BASF Corporation

Groundwater to Surface Water Interface (GSI) Assessment Work Plan

Point Hennepin, Wyandotte, Michigan

August 31, 2021

GSI Assessment Work Plan

Point Hennepin

August 31, 2021

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Acronyms and Abbreviations

DBO	distiller blow off
DGPS	differential global positioning system
EC	electrical conductivity
ECT	Electrical Conductivity Tool
EGLE	Michigan Department of Environment, Great Lakes, and Energy
EM	electromagnetics
ERI	electrical resistivity imaging
FDEM	frequency domain electromagnetics
GSI	groundwater to surface water interface
HPT	Geoprobe® Hydraulic Profiling Tool
MEC	marine electrical conductivity

1 Introduction

On behalf of BASF Corporation (BASF), Arcadis of Michigan, LLC (Arcadis) has prepared this Groundwater to Surface Water Interface (GSI) Assessment Work Plan (Work Plan) for electrical resistivity imaging (ERI) on land near the site perimeter and a near-shore marine geophysical electrical conductivity (MEC) investigation for the Point (Pt.) Hennepin property (the Site) on the Detroit River (see attached **Figure 1**). Pt. Hennepin is a 225-acre island located immediately north of Grosse Ille. The objective of this Work Plan is to identify potential locations of groundwater discharge from the Site to the Detroit River using geophysical methods. The results of the subject investigation will be used to guide the development of a GSI sampling plan for the groundwater in the river bottom prior to discharge to the surface water, which is intended to characterize groundwater from the Site that is discharging to the Detroit River. The ultimate goal is to obtain Michigan Department of Environment, Great Lakes, and Energy (EGLE) closure of the GSI pathway that incorporates a sustainable perimeter groundwater management approach and allows for the establishment of the Site as a wildlife refuge. The general approach and rationale for this Work Plan was presented to the EGLE at a July 21, 2021 meeting.

1.1 Purpose of Investigation

1.1.1 Objective and Approach

The objective of this investigation is to collect geophysical data on land and in the Detroit River, calibrated and ground-truthed by Geoprobe® Hydraulic Profiling Tool (HPT) and Electrical Conductivity Tool (ECT), to refine the existing conceptual Site model (CSM) and to guide the development of a groundwater sampling plan in potential discharge zones into the Detroit River. The groundwater sampling plan in potential discharge zones into the Detroit River, to be completed following the investigation proposed in this workplan, will identify zones of impacted groundwater, if any, emanating from the Site.

Pt. Hennepin is an island made up primarily of distiller blow off (DBO). DBO is a waste product from soda ash production across the river in Wyandotte, which was placed at the Site during the first half of the 20th century. The DBO is contained within perimeter soil berms but has impacted the groundwater that flows radially toward the river. DBO is an alkaline material, the leachate from which has the potential to exhibit elevated electrical conductivity (EC). Previous investigations have documented that groundwater is migrating toward the river primarily through sand present beneath most of Pt. Hennepin. Because of the elevated EC exhibited by the groundwater at the Site, the approach presented in this Work Plan includes the use of ERI to identify zones of preferential flow in the groundwater along the perimeter of the island. The ERI data will be calibrated by confirmation HPT/ECT borings placed along the ERI lines. The combination of ERI and the HPT/ECT borings will also provide a means of estimating the groundwater flux toward the river. These locations of groundwater flux identified at the perimeter of the island will be used to guide a near-shore MEC which will use an electromagnetic (EM) induction conductivity meter (a Geonics EM31-MK2) to quantify the bulk apparent conductivity of the river bottom sediments and thereby locate potential zones where groundwater with elevated total dissolved solids may be discharging at the groundwater surface water interface.

1.1.2 Applicable Regulatory Drivers

The primary regulatory driver at the Site is Michigan Part 201. Pursuant to Section 324.20220e of the Natural Resources and Environmental Protection Act, PA 451 of 1994, BASF is developing a response activity to address venting groundwater from the Site. The primary exposure pathway at the Site is GSI, as there is the potential for impacted groundwater from the Site to be discharging to the river. The approach presented herein follows the EGLE guidance using alternative monitoring points to demonstrate compliance with the GSI pathway (EGLE 2018), as they are the most representative of the groundwater discharge conditions at the Site. As indicated above, the groundwater sampling prior to discharge to the Detroit River will occur in a subsequent phase of the investigation.

1.2 Site Description and Historical Investigation

BASF owns Pt. Hennepin, a 225-acre island in the Detroit River across from Wyandotte, Michigan. The property was acquired in 1911 by Michigan Alkali. The island was used as a repository for DBO, a waste byproduct of soda ash production in Wyandotte from 1911 until 1951. Pt. Hennepin was used for settling the DBO slurry piped over from the mainland. The slurry was contained behind perimeter soil dikes, built progressively higher on the island. Approximate six million cubic yards of DBO were deposited within the dike system. Additionally, the island was used for a solution mining operation that withdrew salt brine from 1943 until 1980 when the manufacturing of soda ash ceased. In 1969 and 1970 three sinkholes opened on the island and plans to stabilize and fill the sinkholes were developed. Since that time the Site has undergone stabilization, filling of sinkholes and habitat development.

Numerous phases of remedial investigation were performed since that time, and several soil borings and monitoring wells were installed both within the DBO and along the perimeter road outside of the dikes. Based on the soil borings, geologic cross sections were developed (**Appendix A**). Groundwater sampling from monitoring wells on the interior of the island have shown elevated concentrations of EC, pH, ammonia, select metals, and semi-volatile organic compounds. Groundwater elevations measured in monitoring wells indicate that groundwater beneath the Site is migrating radially from the DBO to the river, with the exception of near the central sinkhole, where groundwater appears to flow toward the island. Based on groundwater sampling to date, the sand layer appears to be the primary potential pathway for contaminant migration. It is unknown at this point whether impacted groundwater is discharging to the river.

Groundwater chemistry at the Site is complicated by the presence of the several sinkholes that developed in the late 1960s and early 1970s. The displacement of earth resulting from the sinkholes caused deep groundwater to mix with the shallow groundwater emanating from the DBO, which has a significant effect on the conceptual site model for the Site. The DBO is generally underlain by a peat layer, which was the surface layer prior to the placement of the DBO. The peat is underlain directly by a lacustrine clay layer, which is underlain by a sand layer as shown on the cross sections in **Appendix A**. In some cases, the sand layer is present directly beneath the peat. The sinkholes in part caused a breach of the clay confining layer and may have allowed a more direct pathway of impacted groundwater to the sand. As stated, purpose of the proposed scope of work is to further refine the CSM and to guide the development of a groundwater sampling plan in potential discharge zones into the Detroit River

The most recent field work at the Site was an apparent conductivity survey performed by Arcadis in 2008 (Geonics EM31 and EM34 EM induction conductivity meters were used to gather the apparent conductivity data).

In 2012 Golder Associates provided an additional review of the apparent conductivity survey results. The apparent conductivity survey was intended to be the first step in determining preferential groundwater pathways at the Site. The results from the apparent conductivity survey have been used to develop this Work Plan and were presented to EGLE in a meeting on July 21, 2021.

2 Assessment Plan

2.1 Electrical Resistivity Imaging

Arcadis will collect galvanic electrical resistivity data to create ERI[1] of the geologic materials along the western and eastern perimeters of the Site. See **Appendix B** for additional details of the ERI methodology. The primary objectives of completing the ERI survey include:

- Development of a continuous cross-section of the geologic conditions such as water saturation, sediment types such as clay, silt or sand using the bulk electrical resistivity of the subsurface as a surrogate for variations in mineralogy, porosity, water saturation, and variability of water chemistry (i.e., total dissolved solids). Laterally continuous sands present beneath the Site are a key potential pathway for groundwater. The extent to which these sand bodies extend to the river bottom and provide a pathway for discharge of these constituents is the focus of this investigation.
- Identification of anomalously electrically conductive zones in the saturated sediments that could indicate the potential for groundwater discharge to the Detroit River.

An essential step of the interpretation of the ERI results is the integration of geologic and chemical information into the ERI cross-sections. Overlay of geologic profiles from individual borings on top of the ERI graphics guides the interpretation of stratification, identification of lithologies, interpretation of erosional unconformities, and observation of sedimentation and depositional environment based on identification of the morphology of structures such as channels.

The ERI interpretation will incorporate existing geologic and chemical information that coincides with the ERI transects and newly gathered geologic and chemical data collected specifically for the purpose of interpreting the ERI cross-sections. The ERI results will be used to guide the placement of confirmation borings based on identification of various characteristics in the images to ground-truth background conditions and anomalous signatures potentially created by high EC groundwater or other features such as DBO waste or other unknown subsurface conditions. See **Section 2.2** below for more details on the proposed approach for the confirmation borings.

Arcadis will conduct the ERI assessment utilizing a team of geological and geophysical specialists who are familiar with both the geologic setting and the collection and processing of electrical resistivity data. The ERI assessment will consist of the following:

- Electrical resistivity data will be collected along two roughly south to north transects that parallel the west and east shorelines. Each transect will be approximately 5,000 feet in length (exact placement and length

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[1] For clarification, raw electrical resistivity data is collected in the field (there are several ways to collect this type of raw data). Post-field work, the raw resistivity data are run through a process known as inversion modeling. The output of the inversion modeling is termed an electrical resistivity image (ERI). For convenience, ERI is often used as a term which encompasses the whole process, from raw data collection to final modeling.

governed by field conditions). The previously collected EM data and the presence of DBO resulted in the focus of the ERI on the east and west sides of the island. The planned approximate locations of the two ERI transects are shown on **Figure 3**.

- The ERI setup will utilize up to 112 electrodes with fixed inter-electrode spacing of approximately 10 to 20 feet. The effective imaging depth of this configuration can be adjusted depending on the project objectives. In this case, the maximum depth of investigation will be set at approximately 75 feet below ground surface, which is sufficiently deep to image below the base of the river and into the glacial till/lacustrine clay that underlies the Site at depth. The sand layer(s) of interest beneath the surface as they are currently understood would be encompassed in this survey.
- A SuperSting R8™ resistivity meter manufactured by Advanced Geosciences Inc. (or equivalent) will be used to collect ERI data.
- An optimized data collection array[2] will be used to collect ERI data. This custom array will provide optimal horizontal and vertical sensitivity required to capture the complexities of the stratigraphic environment within the limitations of this technology.
- The location (x,y,z) of the electrodes in each ERI transect will be mapped by the geophysical field team with a differential global positioning system (DGPS) surveying unit with submeter accuracy.
- The ERI work will be performed prior to the installation of confirmation borings, as information gained from the ERI cross-sections will be used to more effectively target the zones of interest based on the lithological and chemical interpretations. To the extent possible, historical borehole data will also be used to interpret the ERI results.

The apparent resistivity field data will be subjected to an inversion modeling analysis which creates the model of true electrical resistivity distribution. Both Res2DInv (Geotomo Software) and EarthImager (Advanced Geosciences) will be used for processing and inversion modeling.

2.2 HPT/ECT Confirmation Borings

The HPT/ECT investigation will be completed to:

1. Ground-truth and calibrate the results of the ERI survey completed on the west and east perimeters of Pt. Hennepin; and,
2. Quantify the relative hydraulic conductivity of the saturated unit.

The goal of this phase of the investigation is to map the hydrostratigraphy of these areas at high vertical resolution and to resolve details of preferential flow paths possibly indicated by ERI. This information, combined with the ERI results will be used to identify the key locations for near-shore MEC mapping (see **Section 2.3** below for details on the MEC survey). **Appendix B, Exhibit 2** illustrates the concept of ground-truthing the ERI cross-sections.

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[2] The term array refers to the arrangement of current and potential electrodes. There are a number of array types, each with features which are advantageous both in terms of imaging sensitivities and data collection efficiencies. Arcadis will combine efficient arrays which provide both horizontal (e.g., dipole-dipole) and vertical (e.g., schlumberger) sensitivities to improve the modeling process to more closely match geologic conditions.

2.2.1 Hydraulic Profiling and Electrical Conductivity Characterization

It is assumed that approximately 10 borings will be completed along each of the two ERI transects (total of 20 borings) at locations identified in the interpreted ERI cross-sections. Borings will be located in areas where the ERI data suggests locations of anomalously electrically conductive zones. Borings will also be located in locations representative of background conditions for making comparisons that will be used to calibrate the ERI data. The investigation will be completed using the Geoprobe® HPT and the ECT to map zones of higher hydraulic conductivity (K) and anomalously high EC within the sands and gravels. See **Appendix B** for details on this methodology. **Figure 3** identifies ERI transect lines where the HPT/ECT borings will be completed. The borings will be advanced approximately two feet into the basal clay, with the maximum depth of the borings estimated to be 25 feet below ground surface. Final boring locations will be surveyed with a handheld DGPS unit. Note that this is not survey grade but is within submeter accuracy, adequate for these investigation activities.

Before the HPT work is initiated, pre-test calibration will be performed to ensure the HPT pressure response and EC response are consistent between borings. The response test will be completed before and after the first log, and after each subsequent log to verify the system is responding appropriately.

In addition to the response tests, HPT dissipation tests will be completed at each boring. A dissipation test consists of pausing the HPT boring, turning off the flow, and allowing the pressure to return to a static condition. This data is used to verify the elevation of the water table, correct for hydrostatic pressure, and in the calculation that provides an estimated hydraulic conductivity. Dissipation tests will be completed in at least two depth locations per boring, one within a relatively shallow portion of the aquifer and one within a deeper interval of the aquifer near to the total depth of the boring (and in between if additional sands are encountered). The tests will be biased to more hydraulically conductive zones to ensure a static condition can be achieved within a reasonable time frame.

A minimum of two calibration soil borings with continuous soil descriptions will be advanced adjacent to an HPT boring (minimum of one per ERI transect) to verify correlation between soil type, HPT/ECT data, and ERI results.

Continuous logging of EC, pressure, and flow will be completed at each boring location until the glaciolacustrine clay or glacial till beneath the sand layer is encountered at a depth estimated to be approximately 25 feet below grade.

2.2.2 Use of HPT/ECT Results to Calibrate ERI Results

One of the goals of performing HPT/ECT is to provide direct observations to guide the interpretation of the ERI cross-sections and allow a better, refined understanding of the geologic and geochemical conditions along the western and eastern perimeters.

The HPT probe will be linked to a control box where the signal will be received by a field computer. The HPT parameters such as transducer pressure, flow rate, EC, line pressure, probe rate, and diagnostic parameters are recorded and available for export and evaluation immediately following borehole completion.

The Geoprobe® DI Viewer software will be used to view the data, and to complete corrections for hydrostatic and atmospheric pressure effects, if needed. Once corrected, the software can provide a continuous log of estimated hydraulic conductivity (K).

2.3 Near-Shore Marine Electrical Conductivity Survey

To address the off-shore component of the transitional area from groundwater to surface water, a near-shore MEC survey will be performed to further investigate elevated EC identified in the ERI and HPT/ECT borings. There are several methods that can be used for quantifying the apparent EC of the geologic formation, but a class of instruments that utilize the concept of EM induction to measure EC are very effective in many situations. EM instruments that operate in what is known as the frequency domain electromagnetics (known as FDEM instruments) are well suited for investigations in the upper 10s of feet depth. FDEM instruments consist of co-planar transmitter and receiver coils in an integrated instrument that can be managed by one person.

The objective of the MEC survey will be to map the EC response of the river bottom sediments. The MEC survey will be completed in areas expected to be representative of background conditions and in key areas identified by the ERI and HPT/ECT borings where anomalously electrically conductive zones were identified. The actual extents of the MEC survey will be adjusted in the field if background conditions are not reached at the margins of the planned survey area. The goal will be to fully define the extent of anomalously high EC zones, if they exist. Looking forward, the premise is that EC results from the MEC survey will be indicative of the EC of the river bottom sediments. The results of the MEC survey will be used to direct and guide the selection of locations of future sampling in the river bottom following completion of the proposed geophysical investigation.

2.3.1 MEC Survey Procedures

Arcadis will perform a near-shore marine FDEM survey with a Model EM31-MK2 EM conductivity meter manufactured by Geonics Ltd. See **Appendix B** for the bases and rationale on the procedures that will guide this survey. Note that EM31-MK2 does not require ground contact and data is typically collected continuously as the instrument is conveyed across the study area.

For conveyance, the EM31-MK2 system will be mounted to a non-conductive watercraft and will be towed by a piloted vessel (see **Appendix B**, **Exhibit 3** for an example). The watercraft-mounted EM system will be towed along parallel transects roughly 25 feet apart in offshore strips parallel to the shoreline, from the shoreline out to a reasonable water depth beyond where groundwater from the island would be expected to seep into the river (but verified in the field as noted above). See **Figure 3** for the approximate areas to be surveyed with the EM31.

The position of the EM31-MK2 system will be determined with an on-board DGPS receiver. The receiver will be equipped with real-time differential correction, resulting in a horizontal accuracy of less than a meter. The DGPS and EM31 data streams will be automatically merged during data collection by an on-board data logger.

Periodically during the MEC survey the data logger will be downloaded and the data will be reviewed for completeness. A geophysicist will import the raw EC data into an analysis program and create draft field contour maps of the EC for both the VMD and the HMD orientations. As the survey progresses, periodic data review and QA/QC will be performed to both assure the proper data is being gathered and to make interpretive analysis of the EC data to assure that the results are geologically consistent with the on-shore results of the ERI and HPT/ECT work. During this near real-time data review process, the determination will be made as to whether background conditions have been reached radially outward from the anomalous areas, if present.

3 Data Analysis and Interpretation

The ERI and HPT/ECT data sets will be processed and interpreted as the project progresses. Once the ERI cross-sections have been ground-truthed and annotated for geologic interpretations, then the near-shore MEC survey will be completed, during which, as described above, the EC data will be reviewed real-time during the survey to guide field work.

The data from the phases of investigation described above will be integrated and interpreted and will be used as the basis for development of a sampling plan for performing off-shore sampling in the river bottom prior to discharge to the surface water. The information used for the sampling plan development will include final interpretation of the integrated results for locations of possible sand pathways on- and off-shore, possible pathways intersecting the bottom of the river, and locations of anomalously high EC.

4 Reporting

Following the execution of this Work Plan, a summary technical memorandum will be submitted to EGLE including the interpreted graphical results of the ERI, HPT/ECT, and MEC survey. Results will be used to develop the work plan for performing sampling in the Detroit River.

5 Implementation Schedule

The Work Plan implementation will begin upon approval from the EGLE. The ERI and HPT/ECT borings will be completed in the fall of 2021. Following the ERI and HPT/ECT boring work, a meeting will be held with EGLE to review the results and any implications of the results on the MEC survey. Following the meeting with EGLE, the MEC survey will be completed. Because the marine work is weather dependent, it will be completed in spring 2022. The results of the MEC survey and estimate of discharge zones (if identified) will be discussed with EGLE following the implementation of the MEC survey in late spring/early summer 2022.   Following the meeting with EGLE in late spring/early summer 2022, a sampling plan for off-shore sampling in the river bottom will be submitted to EGLE for approval.

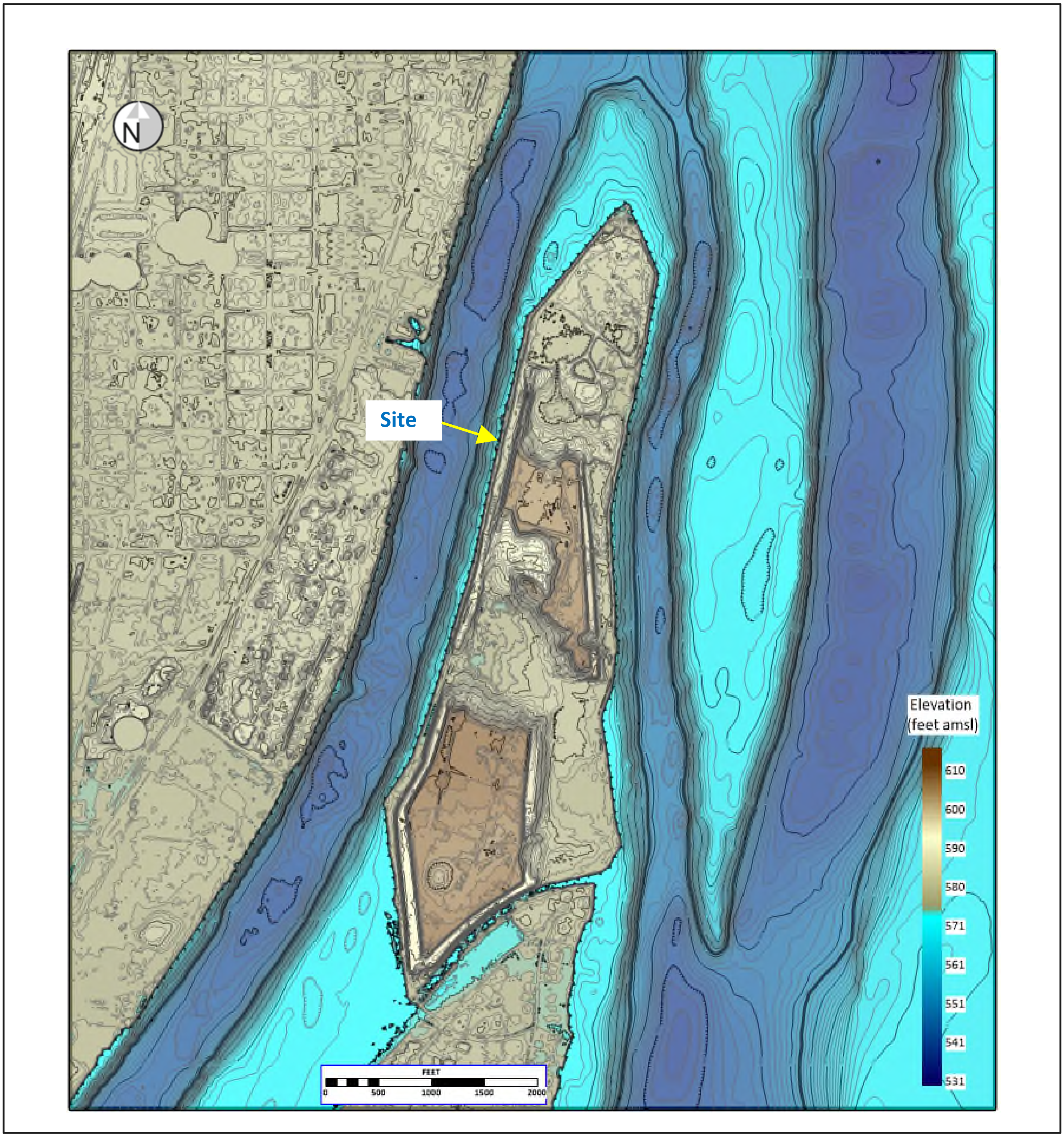
6 Reference

Michigan Department of Environment, Great Lakes, and Energy. 2018. “Groundwater-Surface Water Pathway Compliance Options”. Remediation and Redevelopment Division Resource Materials. April 23.

Figures

Figure 1
Site Location Map

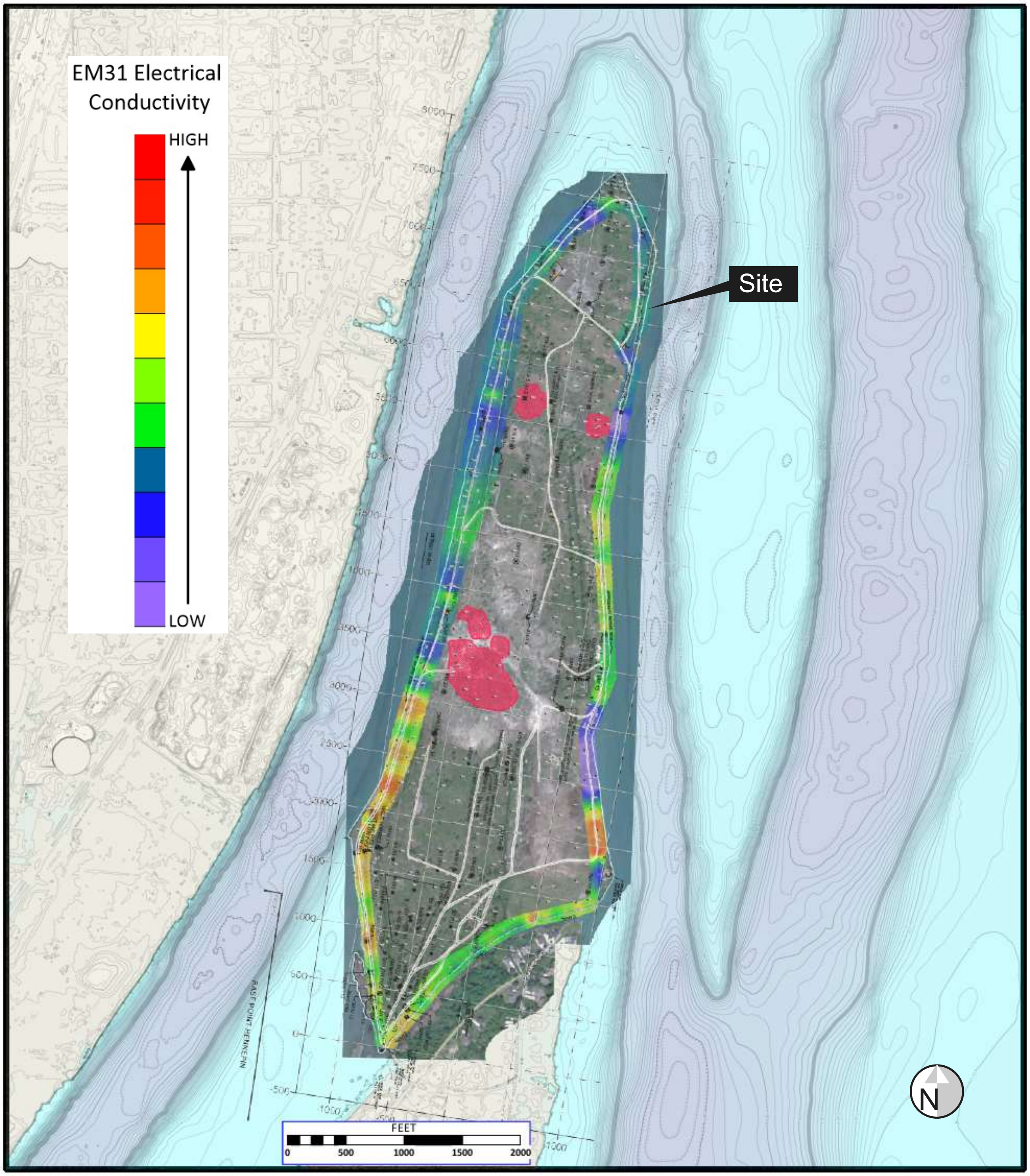
GSI Assessment Work Plan
Point Hennepin, Wyandotte, MI



Source: Wayne and Washtenaw Counties 1.0 PPSM LiDAR (2009)
Trenton Channel Detroit River and Rouge River - 2004-08-25

Figure 2
Electromagnetics Perimeter Profile

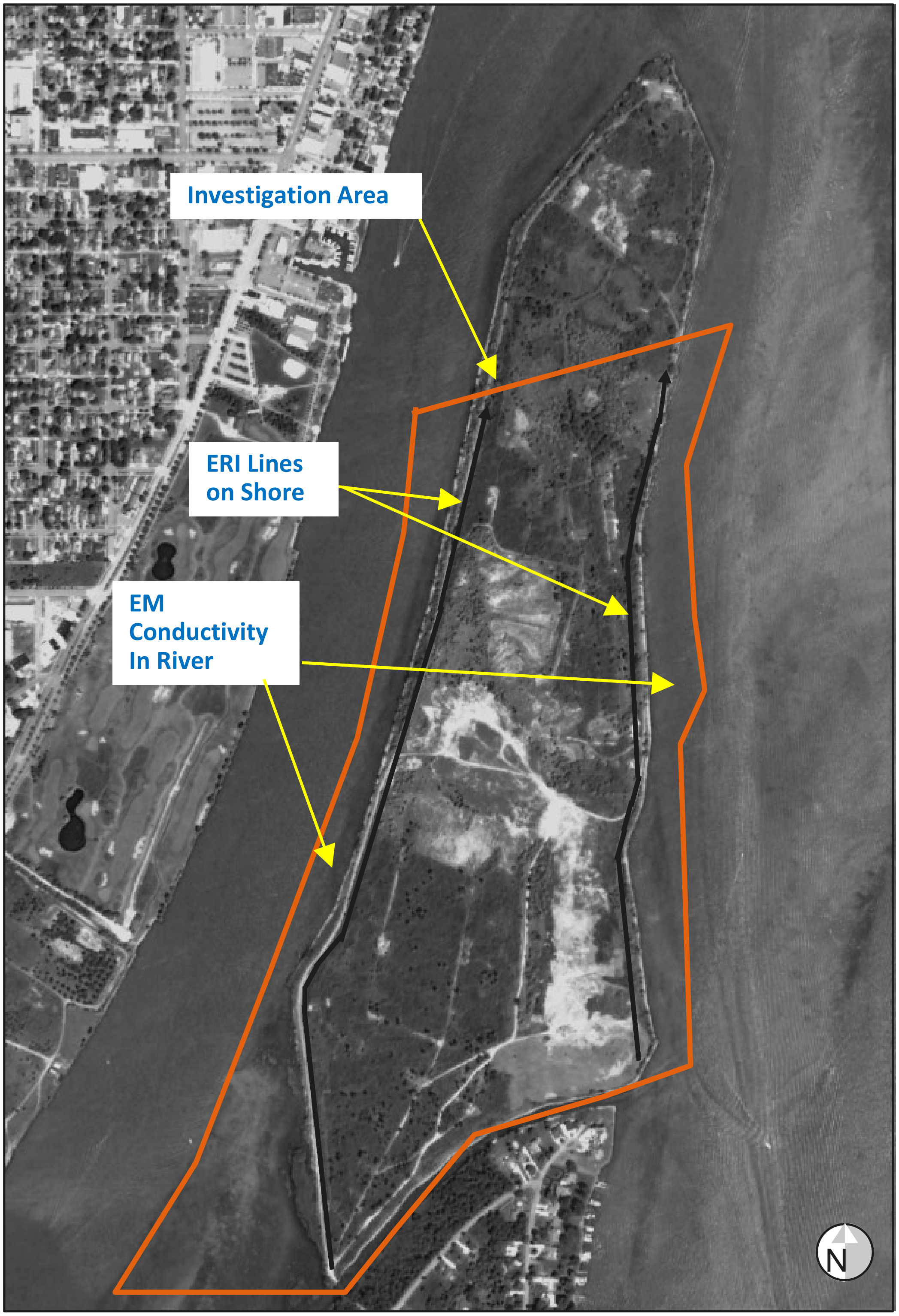
GSI Assessment Work Plan
Point Hennepin, Wyandotte, MI



Source: Wayne and Washtenaw Counties 1.0 PPSM LiDAR (2009)
Trenton Channel Detroit River and Rouge River - 2004-08-25

Figure 3
Site Investigation Locations

GSI Assessment Work Plan
Point Hennepin, Wyandotte, MI

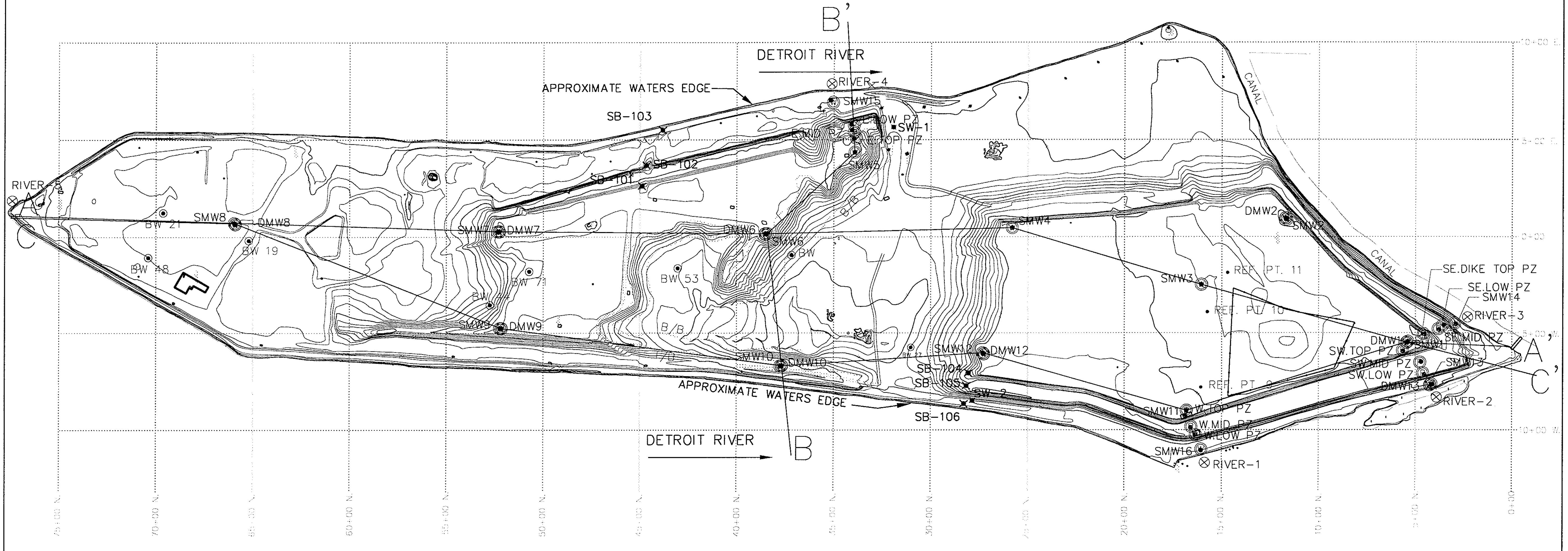


Source: Aerial Imagery Collected in 2009 as part of the National Agriculture Imagery Program

Not to Scale

Appendix A

URS Cross Sections



LEGEND

◉	BRINE WELL: LOCATED IN FIELD
Ⓟ	PIEZOMETER: LOCATED IN FIELD
Ⓦ	MONITOR WELL: LOCATED IN FIELD
⁎	SB-103 URS SOIL BORING, 2003 (APPROXIMATE LOCATION)
●	REFERENCE SUBSIDENCE MONITORING PIPES: LOCATED IN FIELD
×	STANDING SURFACE WATER LOCATION (SW-1)
⌀	UTILITY POLE: LOCATED IN FIELD
-----------	OLD GRAVEL ROAD FROM B.W. ARTHURS PLAN
== == == ==	GRAVEL ROAD: LOCATED IN FIELD

NOTE

OUTLINE OF RIVER, COORDINATE SYSTEM AND OLD ROADS ARE SHOWN FROM BOYD W. ARTHURS DRAWING NO. 52550 OF 11-29-95.

BASE MAP DEVELOPED BY URBAN ENGINEERING CO.,
6748 ALLEN ROAD, ALLEN PARK, MICHIGAN 48101, 10-19-1999

N

SCALE: 1 INCH = 500 FEET

0 250 500 1000

BASF CORPORATION
POINT HENNEPIN
GROSSE ILE, MI

TITLE
GEOLOGIC CROSS SECTION MAP

URS URS CORPORATION, DETROIT, MI., 313-961-9797

DATE 12-05-05	JOB NO. 13808782
DR. NPM	SKETCH NO.
CK. PT	FIGURE 2-5

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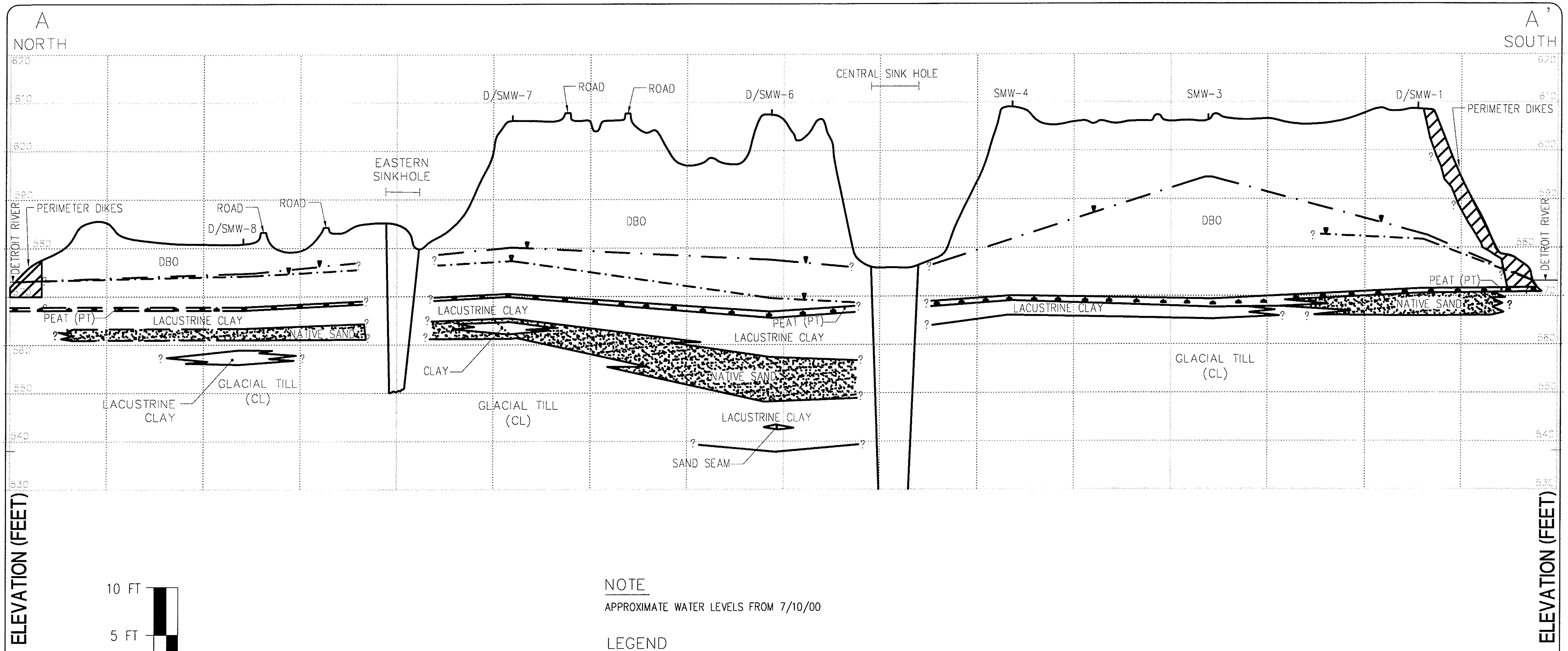

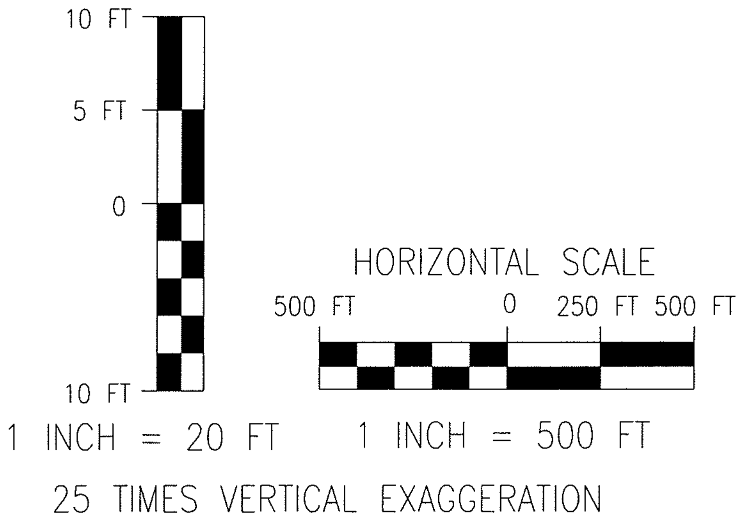

1 INCH = 20 FT

1 INCH = 500 FT

25 TIMES VERTICAL EXAGGERATION

NOTE

APPROXIMATE WATER LEVELS FROM 7/10/00

LEGEND

— · — APPROXIMATE SHALLOW MONITORING WELL GROUNDWATER LEVEL

—·—·— APPROXIMATE DEEP MONITORING WELL GROUNDWATER LEVEL

BASF CORPORATION
POINT HENNEPIN
GROSSE ILE, MI

TITLE
GEOLOGIC CROSS SECTION A-A'

URS URS CORPORATION, DETROIT, MI., 313-961-9797

DATE 12-05-05
JOB NO. 13808782
DR. WC
SKETCH NO.
CK. HNH
FIGURE 2-6

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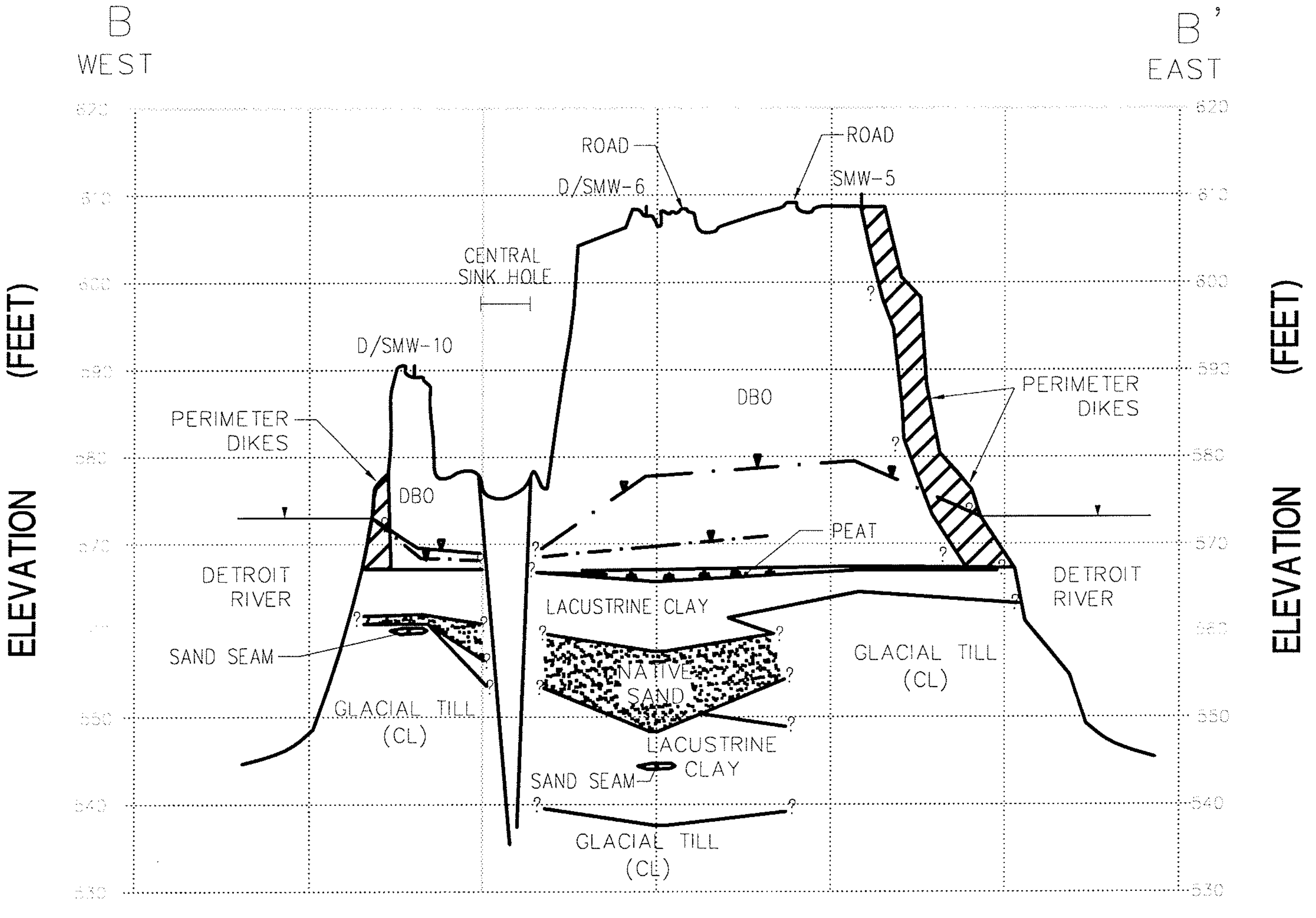

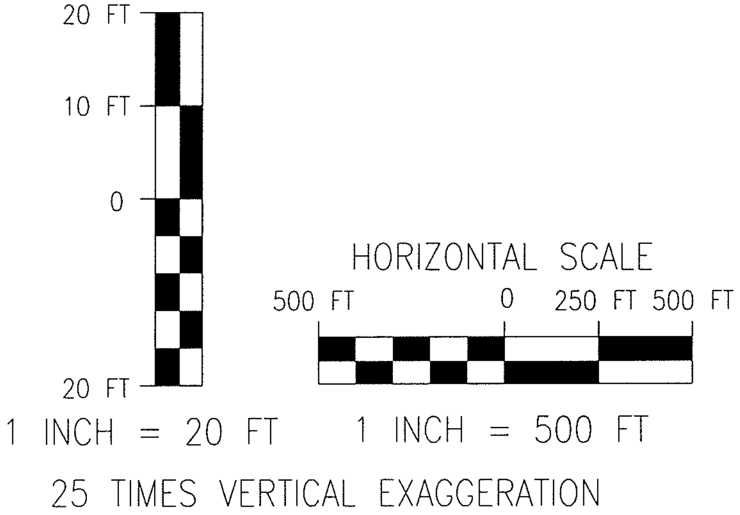

1 INCH = 20 FT

1 INCH = 500 FT

25 TIMES VERTICAL EXAGGERATION

NOTE

APPROXIMATE WATER LEVELS FROM 7/10/00

LEGEND

— · — APPROXIMATE SHALLOW MONITORING WELL GROUNDWATER LEVEL
–·–·– APPROXIMATE DEEP MONITORING WELL GROUNDWATER LEVEL

BASF CORPORATION
POINT HENNEPIN
GROSSE ILE, MI

TITLE
GEOLOGIC CROSS SECTION B - B'

URS URS CORPORATION, DETROIT, MI., 313-961-9797

DATE 12-05-05	JOB NO. 13808782
DR. WC	SKETCH NO.
CK. HNH	**FIGURE 2-7**

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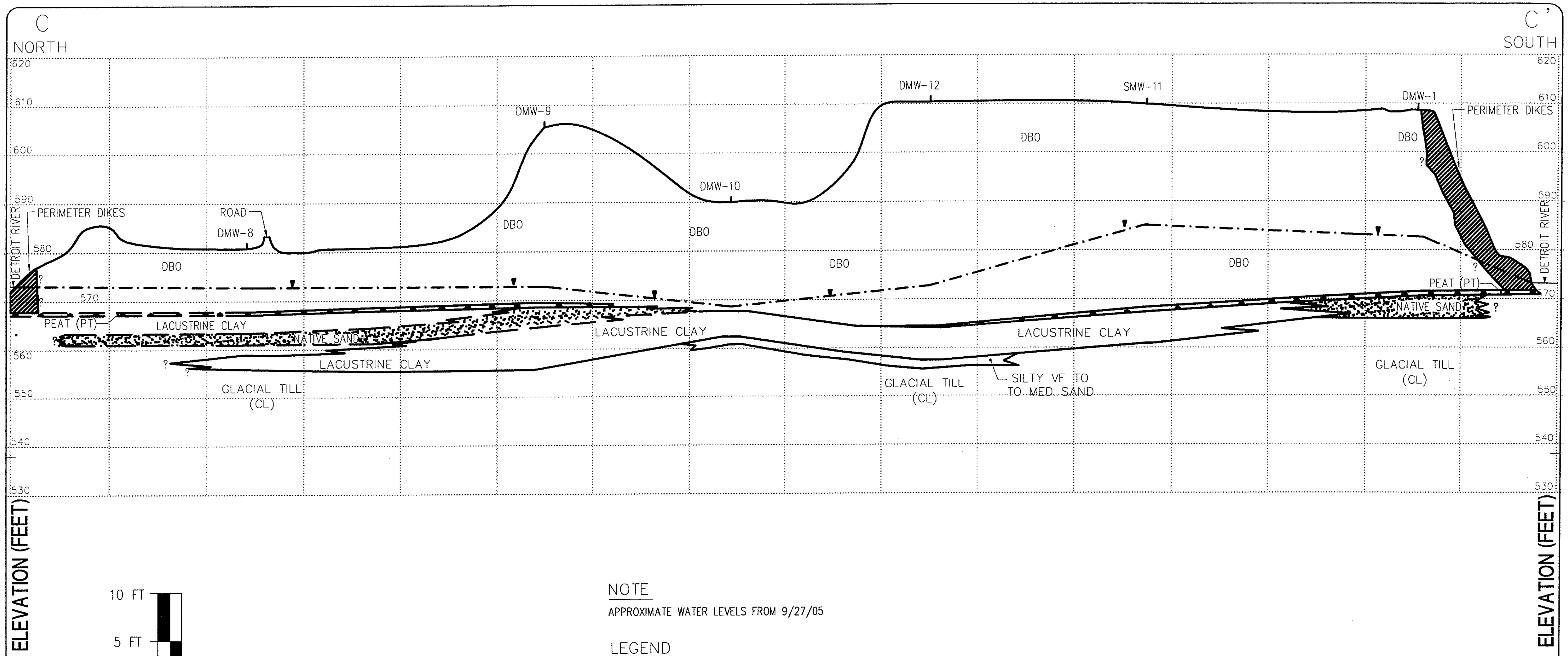

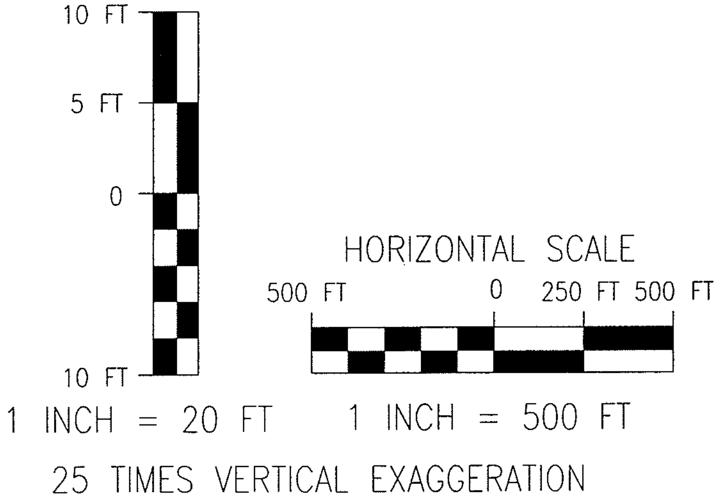

NOTE

APPROXIMATE WATER LEVELS FROM 9/27/05

LEGEND

—·—·— APPROXIMATE DEEP MONITORING WELL GROUNDWATER LEVEL

BASF CORPORATION
POINT HENNEPIN
GROSSE ILE, MI

TITLE
GEOLOGIC CROSS SECTION C-C'

URS URS CORPORATION, DETROIT, MI., 313-961-9797

DATE 12-05-05	JOB NO. 13808782
DR. MM	SKETCH NO.
CK. PT	**FIGURE 2-8**

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NMurphy
12/15/2005 3:19 pm

Appendix B

Geophysics Rationale and Examples

Appendix B

Geophysics Rationale and Examples

GSI Assessment Work Plan
BASF, Point Hennepin, Wyandotte, Michigan

Electric Resistivity Imaging (ERI) Method

The key benefit of gathering ERI data is that it can provide a continuous, broad context for the correlations of the detailed information found within individual soil borings, leading to a more comprehensive and defensible interpretation of the sediments within the stratigraphic constraints associated with the geologic history of the site.

A pair of examples interpreted ERI cross-sections from other locations are provided in **Exhibit 1** below. The upper example (a) is in a glacial sedimentary environment in the great lakes region and the lower example (b) is in an igneous bedrock environment. As the chart at the bottom of **Exhibit 1** illustrates, resistivity (and conductivity[1]) can, to a certain degree be related to lithologies and water chemistry. Although absolute values cannot be directly correlated to lithology, the relative differences and ranges are valid. Complexity is introduced when the electrical conductivity variations (e.g., generally due to naturally or man-made dissolved solids) of the groundwater is overprinted on top of the geology. As a result, it is best practice to not only install soil borings to confirm lithology, but to also collect continuous electrical conductivity (EC) using a direct push type probe and to collect grab samples for field measurements of pH, specific conductivity, ORP, and temperature (resistivity values are temperature dependent).

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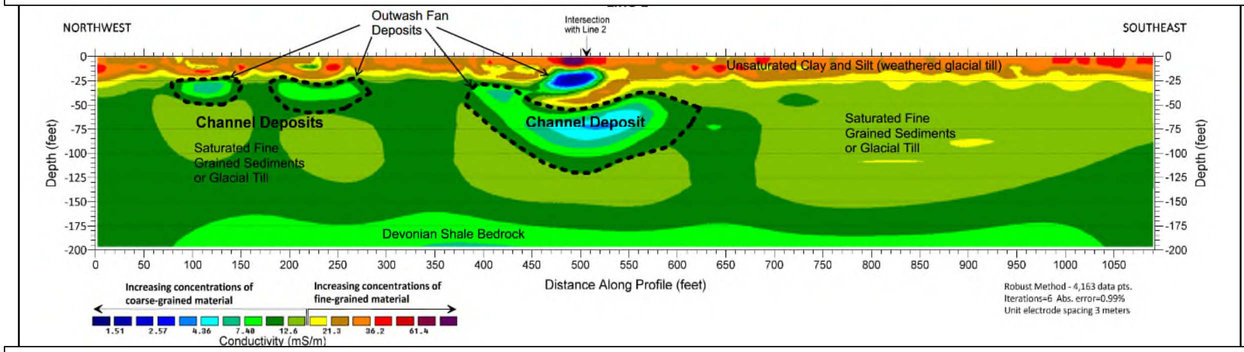
[1] Resistivity and Conductivity are inversely proportional. Generally, resistivity is expressed in units of Ohm-meters (ohm-m) and conductivity in milliSiemens per meter (mS/m). Conversion between the two quantities is: Resistivity = 1000/Conductivity. It is conventional to express the results of ERI surveys in resistivity units (ohm-m). However, in the case of electromagnetic induction measurements, it is conventional to present the data in conductivity unit (mS/m) because this type of measurement is most sensitive to electrically conductive materials.

(a) Example of Natural Geologic Conditions where the groundwater *is not* impacted with dissolved solids



(b) Example of Where High TDS groundwater has decreased electrical resistivity (increase conductivity)

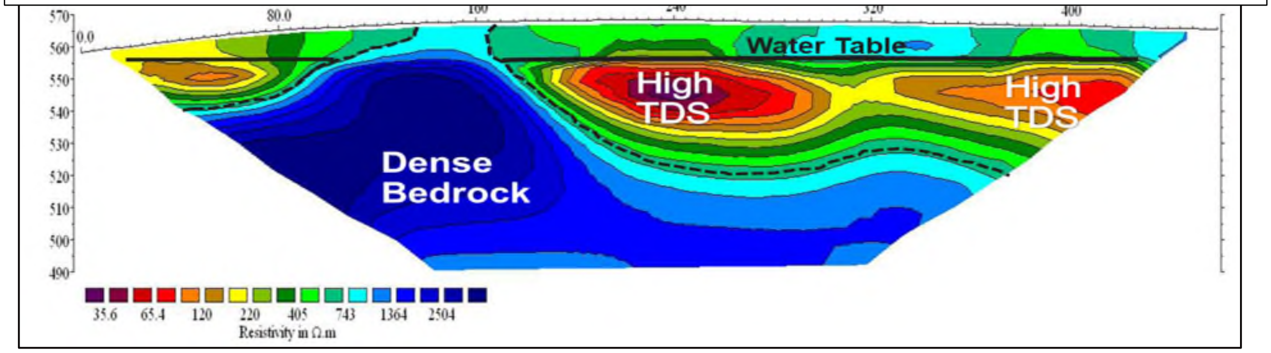
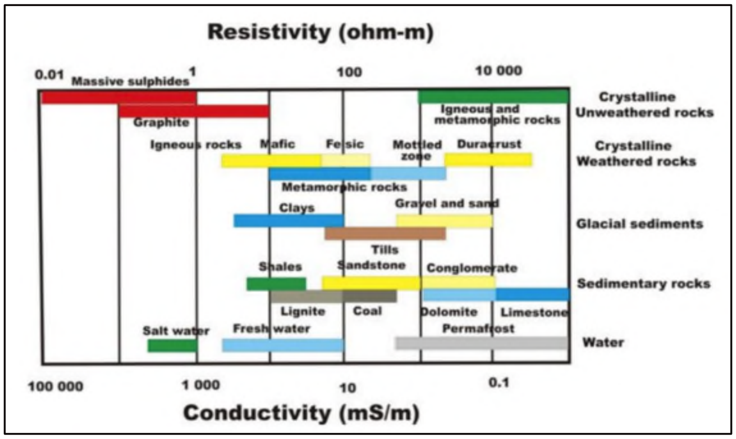


Exhibit 1. Two examples of ERI results in two different geologic settings and illustrate purely geologic, stratigraphic information (a) and a mix of geological and chemical responses (b). Note that the color scales have different ranges to better match the local geological conditions for each example. The upper example (a) is in Pleistocene glacial deposits. Annotations indicate the various glacial facies deposits. The glacial deposits unconformably overlie Devonian shale. Confirmed by drilling, the channel deposits were interpreted as outwash fan deposits at the glacial ice margin. The groundwater chemistry at this site was uniform, so that all of the resistivity variation can be directly related to geologic conditions. The lower example (b) is in a setting where thick soil and sedimentary rock are underlain by mafic igneous rock (basalt). The soil and sedimentary rock are significantly more transmissible, and the bedrock was effectively an aquitard. At this site groundwater chemistry varied significantly due to the presence of a plume of wastewater containing sodium chloride which escaped from a lagoon. The plume in red marked as "High TDS", stands out as anomalous and the concentration of sodium chloride is proportional to the resistivity in the zone above bedrock. The two examples in Exhibit 1 are true resistivity model outputs from Res2DInv.



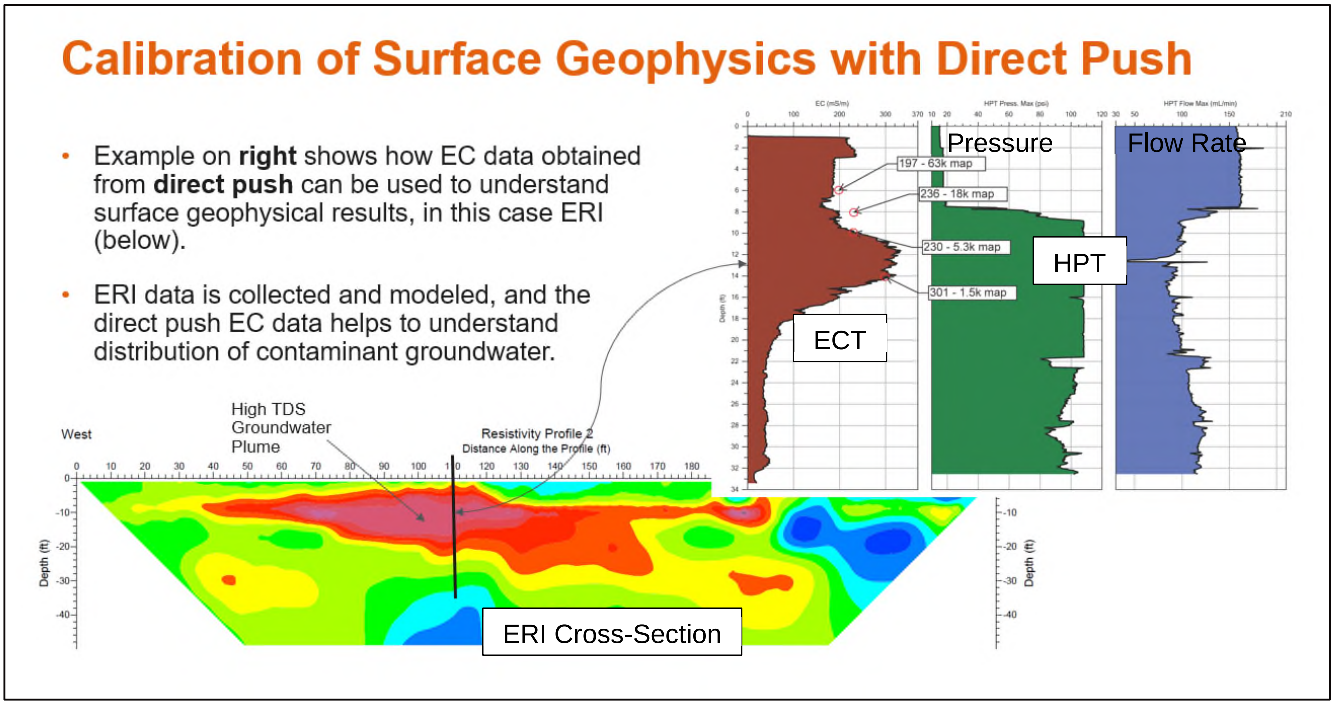
Hydraulic Profiling Tool (HPT) and Electrical Conductivity Tool (ECT) Characterization

Continuous real-time profiling of relative hydraulic conductivity using Geoprobe® HPT utilizes standard direct push drilling equipment to advance the HPT probe into the soil. The probe injects a small continuous jet of water into the soil while simultaneously measuring the fluid back pressure due to injection and the flow rate at a high frequency. Since the HPT pressure response is analogous to relative changes in hydraulic conductivity, the HPT data can be used to locate and define potential migration pathways in the saturated zone.

Continuous real-time profiling of electrical conductivity completed using the Geoprobe® ECT also utilizes standard direct push drilling equipment to advance the ECT probe into the soil. The ECT probe induces a current across electrical dipoles placed in the soil. The system measures electrical current and voltage and from these parameters calculates electrical conductivity (comparable to the true electrical resistivity resulting from the ERI modeling). Generally, higher electrical conductivities typically are representative of finer grained sediments, such as silts and clays, while sands and gravels have distinctively lower conductivities. Ionic contaminants in the soil or groundwater can increase the measured conductivity.

The main purpose of the ECT is to help identify lithologies based on electrical conductivity (see the chart at the bottom of **Exhibit 1**). However, a second, very important purpose of the ECT data is to also identify aquifer zones which contain anomalously electrically conductive groundwater which is high in TDS. Normally, in freshwater environments sands are less electrically conductive than silts and clays, making it possible to distinguish lithologies. However, if a highly electrically conductive groundwater, whether a naturally occurring brine or a man-made chemical leachate, is present in a sand, the sand will likely appear more electrically conductive than other geologic materials. To make a positive determination of a sand impacted with anomalous groundwater conductivities, it is necessary to do a combined interpretation of HPT and ECT results. These interpretations of the HPT and ECT results will be a critical piece of the interpretation of the ERI cross-sections.

Exhibit 2 below illustrates the concept of ground-truthing the ERI cross-sections. These two distinct types of results, ERI providing broad, laterally continuous view and HPT/ECT providing high vertical resolution, can be used to jointly interpret geologic conditions in a manner which is superior to working with either of the data sets alone. The result of the ERI-HPT/ECT marriage will be used to better understand possible zones where anomalous groundwater may be entering the river bottom sediments near-shore.



Calibration of Surface Geophysics with Direct Push

- Example on **right** shows how EC data obtained from **direct push** can be used to understand surface geophysical results, in this case ERI (below).
- ERI data is collected and modeled, and the direct push EC data helps to understand distribution of contaminant groundwater.

Exhibit 2. Graphic illustration of the process of ground-truthing ERI using direct observations including HPT and ECT

Marine Electrical Conductivity Survey

During the operation of the frequency domain electromagnetics (FDEM) instrument, the transmitter coil is energized by an alternating current and radiates a continuous electromagnetic field (EMF) into the earth. This transmitted primary field induces secondary electrical currents in the earth below the instrument (in this case fresh water and river bottom sediments). The magnitude of the induced current is directly and linearly proportional to the EC of the earth beneath the instrument at what is known as low induction numbers[2], valid for most naturally occurring geologic materials. The induced secondary current flow generates a corresponding secondary EMF, phase-lagged behind the primary field, that is detected by the receiver coil on the instrument. The receiver coil also detects the primary field and uses the ratio of the secondary to primary field to calculate the EC of the earth. This reading represents a bulk EC measurement (i.e., composite of geologic materials and the conductivity of the fluid filling the pores), more properly known as the apparent EC, within a volume of ground directly beneath the instrument down to its effective depth of penetration. Because most minerals are poor electrical conductors, electrical current preferentially flows in the fluids filling the pores between mineral grains. This means that the product of the electrical conductivity of the pore-filling fluid (i.e., groundwater) and the interconnected porosity dominates electrical current flow. Somewhat of an exception is where clay minerals are present. Some clay minerals high in cation exchange capacity can increase the electrical conductivity of the formation because the ions sorbed to the clays are free to move under an applied electrical current.

Greenwood (2004) has documented the efficacy of the use of the Geonics EM31 and EM34[3] for the mapping of porewater salinity in coastal environments and their procedures will be used as guidance for this survey. The EM31-MK2 was designed to map the apparent EC in the upper 18 feet of the subsurface. Its operating frequency is 9.8 kHz, and the co-planar coils are separated by 12 feet. It has two modes of operation in terms of the orientation of the instrument's coils relative to the ground surface: 1) horizontal magnetic dipole (HMD) with approximate 0 to 9-foot effective sensing depth and vertical magnetic dipole (VMD) with approximate 9 to 18-foot effective sensing depth.

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[2] A dimensionless parameter used to characterize electromagnetic induction response. Materials with low induction numbers include most naturally occurring geologic materials where the groundwater has specific conductance in the typical range of freshwater. See chart at bottom of Exhibit 1. Materials which have an electrical conductivity in the 1000's of mS/m do not have low induction numbers and would fall outside the proportional range of FDEM conductivity measurements. Note that salt water is one such material. It is expected that the impacted groundwater may fall outside the proportional range of the low induction number assumption as well.

[3] The penetration depth is instrument-specific and is determined by the transmitter frequency, coil separation, height of instrument off the ground surface, and orientation of the coils. The configuration of the EM31 yields a maximum penetration depth of approximately 18 feet. The EM34 has 3 coil spacings with maximum penetration depths of approximately 50, 100 and 200 feet.

Exhibit 3. Figure from Greenwood (2004) illustrating their way of mounting the EM31 in a non-metallic canoe.

Greenwood, W. J., 2004, "Mapping Porewater Salinity with Electromagnetic and Electrical Methods in Shallow Coastal Environments: Terra Ceia, Florida". University of South Florida. Graduate Theses and Dissertations. https://scholarcommons.usf.edu/etd/1055

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