Remediation Area D calculated upwelling velocities with the cap in place are less than 1 cm/year. In Remediation Area B, with operation of the anticipated hydraulic containment system, calculated upwelling velocities are also less than 2 cm/year.

The data and evaluations described in this report provide an excellent foundation for the design of the remedy for Onondaga Lake. The upwelling velocities that are described in this report will be utilized in the Cap Model for purposes of cap design.

Section 8
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FIGURES

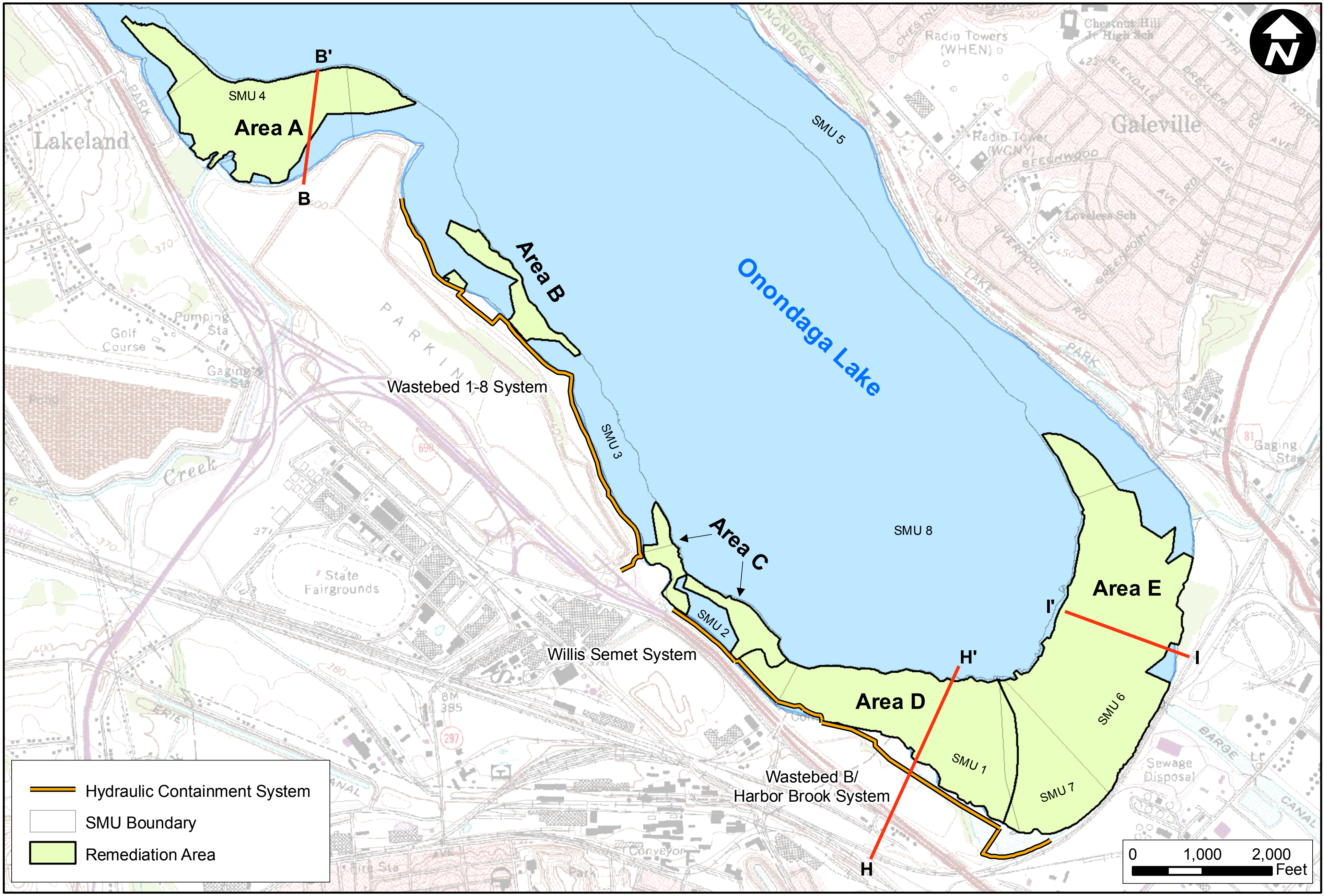


Figure 1 Remediation Areas and Cross-Section Location Map

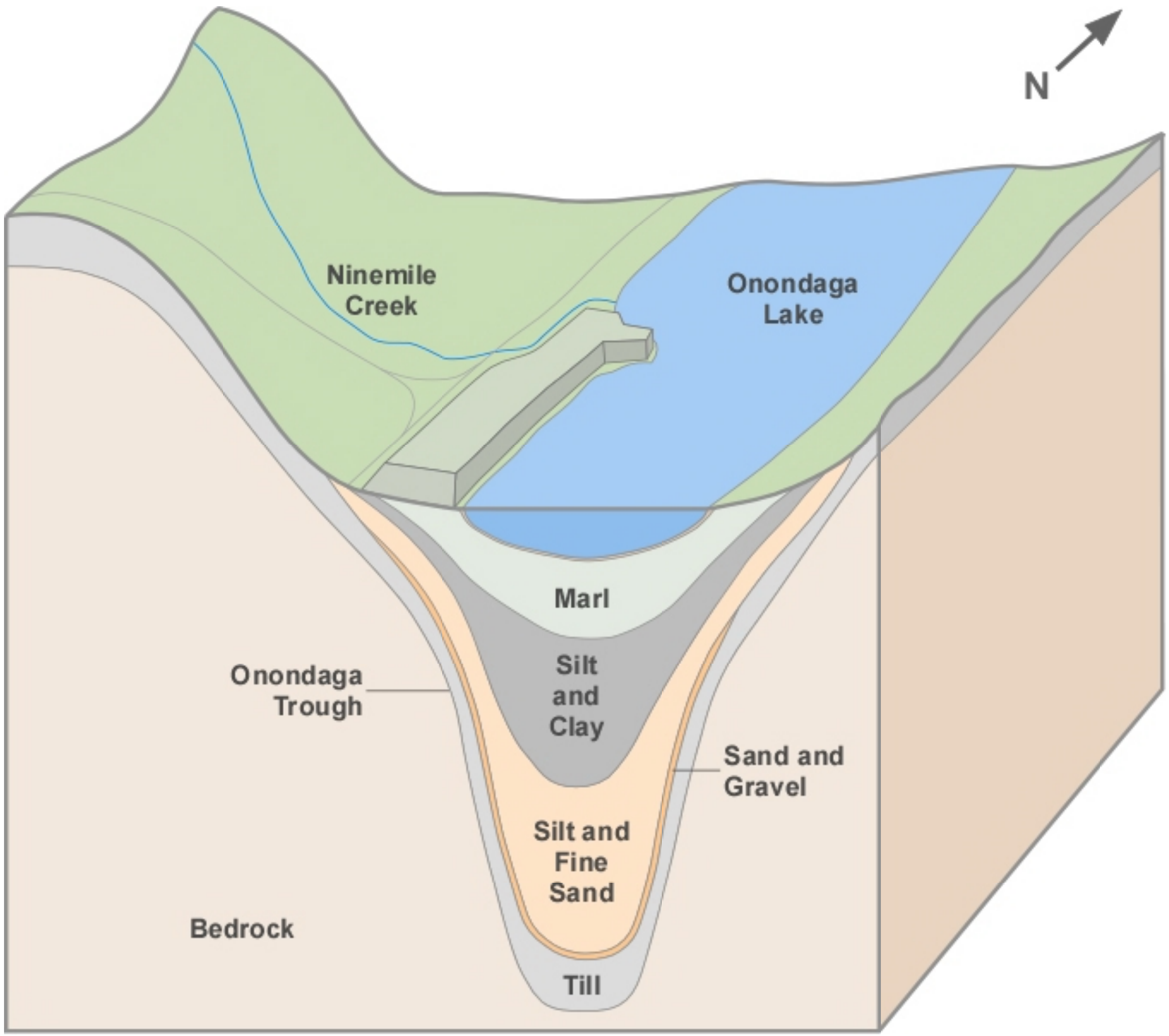


Figure 2 Hydrogeologic Setting of Onondaga Lake

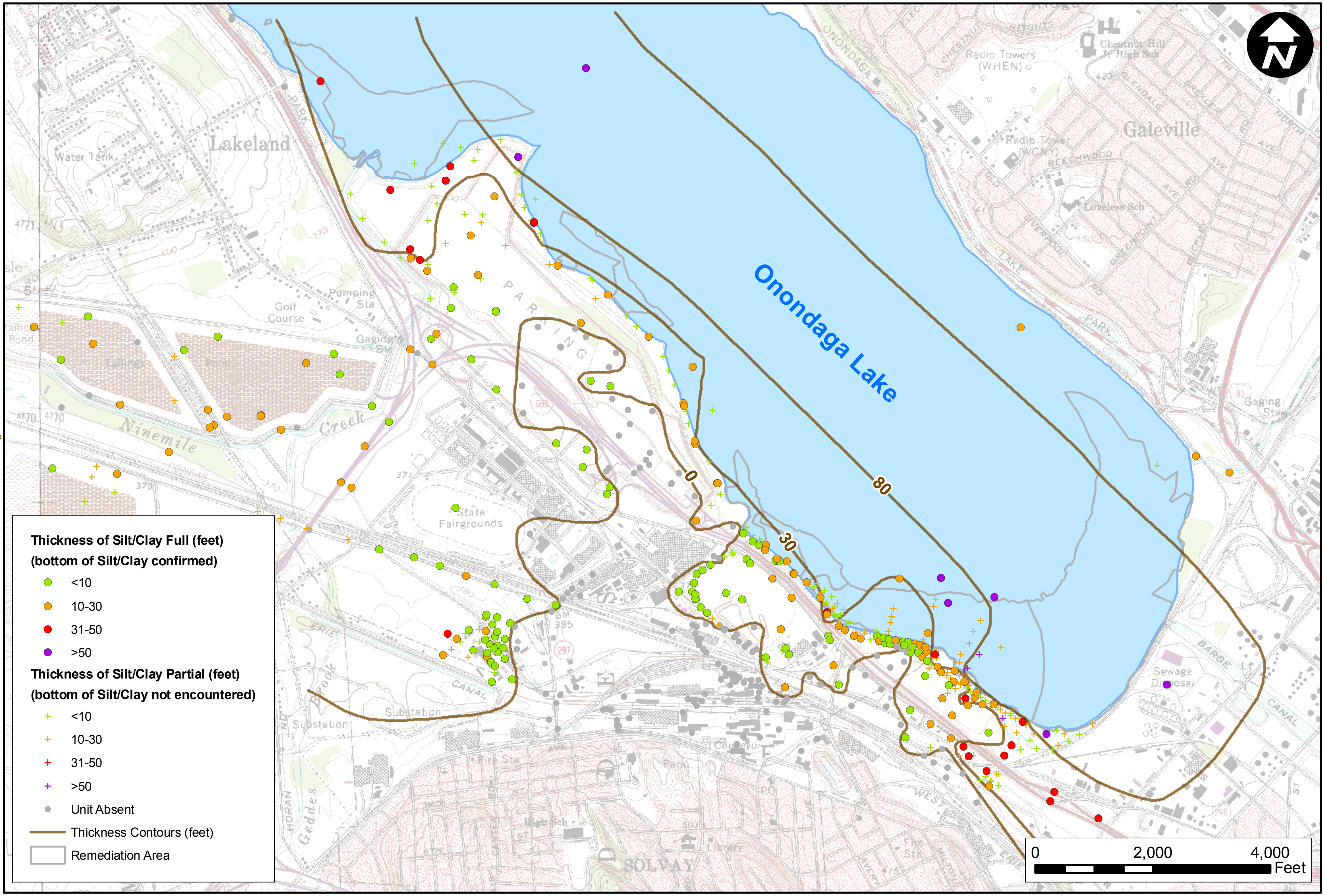


Figure 3 Thickness of Silt and Clay Unit

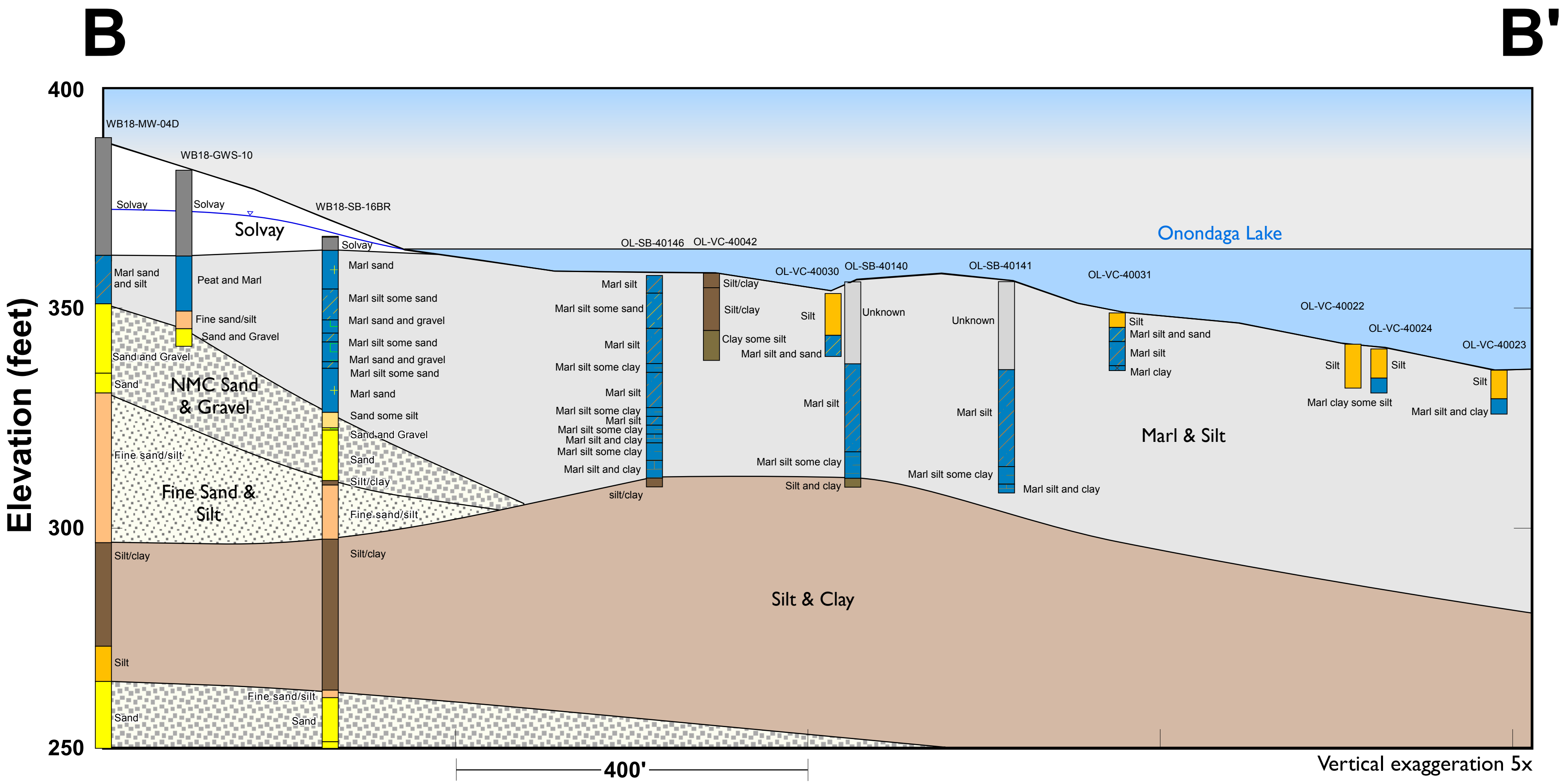


Figure 4 Remediation Area A - Hydrogeologic Cross Section B-B’

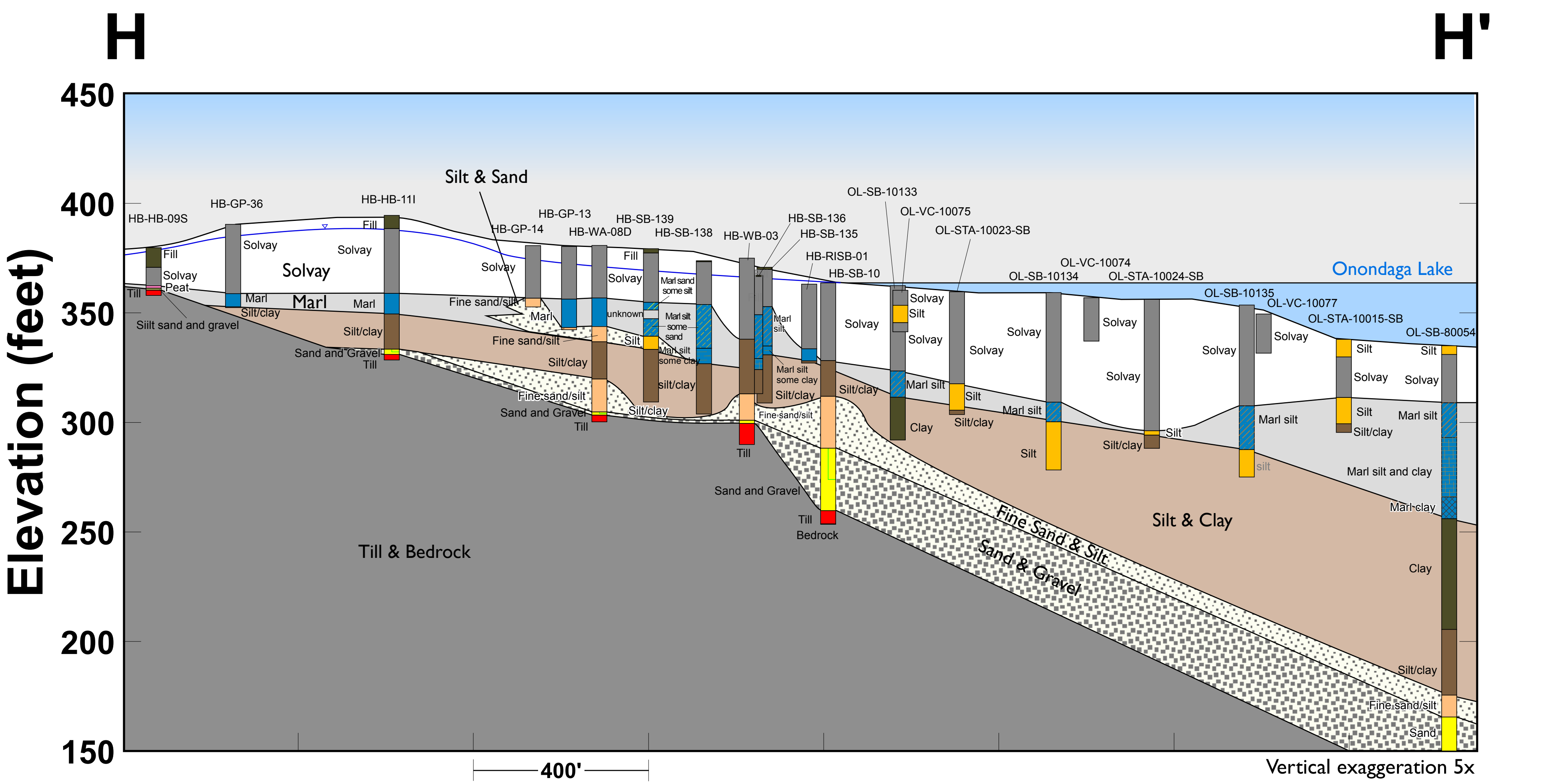
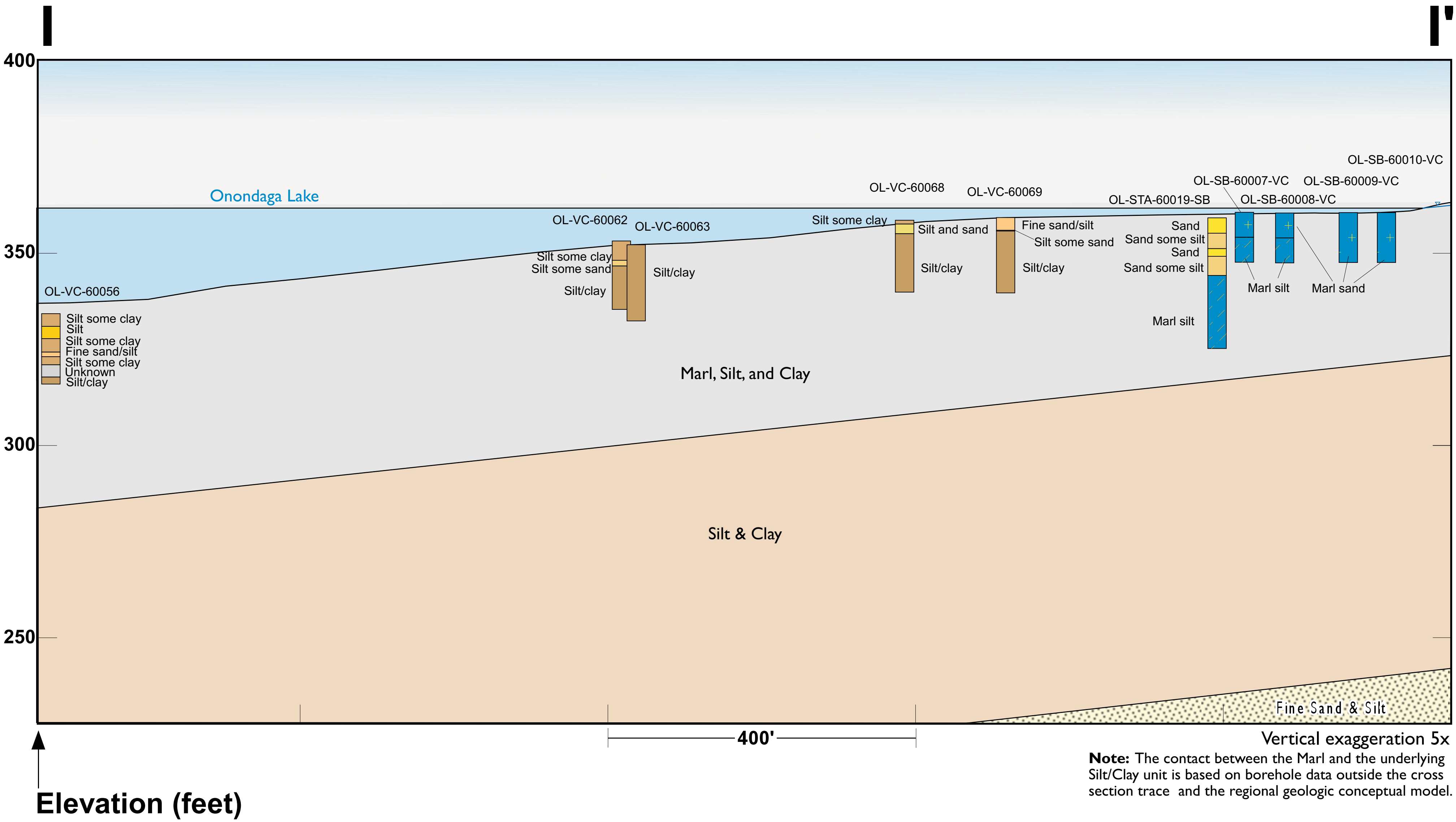


Figure 5 Remediation Area D - Hydrogeologic Cross Section H-H’



Note: The contact between the Marl and the underlying Silt/Clay unit is based on borehole data outside the cross section trace and the regional geologic conceptual model.

Figure 6 Remediation Area E - Hydrogeologic Cross Section I-I'

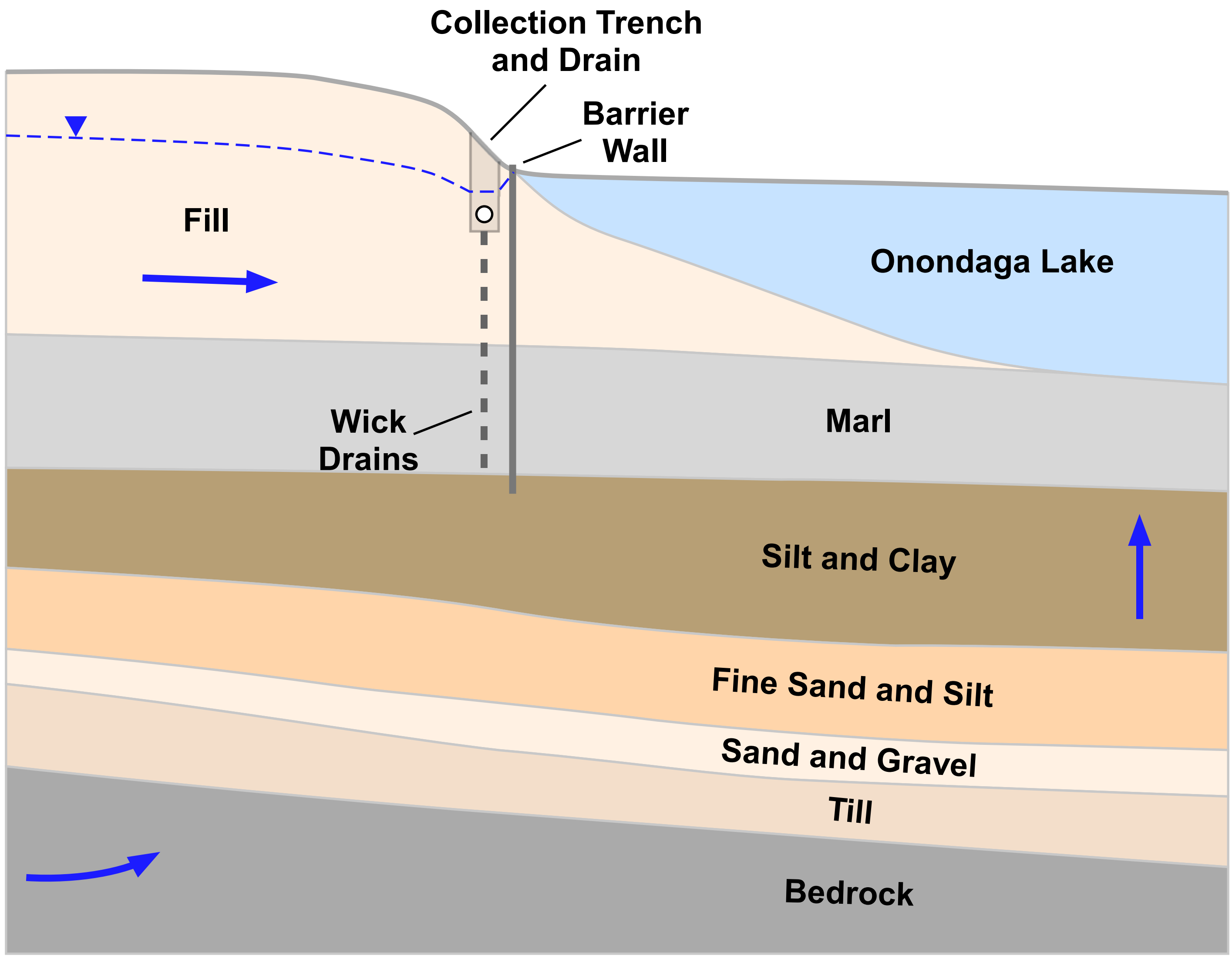


Figure 7 Schematic Hydraulic Barrier System and Groundwater Flow through Silt and Clay Unit

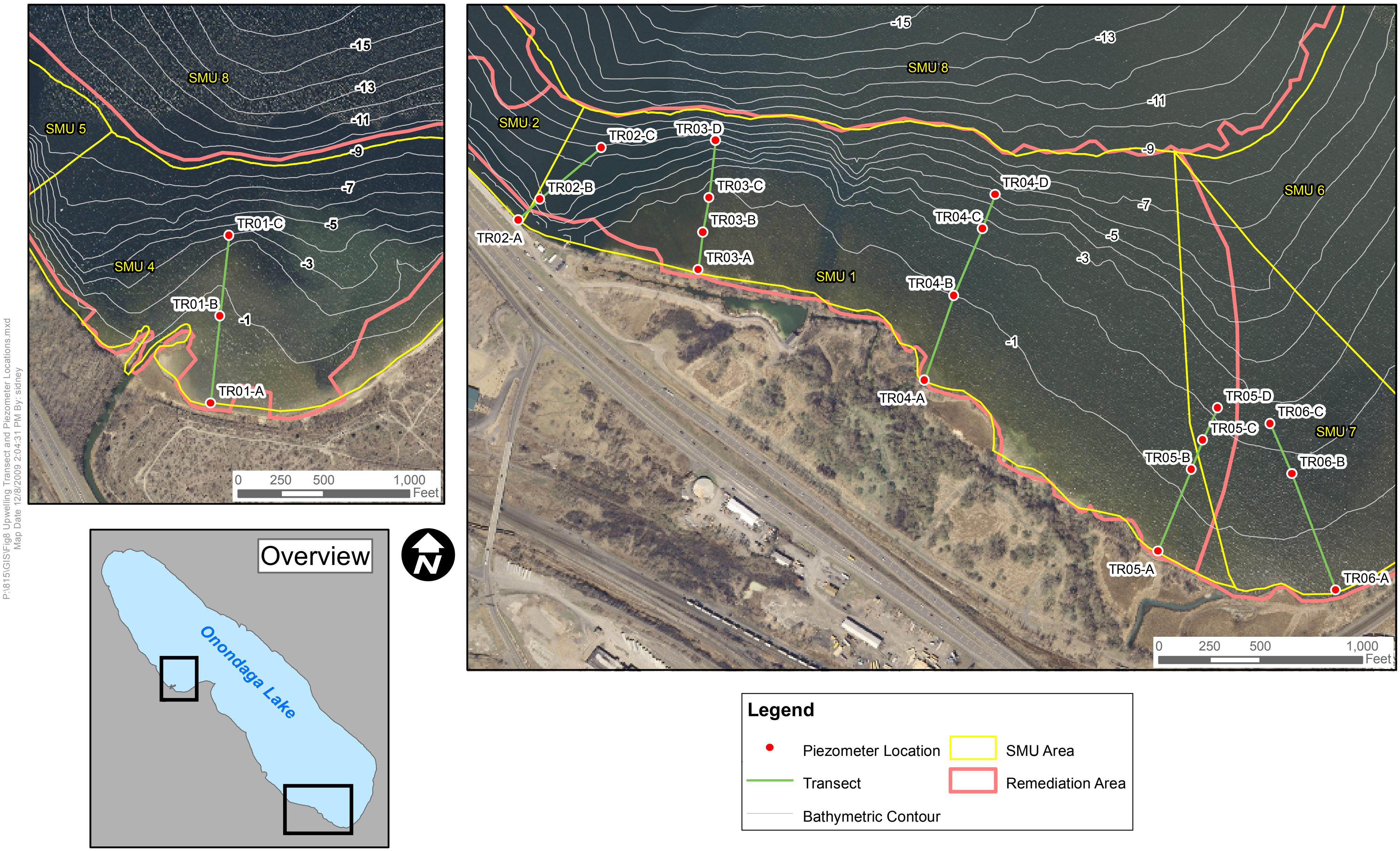


Figure 8 Upwelling Transect and Piezometer Locations

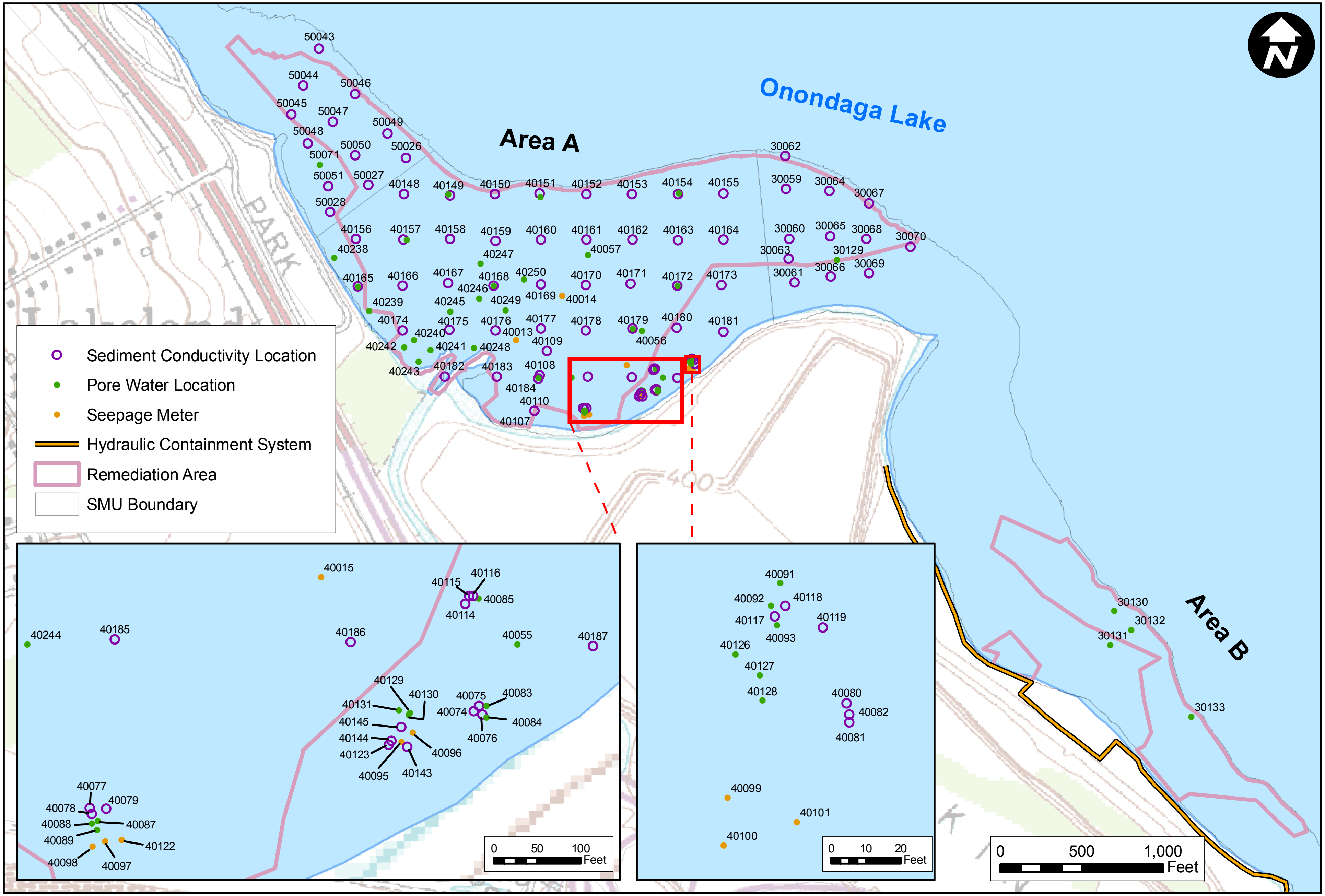


Figure 9 Location Map with Upwelling Measurement and Seepage Meter Locations - Remediation Areas A and B

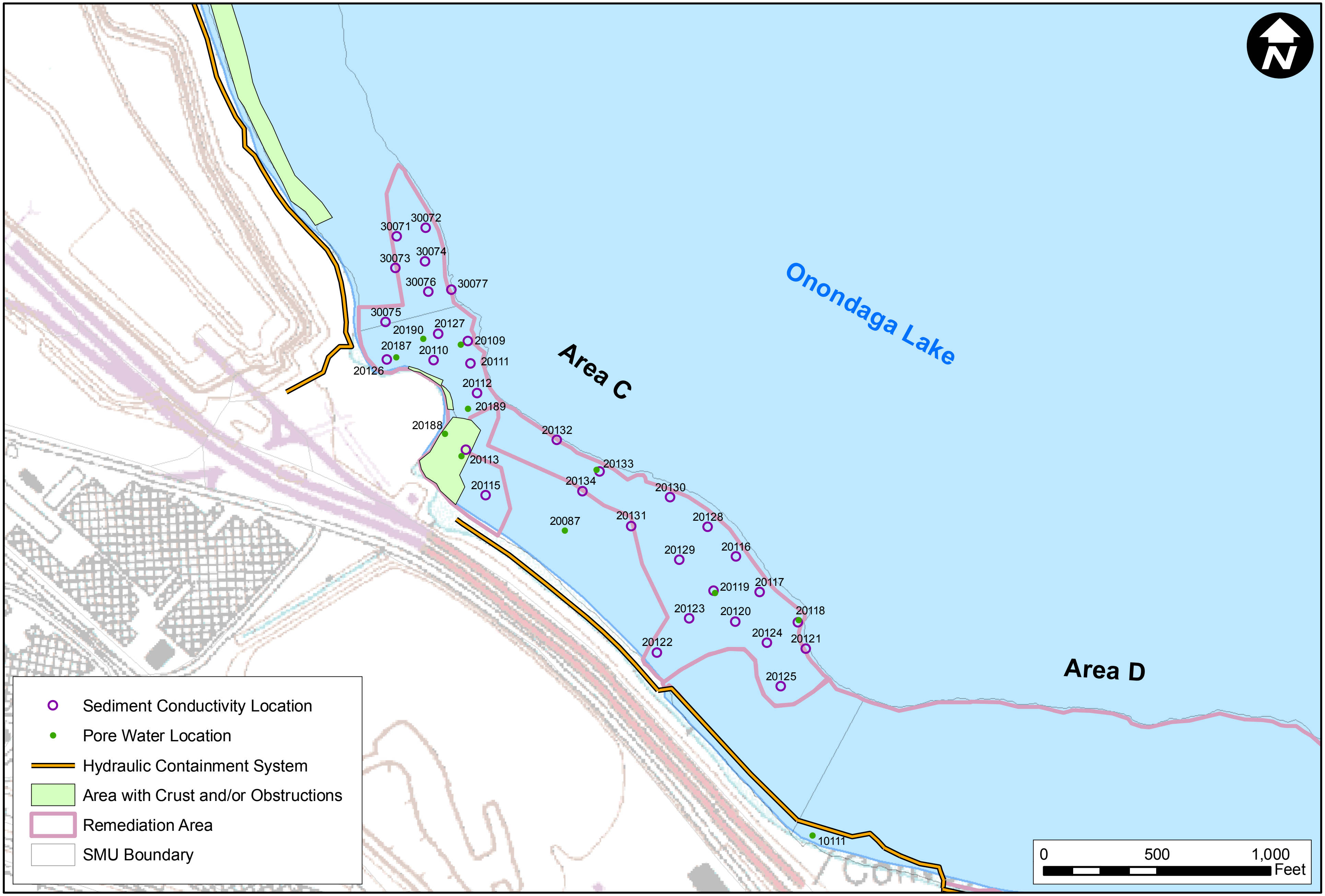


Figure 10 Location Map with Upwelling Measurement Locations - Remediation Area C

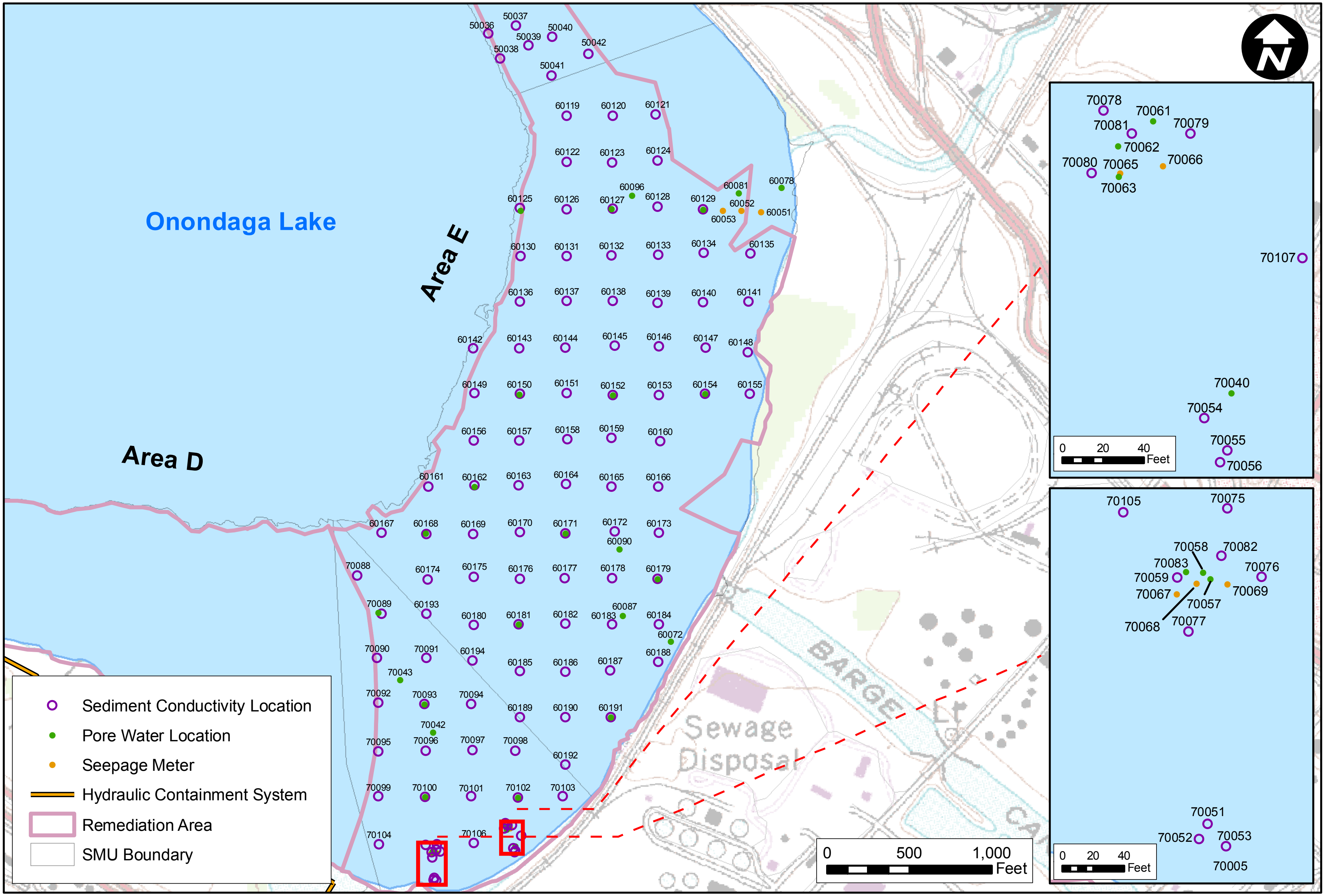


Figure 11 Location Map with Upwelling Measurement and Seepage Meter Locations - Remediation Area E

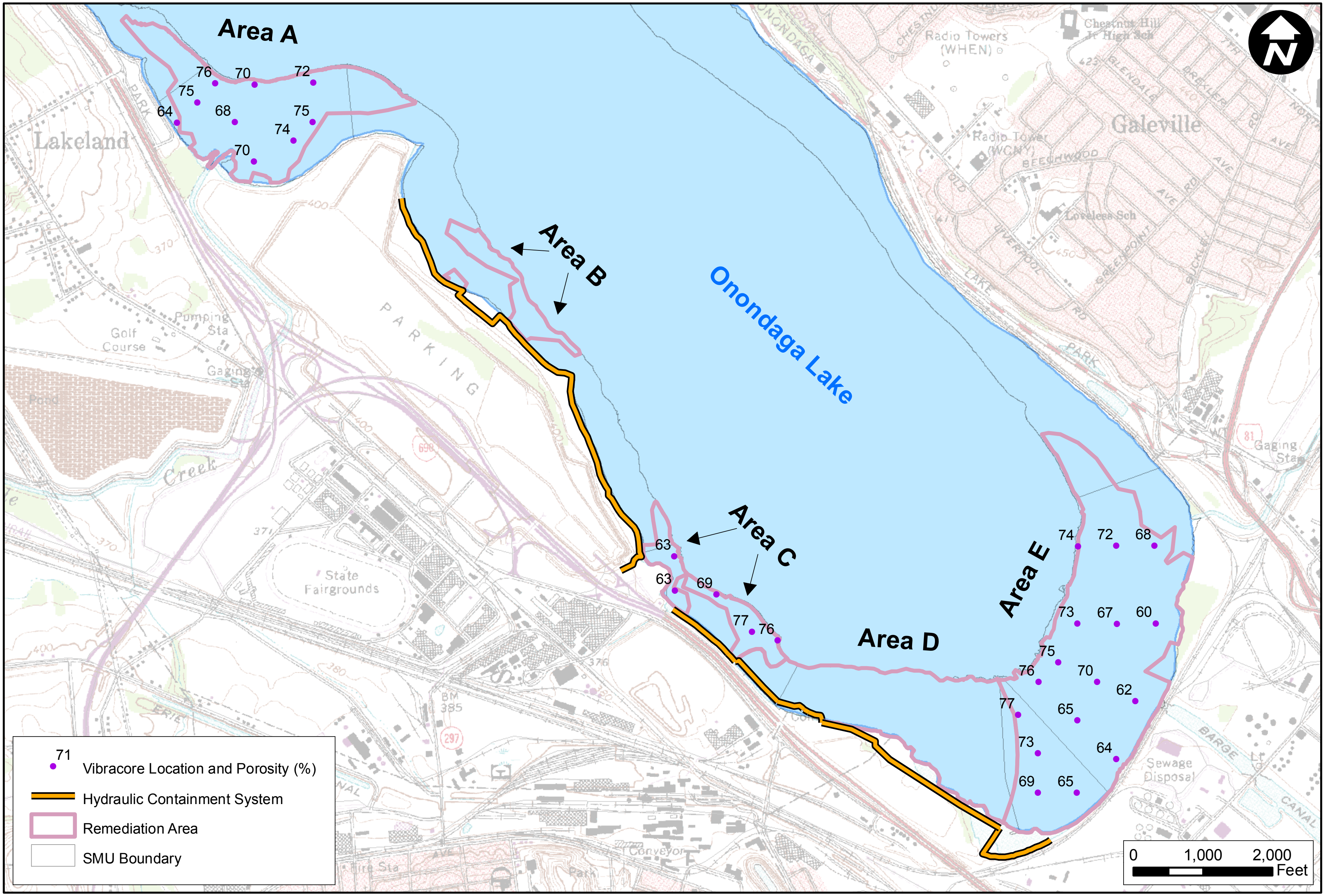


Figure 12 Average Porosity at Vibracore Locations

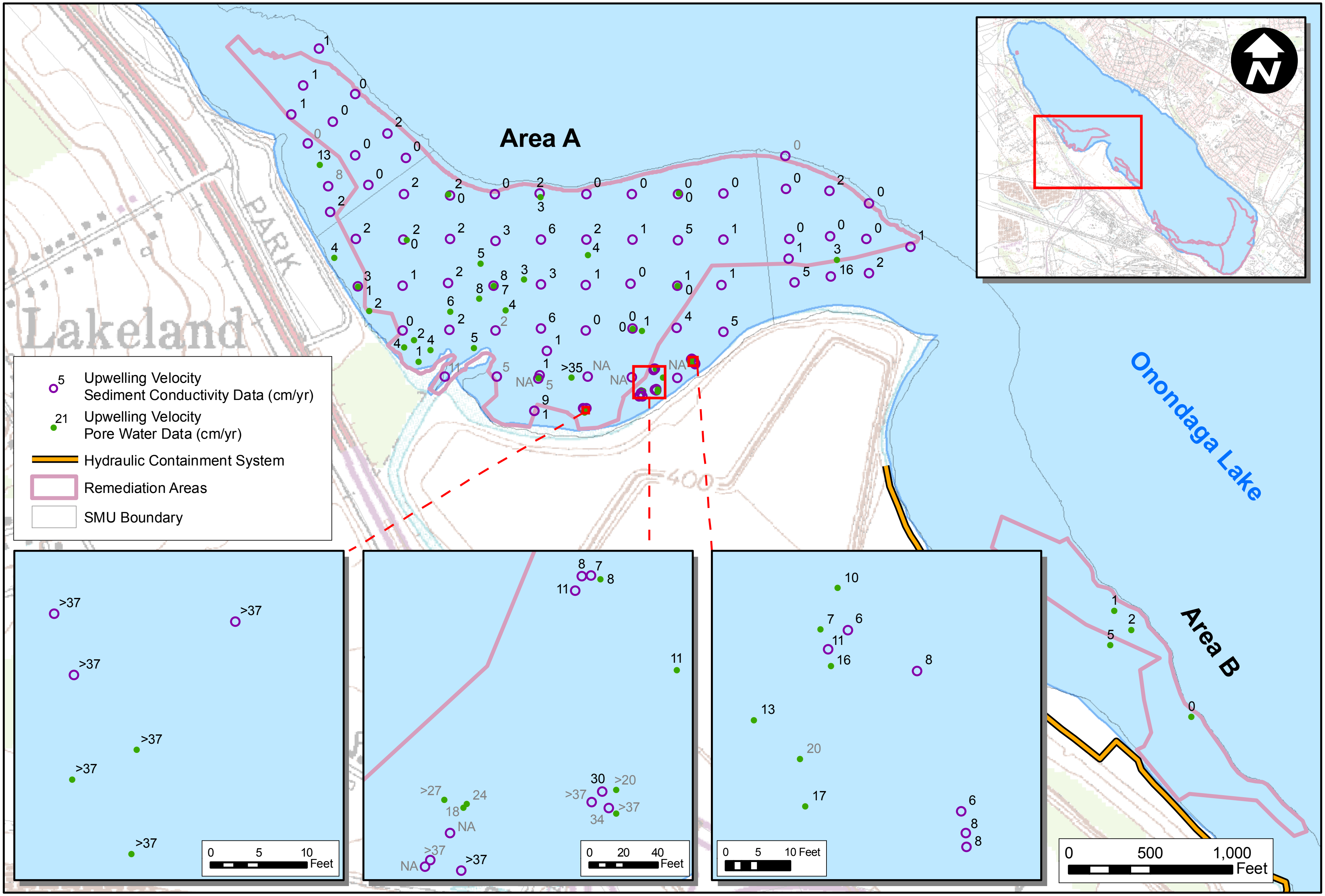


Figure 13a Upwelling Velocity in Remediation Areas A and B

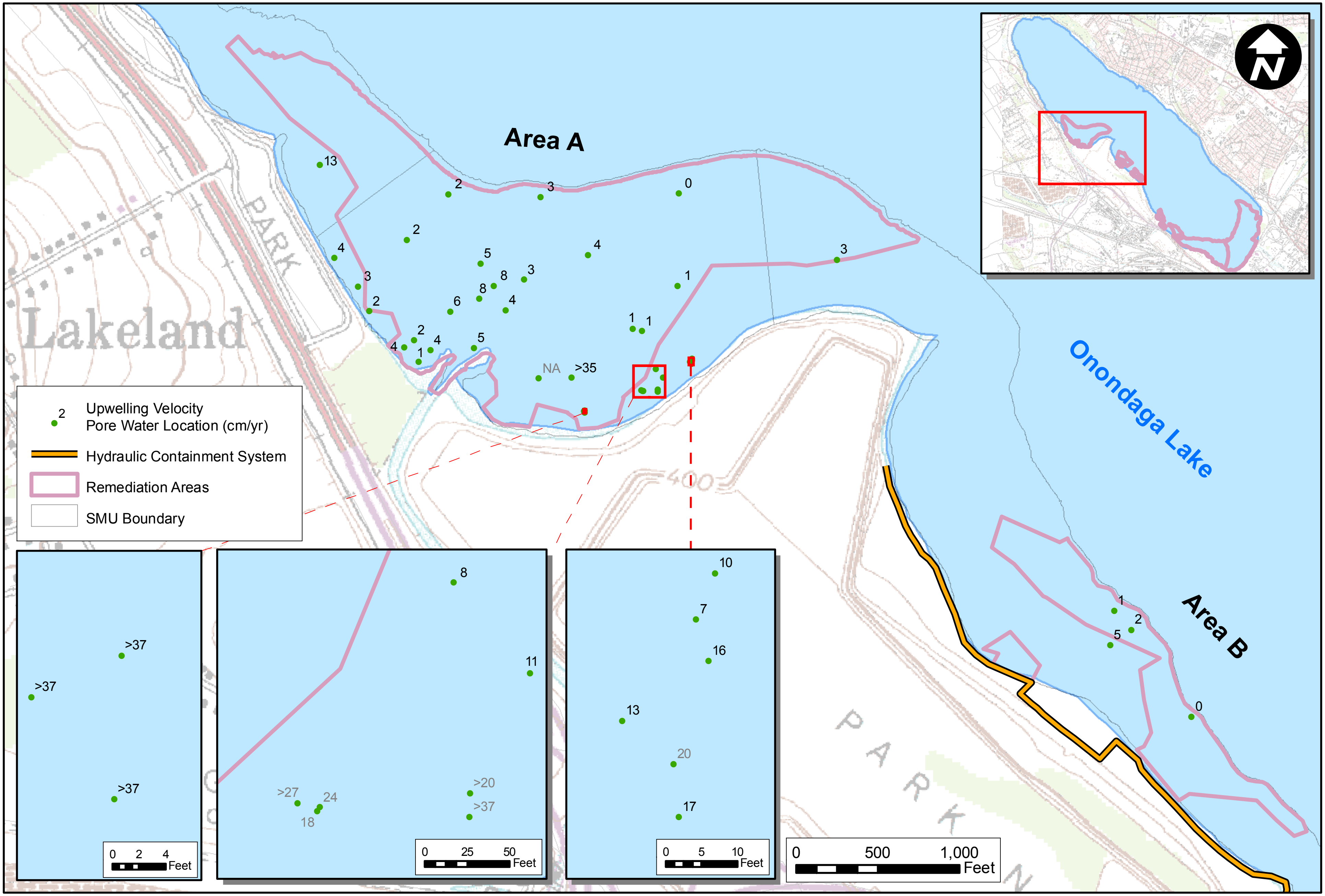


Figure 13b Upwelling Velocity in Remediation Areas A and B - Pore Water Data

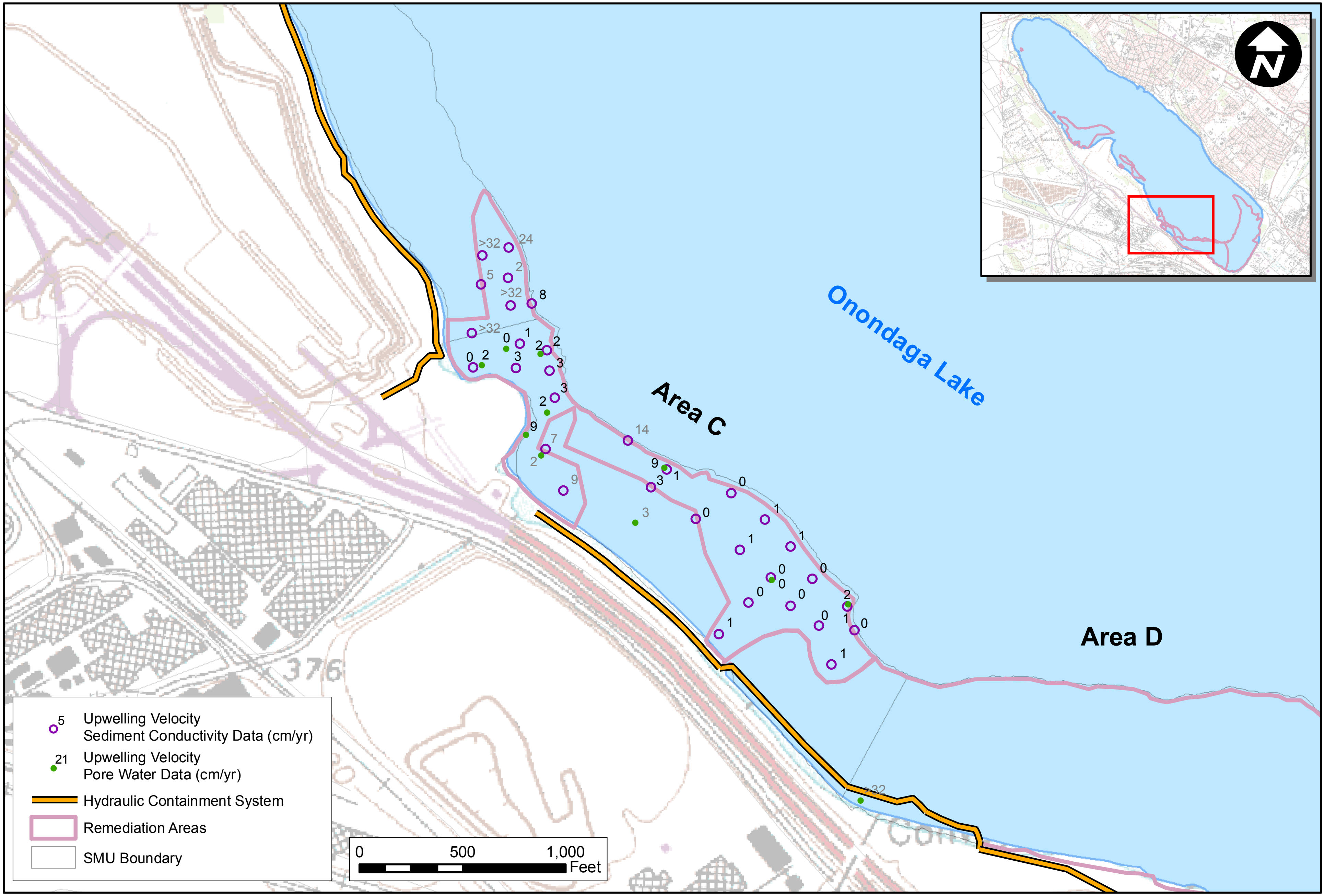


Figure 14a Upwelling Velocity in Remediation Area C

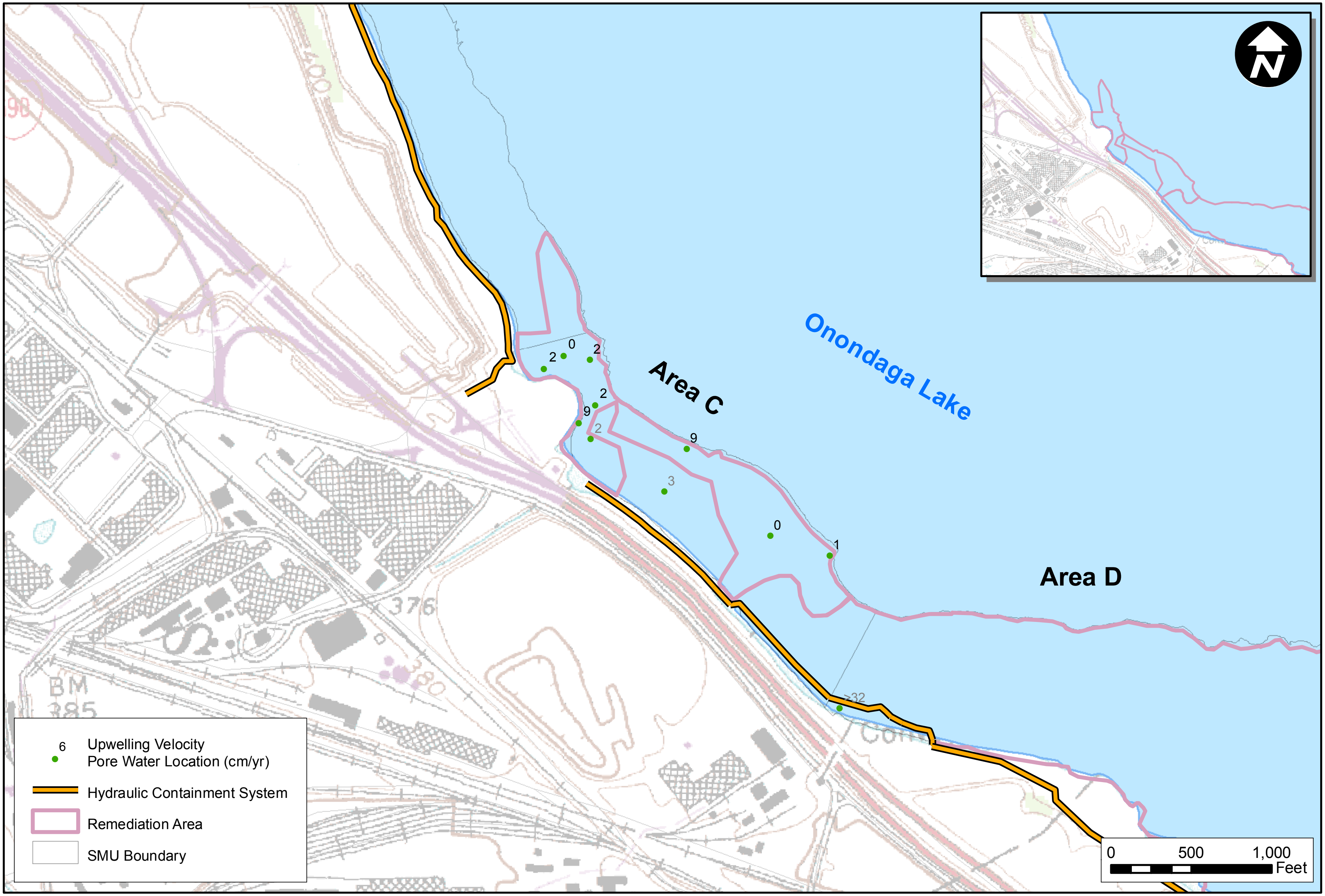


Figure 14b Upwelling Velocity in Remediation Area C - Pore Water Data

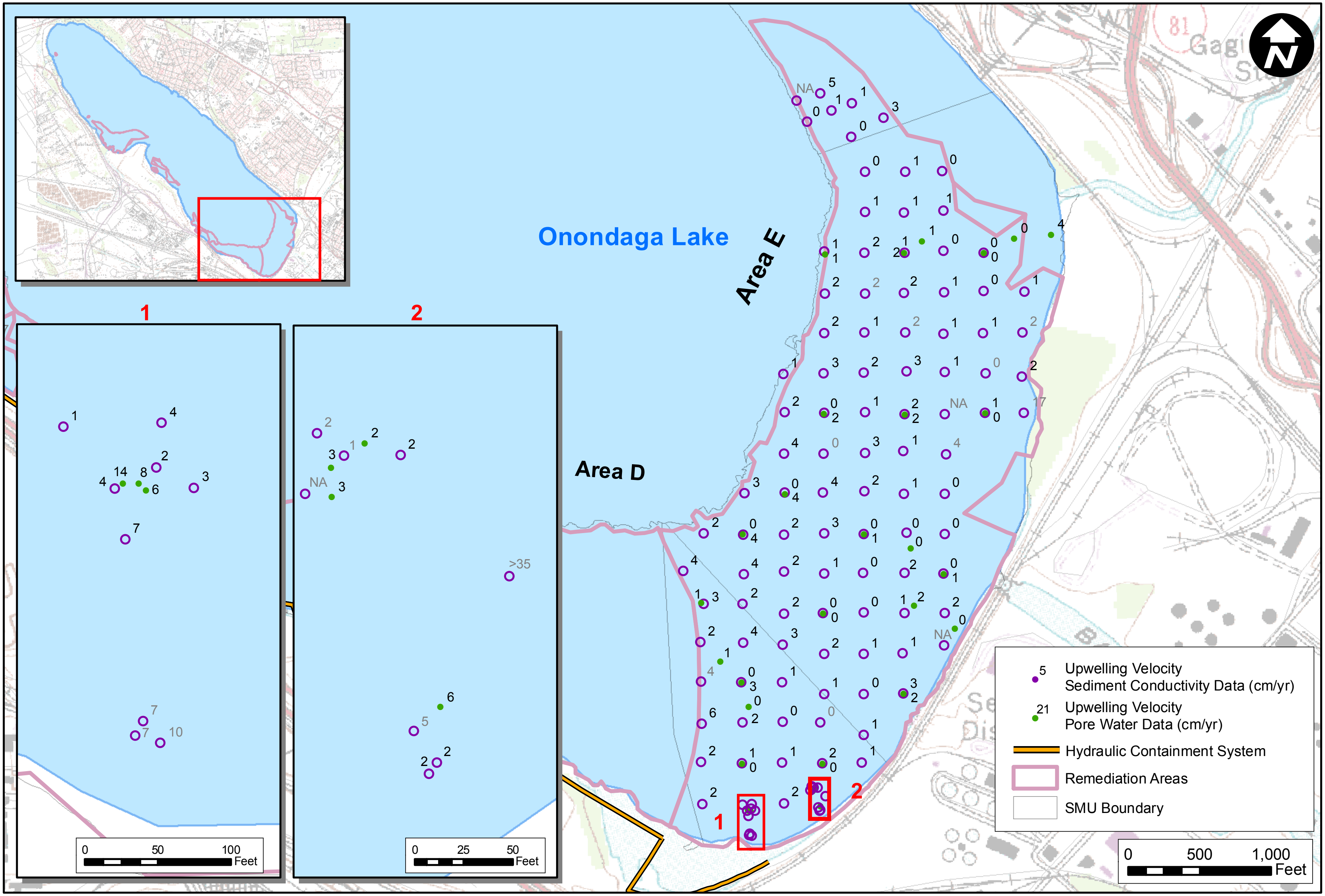


Figure 15a Upwelling Velocity in Remediation Area E

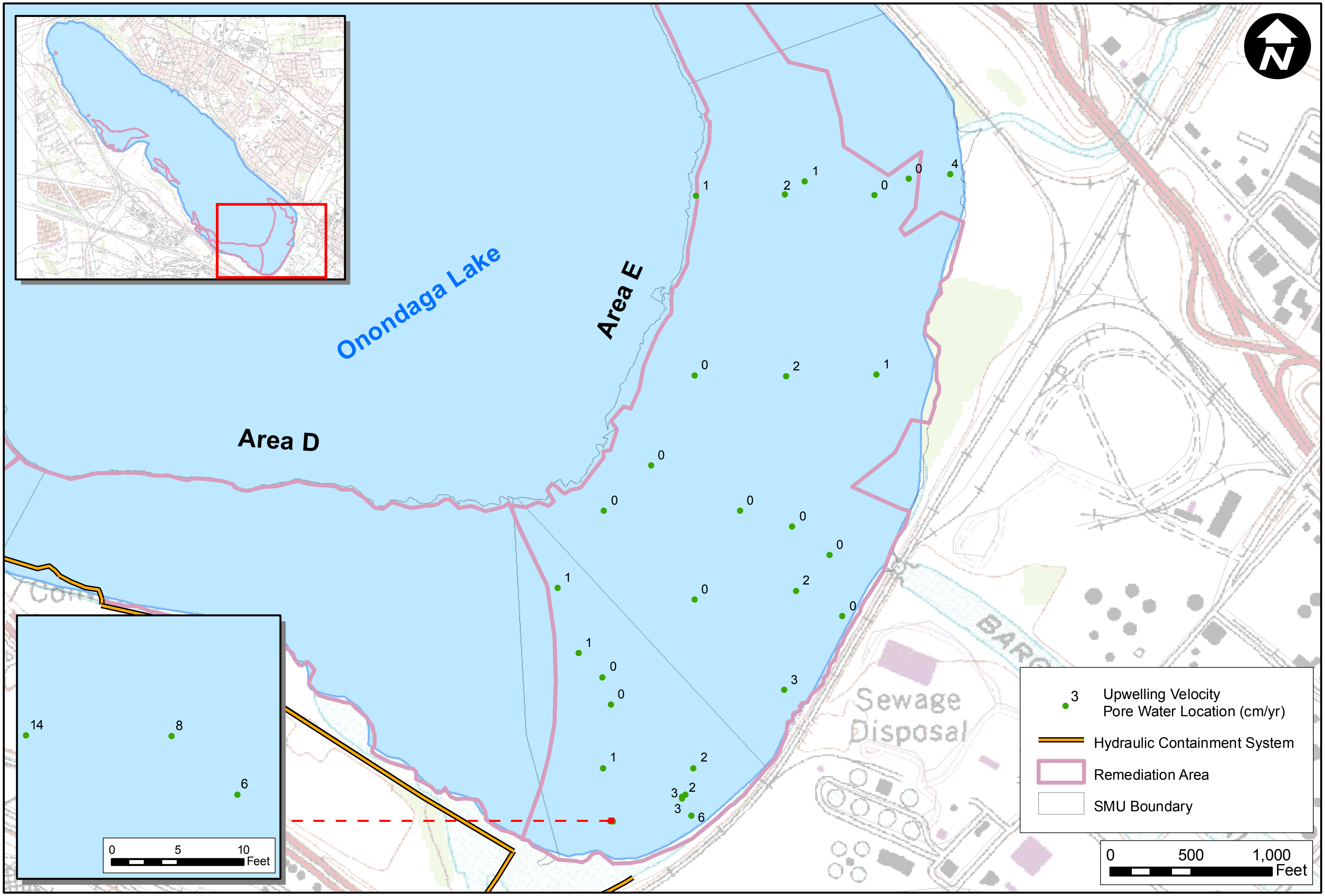


Figure 15b Upwelling Velocity in Remediation Area E - Pore Water Data

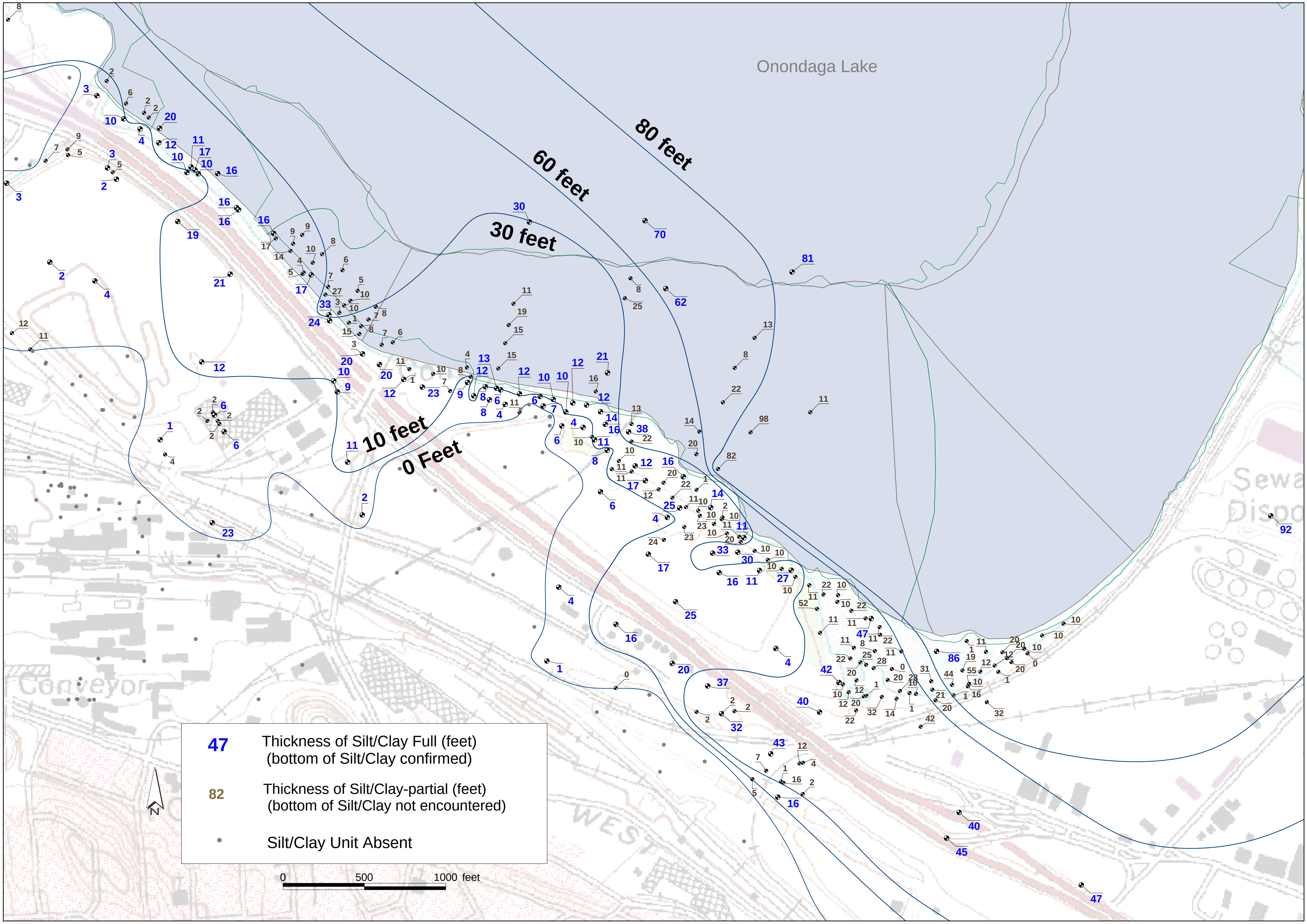


Figure 16 Thickness of Silt and Clay Unit in Remediation Area D

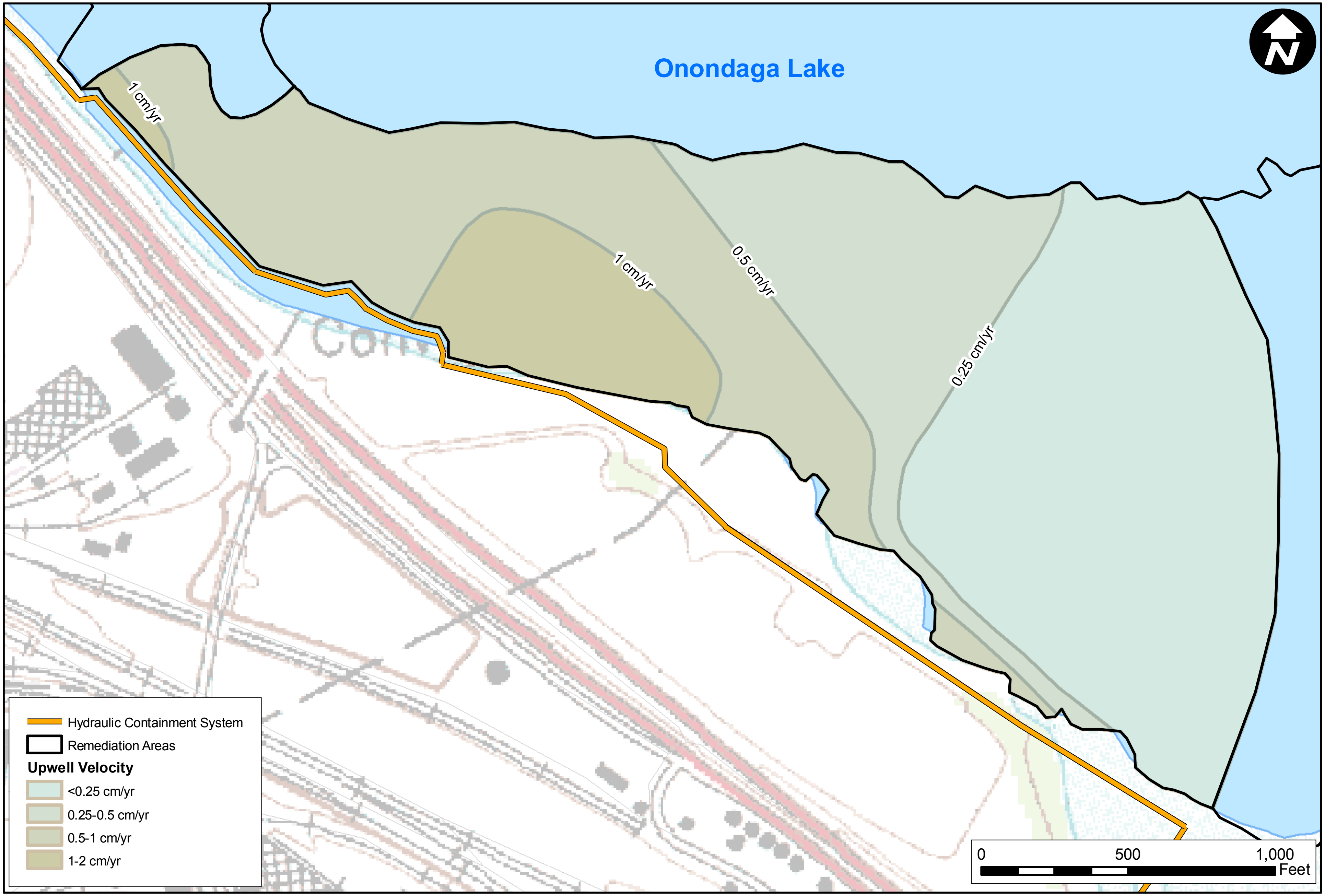


Figure 17 Upwelling Velocities in Remediation Area D

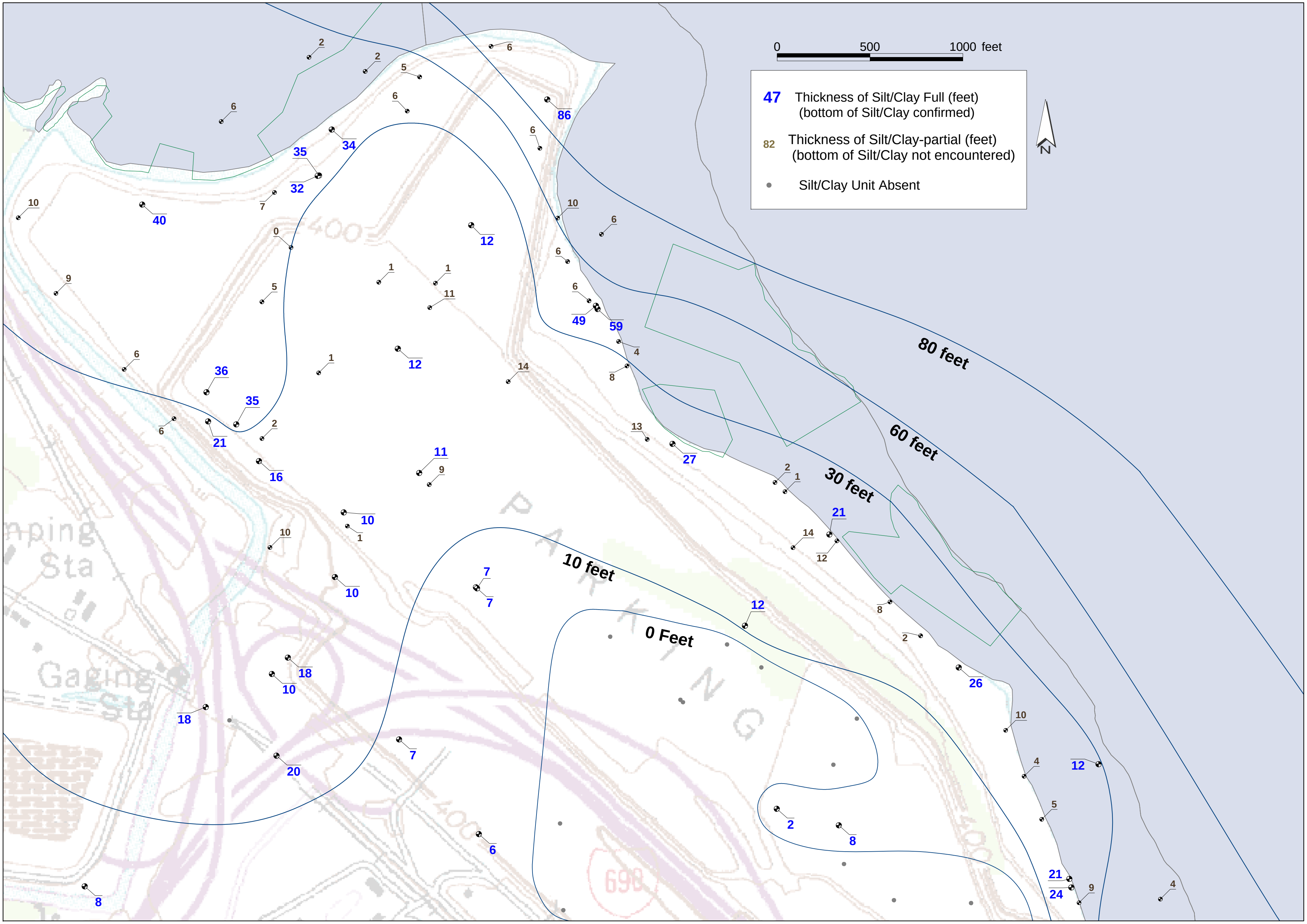


Figure 18 Thickness of Silt and Clay Unit in Remediation Area B

TABLES

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
10111		VC	> 32	52.82	poor
20087		VC	2.9	4.17	fair for 10-foot analysis
20109	C	GP	1.5	0.05	good
20110	C	GP	3.3	0.52	fair
20111	C	GP	~0	0.18	good
20111	C	GP	2.6	0.38	fair
20111	C	VC	1.6	0.54	fair
20112	C	GP	2.6	0.26	fair
20113	C	GP	1.0	0.07	fair
20113	C	GP	7.3	1.88	poor
20113	C	VC	2.4	0.56	good
20115	C	GP	1.0	0.02	good
20115	C	GP	8.5	2.70	poor
20116	C	GP	0.8	0.05	good
20116	C	GP	~0	0.03	good
20117	C	GP	0.1	0.01	good
20117	C	GP	~0	0.02	good
20118	C	GP	1.6	0.10	good
20118	C	GP	0.5	0.08	fair
20118	C	VC	0.7	0.20	good
20119	C	GP	~0	0.01	good
20119	C	VC	~0	0.32	good
20120	C	GP	0.4	0.01	good
20121	C	GP	~0	0.02	good
20121	C	GP	~0	0.01	good
20122	C	GP	1.1	0.05	good
20122	C	GP	0.9	0.01	good
20123	C	GP	~0	0.08	poor
20123	C	GP	0.2	0.02	good
20124	C	GP	0.1	0.01	good

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
20125	C	GP	0.8	0.04	good
20126	C	GP	~0	0.01	good
20127	C	GP	1.3	0.04	fair
20128	C	GP	0.1	0.03	good
20128	C	GP	0.5	0.03	good
20129	C	GP	0.7	0.09	good
20129	C	GP	0.3	0.01	good
20130	C	GP	0.1	0.02	good
20130	C	GP	~0	0.01	good
20131	C	GP	0.3	0.01	good
20132	C	GP	1.1	0.03	good
20132	C	GP	14.4	4.17	poor
20133	C	GP	1.0	0.09	fair
20133	C	VC	8.5	6.73	poor
20134	C	GP	3.3	0.35	good for 5-foot analysis
20187	C	VC	1.8	0.07	good
20188	C	VC	9.7	2.81	good
20189	C	VC	2.0	0.66	good
20190	C	VC	0.2	0.27	good
30059	A	GP	0.2	0.03	good
30060	A	GP	0.3	0.05	good
30061		GP	4.6	0.50	fair but poor fit to data
30061		GP	4.2	0.43	fair
30062		GP	0.1	0.05	poor
30063	A	GP	0.9	0.05	fair
30064	A	GP	1.5	0.11	fair
30065	A	GP	0.1	0.02	fair
30066		GP	16.1	1.59	fair for 5-foot analysis
30067	A	GP	~0	0.06	good
30068	A	GP	~0	0.04	fair

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
30069		GP	2.3	0.06	good
30070		GP	0.9	0.04	good
30071	C	GP	> 32	22.43	poor
30071	C	GP	0.9	0.09	poor
30072	C	GP	24.1	1.69	poor
30072	C	GP	1.2	0.25	poor
30073	C	GP	4.8	1.27	poor
30073	C	GP	5.0	1.02	poor
30074	C	GP	2.0	0.36	poor
30075	C	GP	NA	-	analysis not possible
30075	C	GP	18.9	14.04	poor
30075	C	GP	7.7	206.14	poor
30075	C	GP	13.0	4.15	poor
30075	C	GP	> 32	26.43	poor
30075	C	GP	NA	-	analysis not meaningful
30075	C	GP	NA	-	analysis not meaningful
30076	C	GP	1.3	0.25	poor
30076	C	GP	NA	-	analysis not meaningful as lots of scatter in data
30076	C	GP	> 32	14.99	poor
30076	C	GP	0.5	0.11	poor
30077	C	GP	7.5	2.28	fair for 5-foot analysis
30129	B	VC	2.7	0.65	good
30130	B	VC	0.8	0.32	good
30131		VC	4.7	0.63	good
30132	B	VC	3.2	0.62	good
30133	B	VC	0.1	0.07	good
40055		VC	10.8	1.43	good
40056	A	VC	1.4	0.18	good
40057	A	VC	3.9	5.59	fair for 5-foot analysis
40074		GP	> 37	11.29	fair

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
40074		GP	> 37	10.93	poor
40075		GP	29.6	3.09	fair for 5-foot analysis
40076		GP	33.5	6.11	poor
40076		GP	NA	-	poor
40077	A	GP	> 37	16.81	high upwelling velocity
40078	A	GP	> 37	16.57	high upwelling velocity
40079	A	GP	> 37	17.09	high upwelling velocity
40079	A	GP	> 37	13.41	high upwelling velocity
40080		GP	6.3	0.41	fair
40081		GP	7.5	0.41	good
40082		GP	8.0	0.36	good
40083		VC	> 20	8.89	poor, minimum velocity estimate
40084		VC	> 37	22.73	poor
40085		VC	8.1	1.11	good
40087	A	VC	> 37	13.70	fair
40088	A	VC	> 37	10.69	fair
40089	A	VC	> 37	11.98	fair
40091		VC	10.3	2.11	good
40092		VC	6.9	1.49	good
40093		VC	16.0	5.26	good
40107	A	GP	1.4	0.01	good
40108	A	GP	1.4	0.02	good
40109	A	GP	0.6	0.01	fair
40110	A	GP	NA	-	poor
40110	A	GP	8.7	0.55	fair to good
40114		GP	10.6	0.51	good
40115		GP	8.3	0.44	good
40116		GP	6.8	0.39	good
40117		GP	11.1	0.66	fair
40118		GP	5.7	0.43	good

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
40119		GP	8.3	0.80	good
40123		GP	NA	-	no trend in data
40126		VC	12.8	2.78	good
40127		VC	19.6	5.94	poor
40128		VC	17.0	1.65	good
40129		VC	23.6	8.07	fair to poor
40130		VC	17.9	6.14	poor
40131		VC	> 27	12.80	poor, minimum velocity estimate
40143		GP	> 37	7.76	fair
40144		GP	> 37	21.18	poor
40145		GP	NA	-	off scale at 0.4 feet
40148	A	GP	1.5	0.15	fair
40149	A	GP	~0	0.03	good
40149	A	VC	1.5	1.50	fair
40150	A	GP	0.3	0.03	good
40151	A	GP	2.0	0.07	good
40151	A	VC	3.4	0.70	fair
40152	A	GP	~0	0.02	good
40153	A	GP	~0	0.02	good
40154	A	GP	0.2	0.02	good
40154	A	VC	~0	0.16	good
40155	A	GP	0.3	0.01	good
40156	A	GP	1.8	0.10	good
40157	A	GP	~0	0.03	good
40157	A	VC	1.7	0.34	good
40158	A	GP	2.2	0.12	good
40159	A	GP	3.0	0.23	fair
40160	A	GP	6.0	0.57	good
40161	A	GP	1.7	0.07	good
40162	A	GP	1.0	0.06	good

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
40163	A	GP	5.4	0.23	fair
40163	A	GP	5.4	0.25	fair
40164	A	GP	0.9	0.03	good
40165		GP	0.5	0.03	fair
40165		VC	2.6	0.30	good
40166	A	GP	1.3	0.04	good
40167	A	GP	2.3	0.06	fair
40168	A	GP	7.1	0.25	good
40168	A	VC	7.5	1.38	good
40169	A	GP	2.6	0.08	good
40170	A	GP	1.0	0.02	fair
40171	A	GP	0.2	0.02	good
40172	A	GP	~0	0.05	good
40172	A	VC	1.3	0.45	good
40173		GP	0.8	0.03	good
40174	A	GP	0.2	0.02	good
40175	A	GP	2.3	0.11	good
40176	A	GP	2.3	0.57	poor
40177	A	GP	5.5	0.29	good
40178	A	GP	~0	0.11	good
40179	A	GP	~0	0.02	good
40179	A	VC	1.3	0.37	good
40180		GP	3.6	0.10	good
40181		GP	5.3	0.55	good
40182	A	GP	11.3	2.67	poor
40183	A	GP	5.3	0.75	poor
40183	A	GP	2.3	0.22	poor
40184	A	GP	4.5	0.33	poor
40184	A	GP	0.4	0.06	fair
40184	A	VC	NA	-	not analyzable due to data scatter

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
40185	A	GP	NA	-	off scale at 0.4 feet
40185	A	GP	NA	-	off scale at 0.95 feet
40186	A	GP	NA	-	off scale at 1 foot
40186	A	GP	3.0	0.30	fair
40187		GP	NA	-	insufficient data to analyze
40238		VC	3.2	0.29	good
40239	A	VC	1.6	0.11	good
40240	A	VC	1.3	0.39	good
40241	A	VC	5.0	0.42	good
40242	A	VC	3.6	0.70	good
40243	A	VC	0.6	0.14	good
40244	A	VC	> 35	17.19	good
40245	A	VC	6.1	0.38	good
40246	A	VC	7.8	1.31	good
40247	A	VC	4.7	0.49	good
40248	A	VC	5.0	0.00	good
40249	A	VC	4.6	1.08	good
40250	A	VC	2.7	0.90	good
50026	A	GP	0.3	0.02	good
50027	A	GP	0.4	0.04	good
50028		GP	1.5	0.05	good
50036	E	GP	NA	-	insufficient data to analyze
50037	E	GP	4.6	0.88	fair
50038	E	GP	0.4	0.02	good
50039	E	GP	0.6	0.02	good
50040	E	GP	0.5	0.02	good
50041	E	GP	0.4	0.01	good
50042	E	GP	2.5	0.09	fair
50043		GP	0.6	0.02	good
50044	A	GP	0.7	0.02	good

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
50045	A	GP	1.1	0.05	good
50046	A	GP	0.2	0.03	good
50047	A	GP	0.1	0.02	good
50048		GP	0.4	0.07	poor
50049	A	GP	1.7	0.12	good
50050	A	GP	0.4	0.02	good
50051		GP	8.3	0.76	fair to poor
50071		VC	16.8	4.65	good
60072	E	VC	~0	0.24	fair
60078		VC	4.4	0.89	good
60081	E	VC	~0	0.25	fair
60087	E	VC	2.0	0.15	good
60090	E	VC	0.3	0.08	good
60096	E	VC	0.7	0.13	good
60119	E	GP	~0	0.03	good
60120	E	GP	0.5	0.02	good
60121	E	GP	0.2	0.02	good
60122	E	GP	0.6	0.02	good
60123	E	GP	0.9	0.03	good
60124	E	GP	1.1	0.05	good
60125	E	GP	0.6	0.06	good
60125	E	GP	0.8	0.06	good
60125	E	GP	0.9	0.03	good to fair to 7 feet
60125	E	VC	0.8	0.34	good
60126	E	GP	1.6	0.05	good
60127	E	GP	1.0	0.05	fair
60127	E	VC	1.7	0.47	fair, first data points offset
60128	E	GP	0.2	0.02	good
60129	E	GP	~0	0.01	fair
60129	E	VC	0.3	0.30	fair

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
60130	E	GP	1.5	0.10	good
60130	E	GP	0.3	0.03	good
60130	E	GP	0.5	0.05	good
60131	E	GP	1.9	0.08	fair to poor
60132	E	GP	2.4	0.15	good
60133	E	GP	1.0	0.06	good
60134	E	GP	0.4	0.04	good
60135	E	GP	0.8	0.02	fair
60136	E	GP	1.8	0.10	fair to good
60136	E	GP	2.1	0.27	poor
60136	E	GP	2.0	0.07	good
60136	E	GP	1.1	0.10	good
60137	E	GP	1.4	0.08	good
60138	E	GP	2.1	0.10	poor
60139	E	GP	0.9	0.10	fair
60140	E	GP	0.7	0.04	fair
60141	E	GP	1.8	0.27	fair to poor
60142		GP	1.3	0.05	good
60142		GP	0.7	0.08	good
60142		GP	1.4	0.05	good
60143	E	GP	2.5	0.12	good
60143	E	GP	0.4	0.08	poor
60143	E	GP	2.5	0.08	good
60144	E	GP	1.8	0.09	good
60145	E	GP	2.6	0.18	good
60146	E	GP	0.5	0.02	good
60147	E	GP	~0	0.23	poor
60148	E	GP	2.2	0.22	fair
60149	E	GP	2.2	0.12	good
60149	E	GP	2.2	0.09	good

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
60149	E	GP	2.1	0.10	good
60150	E	GP	2.4	0.13	good to fair
60150	E	GP	1.9	0.07	good to fair
60150	E	GP	2.1	0.07	good
60150	E	VC	~0	0.10	good
60151	E	GP	0.8	0.08	fair to good
60152	E	GP	1.9	0.09	good
60152	E	VC	2.1	0.47	good
60153	E	GP	NA	-	insufficient data to analyze
60154	E	GP	0.4	0.04	fair
60154	E	VC	1.1	0.10	good
60155	E	GP	16.8	3.55	fair to poor
60156	E	GP	3.4	0.09	good
60156	E	GP	4.0	0.20	good
60157	E	GP	~0	0.11	poor
60158	E	GP	2.5	0.15	good
60159	E	GP	0.6	0.05	good to fair
60160	E	GP	3.6	0.96	poor
60161	E	GP	2.5	0.09	good to fair
60161	E	GP	1.9	0.05	good
60161	E	GP	3.1	0.13	good
60162	E	GP	2.1	0.07	good
60162	E	GP	3.8	0.13	good to fair
60162	E	GP	2.6	0.16	good
60162	E	VC	~0	0.23	fair
60163	E	GP	4.3	0.22	good
60163	E	GP	3.3	0.20	good
60164	E	GP	1.8	0.21	fair
60165	E	GP	0.5	0.02	good
60166	E	GP	0.2	0.04	good

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
60167	E	GP	1.9	0.05	good
60167	E	GP	2.1	0.06	good
60167	E	GP	1.9	0.10	good
60168	E	GP	3.2	0.12	good
60168	E	GP	3.5	0.12	good
60168	E	GP	3.5	0.18	good to 5 feet
60168	E	VC	~0	0.23	good
60169	E	GP	2.3	0.13	fair
60170	E	GP	2.2	0.07	good
60170	E	GP	1.8	0.06	good to 5 feet
60170	E	GP	2.8	0.09	good
60171	E	GP	0.8	0.04	good
60171	E	VC	~0	0.18	good
60172	E	GP	0.2	0.02	good
60173	E	GP	0.2	0.04	good to five feet
60174	E	GP	3.7	0.15	good
60175	E	GP	1.8	0.11	good
60176	E	GP	1.4	0.06	good
60177	E	GP	0.2	0.04	good
60178	E	GP	2.0	0.06	good
60179	E	GP	0.6	0.24	good
60179	E	VC	0.2	0.60	fair
60180	E	GP	2.0	0.06	good
60181	E	GP	0.2	0.03	good
60181	E	VC	~0	0.04	good
60182	E	GP	0.2	0.05	good
60183	E	GP	1.1	0.06	good
60184	E	GP	1.6	0.07	good to five feet
60185	E	GP	1.5	0.21	fair
60186	E	GP	1.2	0.11	fair

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
60187	E	GP	1.4	0.07	fair
60188	E	GP	NA	-	profile not analyzable
60189	E	GP	0.5	0.04	fair
60190	E	GP	0.4	0.05	fair to 5 feet
60191	E	GP	2.1	0.16	fair
60191	E	VC	2.7	0.84	fair
60192	E	GP	1.1	0.04	good
60193	E	GP	2.2	0.08	good
60194	E	GP	3.1	0.30	fair
70040	E	VC	5.5	1.27	good
70042	E	VC	~0	0.14	good
70043	E	VC	0.6	0.49	good
70051	E	GP	7.0	2.25	poor
70051	E	GP	4.9	0.69	poor
70052	E	GP	7.0	1.70	poor
70053	E	GP	9.8	1.74	poor
70053	E	GP	6.3	1.69	poor
70053	E	GP	NA	-	data not analyzable
70054	E	GP	4.6	0.31	poor
70054	E	GP	0.8	0.16	poor
70055	E	GP	1.7	0.04	good
70056	E	GP	2.1	0.07	fair
70057	E	VC	5.5	1.36	good
70058	E	VC	8.2	0.98	good
70059	E	VC	13.8	4.07	fair
70061	E	VC	2.2	0.62	good
70062	E	VC	3.1	2.00	fair, data scattered
70063	E	VC	2.9	0.53	good
70075	E	GP	3.5	0.17	fair
70076	E	GP	3.2	0.18	fair

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
70077	E	GP	7.0	0.71	fair to 3 feet
70078	E	GP	1.6	0.04	poor
70079	E	GP	2.2	0.07	fair
70080	E	GP	NA	-	data not analyzable -- may be very high upwelling velocity
70081	E	GP	0.7	0.06	poor
70082	E	GP	1.7	0.05	good
70083	E	GP	3.5	0.28	fair
70088	E	GP	2.8	0.08	good to 6 feet
70088	E	GP	3.5	0.22	good to 6 feet
70088	E	GP	1.9	0.06	good to 6.5 feet
70089	E	GP	2.5	0.12	good
70089	E	VC	0.9	0.17	good
70090	E	GP	1.9	0.08	good
70091	E	GP	3.5	0.29	fair to 6.5 feet
70092	E	GP	4.2	0.58	poor
70093	E	GP	3.2	0.14	good
70093	E	VC	~0	0.27	good
70094	E	GP	0.7	0.02	good for 5-foot analysis
70095	E	GP	5.9	0.54	good to 4 feet
70096	E	GP	1.5	0.06	good
70097	E	GP	0.2	0.04	good
70098	E	GP	0.2	0.23	poor
70099	E	GP	2.1	0.14	good to fair
70100	E	GP	0.4	0.01	good
70100	E	VC	1.2	0.45	good
70101	E	GP	0.5	0.02	good
70102	E	GP	0.4	0.05	good to 7 feet
70102	E	VC	2.4	0.63	good
70103	E	GP	1.0	0.10	fair to 6 feet
70104	E	GP	2.0	0.04	good

Table 1

Summary of Upwelling Velocities

Location ID	Remediation Area	Type	Upwelling Velocity (cm/year)	90% Conficence Interval (+/-) (cm/year)	Comment
70105	E	GP	1.0	0.09	good to 4 feet
70106	E	GP	1.6	0.02	fair to 4.5 feet
70107	E	GP	~0	0.04	fair to poor
70107	E	GP	NA	-	data limited and not analyzable
70107	E	GP	> 35	5.57	fair

Note: "NA" indicates the chloride depth profile does not have a form suitable for analysis.

Table 2

Comparison of Upwelling Velocities at Locations with Pore Water and Sediment Conductivity Data

Location ID	Upwelling Velocity (cm/year)	
	Pore Water	Sediment Conductivity
20111	1.6	~ 0, 2.6
20113	2.4	1.0, 7.3
20118	0.7	0.5, 1.6
20119	~ 0	~ 0
20133	8.5	1.0
40149	1.5	~ 0
40151	3.4	2.0
40154	~ 0	0.2
40157	1.7	~ 0
40165	2.6	0.5
40168	7.5	7.1
40172	1.3	~ 0
40179	1.3	~ 0
40184	NA	4.5, 0.4
60125	0.8	0.6, 0.8, 0.9
60127	1.7	1.0
60129	0.3	~ 0
60150	~ 0	2.4, 1.9, 2.1
60152	2.1	1.9
60154	1.1	0.4
60162	~ 0	2.1, 3.8, 2.6
60168	~ 0	3.2, 3.5, 3.5
60171	~ 0	0.8
60179	0.2	0.6
60181	~ 0	0.2
60191	2.7	2.1
70089	0.9	2.5
70093	~ 0	3.2
70100	1.2	0.4
70102	2.4	0.4

Note: "NA" indicates the chloride-depth profile does not have a form suitable for analysis.

Table 3

Comparison of Upwelling Velocities at Locations with Multiple Sets of Sediment Conductivity Data

Location	Upwelling Velocity (cm/yr)	
	Largest	Other
20111	2.6	~ 0
20113	7.3	1.0
20115	8.5	1.0
20116	0.8	~ 0
20117	0.1	~ 0
20118	1.6	0.5
20121	~ 0	~ 0
20122	1.1	0.9
20123	0.2	~ 0
20128	0.5	0.1
20129	0.7	0.3
20130	0.1	~ 0
20132	14.4	1.1
30061	4.6	4.2
30071	>32	0.9
30072	24.1	1.2
30073	5.0	4.8
30075	>32	18.9, 7.7, 13.0, NA, NA, NA
30076	>32	1.3, 0.5, NA
40074	>37	>37
40076	33.5	NA
40079	>37	>37
40110	8.7	NA
40163	5.4	5.4
40183	5.3	2.3
40184	4.5	0.4
40185	NA	NA
40186	3.0	NA
60125	0.9	0.8, 0.6
60130	1.5	0.3, 0.5

Table 3

Comparison of Upwelling Velocities at Locations with Multiple Sets of Sediment Conductivity Data

Location	Upwelling Velocity (cm/yr)	
	Largest	Other
60136	2.1	2.0, 1.8, 1.1
60142	1.4	1.3, 0.7
60143	2.5	2.5, 0.4
60149	2.2	2.2, 2.1
60150	2.4	2.1, 1.9
60156	4.0	3.4
60161	3.1	2.5, 1.9
60162	3.8	2.6, 2.1
60163	4.3	3.3
60167	2.1	1.9, 1.9
60168	3.5	3.5, 3.2
60170	2.8	2.2, 1.8
70051	7.0	4.9
70053	9.8	6.3, NA
70054	4.6	0.8
70088	3.5	2.8, 1.9
70107	>35	~ 0 , NA

Note: "NA" indicates the chloride-depth profile does not have a form suitable for analysis.

Table 4

Calculated Vertical Groundwater Velocities across the Silt and Clay Unit at Selected Monitoring Well Locations

Well ID	Water Level Elevation (feet, NAVD 88)	Density (g/cm3)	Midscreen Elevation (feet, NAVD 88)	Freshwater Head (feet, NAVD 88)	Silt and Clay Thickness (feet)	Vertical Velocity (cm/year)
HB-HB-20D	363.7	1.11	233.5	378.0	86	0.22
HB-HB-20I	363.5	1.02	330.5	364.2		
HB-HB-05D	368.7	1.07	275	375.3	30	0.59
HB-HB-05I	365.1	1.07	328.9	367.6		
WA-WA-1D	370.3	1.04	268.5	374.4	24	1.02
WA-WA-1I	364.5	1.04	335.4	365.7		
WA-WA-3D	373.2	1.02	311.9	374.4	23	0.82
WA-WA-3I	367.2	1.03	345.5	367.9		
WB18-MW-03D	368.3	1.06	233.3	376.4	55	0.21
WB18-MW-03I	365.3	1.08	321.3	368.8		
WB18-MW-02D	369.1	1.06	273.3	374.8	21	1.15
WB18-MW-02I	364.0	1.07	338.3	365.8		

Notes: Water level data, density data and silt and clay thickness from (O'Brien & Gere 2008 and 2009). Water level data represent best estimate of average water levels. Upwelling velocity calculated using Equation (4).