MEMO

To: Brian Jankauskas, New York Department of Environment and Conservation

From: Arlene Lillie, John Bartos, Nigel Goulding

CC: Jim Vondracek – Ashland
Stephen Havlik, BASF

Date: October 21, 2015

Re: Hudson River Hydrology and Geomorphology Review

To support the RCRA Facility Investigation (RFI) for off-site sediments in the Hudson River for the former Hercules/Ciba-Geigy manufacturing plant near Glens Falls, NY (the Site), EHS Support LLC (EHS Support), on behalf of Ashland and BASF, completed a review of available hydrology and geomorphology data collected by U.S. Environmental Protection Agency (USEPA) and General Electric (GE) as part of their hydrological evaluations of the GE Hudson River Superfund Site. This assessment was conducted to address New York State Department of Environmental Conservation (NYSDEC) comments, issued November 4, 2014 regarding the Site September 2014 RFI report for off-site sediments.

This memorandum provides a summary of our understanding of the reviewed hydrology and geomorphology data collected by both the USEPA and GE as part of their hydrological evaluations. The evaluation presented herein was conducted in concert with an evaluation of fate and transport of metals in fluvial surface water and information from each study support the discussions herein. Therefore, it is recommended that this memorandum be read in conjunction with the correlating technical memorandum regarding the fate and transport evaluation (EHS Support, 2015).

As described throughout this document a comprehensive program of investigations has been conducted by USEPA and GE on the Hudson River downstream of the Site. These assessments have included remote scanning technologies (for example side scan sonar) and direct sampling of sediments. Using these previously collected assessments, this memorandum's objective is to document the different depositional areas within the river, the spatial extent of each type of sediments associated with the depositional areas, and determine the spatial extent of sediments that remain outside of the remediation confirmation units. A secondary objective was to explore the relationship between Contaminants of Concern (CoCs) in the fine-grained sediments to evaluate if PCBs is useful indicator of relative variation in metals concentrations. All of this information together with the spatial extent of remaining historical fine-grained sediments is supportive of forming a conceptual site model of potential for threat to human health and the environment from residual site COCs that may be present in these areas.

The composite findings of these assessments have been summarized by GE and are included as sediment type classification maps included Attachment A and discussed in detail in the sections below.

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1.0 KEY RIVER FEATURES

The extensive USEPA and GE program of assessment extended from the Bakers Falls Dam (river mile marker 197) to the Federal Dam at Troy (river mile marker 154). For reference, the Site is located at river maker 199. Numerous dam and lock structures are present along this stretch of river to support shipping navigation (refer Figure 1). The key lock and dam structures from the site to river mile marker 180 are shown on Figures 2 through 7 and include:

1. South Glens Falls Dam (river mile marker 200) located upstream of the site (Figure 2)
2. Bakers Falls Dam (i.e. Hudson Falls Dam) (river mile marker 197; Figure 2)
3. The navigation channels around Rogers Island extending from river mile marker 194.6 to Lock 7 at river mile marker 193.7 (Figure 3)
4. The navigation channel around Griffin Island (river mile marker 190.5 to 189.5; Figure 5)
5. Thompson Island Dam (river mile marker 188.5; Figures 5 and 6)
6. The navigation canal extending from upstream of Thompson Island Dam to Lock 6 (river mile markers 189 to 186; Figure 6)
7. Fort Miller Dam and Lock 6 (river mile marker 186.3; Figure 6)
8. Northhumberland Dam (river mile marker 183.4; Figure 7)
9. The navigation canal extending from Northhumberland dam (river mile marker 183.4) to Lock 5 (river mile marker 182.3; Figure 7)
10. Lock 5 (river mile marker 182.3; Figure 7)

Review of aerial photographs for the river identify key sections of the river as high velocity sections with riffle flow observed over a rough (likely rocky) bottom. A riffle is a short, relatively shallow and coarse bedded length of stream over which the stream flows at relatively slower velocity with more turbulence than in the nearby deeper sections of the river. Riffles are instrumental in the formation of meanders with deeper pools forming alternately at usually intervals about 6 times the width of the river. The key riffle flow sections are shown on the aerial images as major ripples in Figures 2 through 7 (2011 imagery) and Figures B1 through B5 in Attachment B (2004 imagery), and include:

1. From downstream of South Glens Falls Dam (mile marker 200 upstream of the site) to ponded backwater behind Bakers Falls dam (197.7) where riffle flow is observed with rocky outcrops throughout the river (Figure 2 and Figures B1 and B2)
2. Downstream of Bakers Falls Dam where riffle flow is observed from river mile marker 197 to 196.5 (Figure 2B)
3. A confined area immediately downstream of Thompson Island Dam (mile marker 188.5; Figure B3)
4. Downstream of Fort Miller Dam to just below river mile marker 186 (Figure B4)
5. Downstream of Northhumberland Dam to just below river mile marker 183 (Figure B5)

The remaining areas of the Hudson River are dominated by a meandering system of the river and back pools of the dams that extends throughout the study area (Figures 1 through 7).

These key areas have important implications in terms of the deposition and presence of sediment with the lock and dam structures representing areas of major deposition (particularly on the upstream side of the structures) as well as modification by navigational dredging activities. The riffle flow sections of the Hudson River, which are characterized by rocky bottoms, steeper grades, shallower depths, lower velocity and increased turbulence, are areas where limited or no sediment deposition will occur.

An assessment of selected fundamentals of river Hydrology and Geomorphology is provided below for background to support the interpretation discussed in later sections.

2.0 FUNDAMENTALS OF HYDROLOGY AND GEOMORPHOLOGY IN FLUVIAL SETTINGS

The two fundamental controls on erosion and transport of sediments in fluvial environments are the velocity profiles and grain size diameter of materials within the river. The relationship between sediment transport and erosion is dictated by the stream power and shear force acting on the grains, with increasing stream power increasing the size of particles that can be transported.

Both of the equations are selective representative equations to illustrate key processes and dependencies that have been developed and applied to describe sediment transport, deposition, and erosion in both cohesive and non-cohesive sediments. The equations found below imply that the mean velocity and shear stress control the process of sediment transport and erosion. Simons and Richardson (1966) described this relationship in their equation which implies that stream power increases with velocity, water depth, or slope of the channel:

$$\tau \cdot v_r = \frac{\rho \cdot g \cdot Q_s}{w} \cdot S$$

Variables:

P_s is the stream power,
Q_s is the volumetric discharge rate,
ρ is the fluid density including the suspended sediment,
w is the channel width
τ is the shear stress,
g is the acceleration due to gravity,
v_r is the velocity, and
S is the slope of the channel.

Using the principles contained within Simons and Richardson (1966), Knighton (1987) proposed the following equation for the relationship between shear stress acting on the river bed and the river dynamics:

$$\tau = \rho \cdot g \cdot d \cdot \tan(\alpha) \qquad \frac{dynes}{cm^2}$$

Variables:

τ is the shear stress,
ρ is the fluid density including the suspended sediment,
g is gravity,
d is the river depth, and
α is the slope of the channel.

These relationships between stream flow velocity and mean grain size are illustrated by the Hjulstrom-Sundborg Diagram summarized by Sundborg (1956). This graph (Exhibit A) shows the empirical relationship in three sediment transport phases. At very high stream flow velocities, the grains are fully suspended and there is a net loss of sediment from the stream bed, called erosion; in this phase particles are eroded and transported in the water column and there is no net deposition. The second phase, at a lower velocity, is transport which has the grain being moved by two different mechanisms. The first mechanism is entrainment which is the bulk movement of grains in suspension without net loss of the sediments (i.e., no erosion). The second mechanism that occurs at lower stream velocities is bedload transport. Bedload transport is when grains move by rolling or saltating which forms plane beds under conditions of limited transport. The last phase, occurring at even lower velocity, is deposition where the grain "settles" from the water column onto the sediment bed.

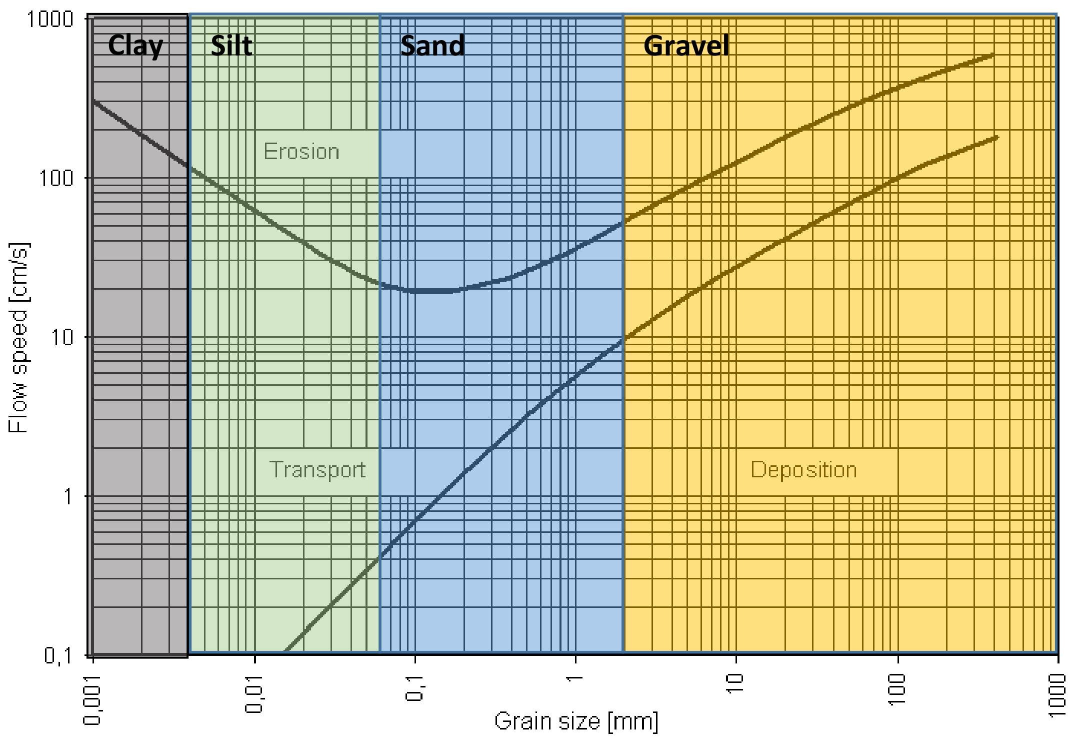


Exhibit A - Hjulstrom-Sundborg Diagram (annotated with silt, clay and gravel grain size ranges)

The "U-shaped" curve, the critical erosion velocity, marking the transition between the transport and erosion phases reflects the resistance of clays to erosion and the geometric progression of grain mass with increasing diameter. The reverse is also true for the bottom curve, the mean settling velocity, from erosion to transport to sedimentation with decreasing velocity is relatively abrupt for coarse-grained grains because of the mass relationship. Finer grained sediments like silts and clays can remain in transport for a much larger range of velocity conditions. Once a particle settles in the "deposition" phase of the Hjulstrom-Sundborg Diagram, the velocity has to be greater than the mean settling velocity for the finer sediment to become resuspended.

The implication is that steady or gradually varying velocity conditions result in hydraulic sorting of the sediment grains and will produce well-sorted deposits (i.e., deposits with a relatively narrow range of grain sizes) or gradational trends in grain-size distribution that accompany bedding forms. Abrupt changes in the flow velocity can result in sediment deposits with a broad range of grain sizes because interparticle interference enhances sedimentation rates. Poorly sorted deposits (those with a broad range of grain sizes) reflect dynamic changes in stream velocity.

2.1 Deposition within Meandering Rivers

In natural rivers, the processes described above vary significantly along the length and width of a river system with classical patterns of erosion and deposition observed in different river segments or areas. As described by Collinson (1969), the river pattern is influenced by the size and volume of the sediment, slope of the channel, volume and variability of discharge, and characteristics of the basin through which the river is evolving. The basic patterns are braided, anastomosing, meandering, and straight rivers. The Hudson River is considered a meandering river that has been anthropogenic modified by dams that established deep pools behind the dams and scouring of the sediments downstream A meandering river typically has one channel that winds its way across the flood plain. The river has a low sediment load and low gradient in comparison to the other three river types.

The type of beds that form (bedforms) in the river bed sediment is dependent on the relationship between stream power and fluvial sedimentation process. Simmons and Richardson (1966) illustrated an empirical relationship between the stream power and the median grain diameter and the types of bedforms that develop like plane beds, and ripples as illustrated on Exhibit B.

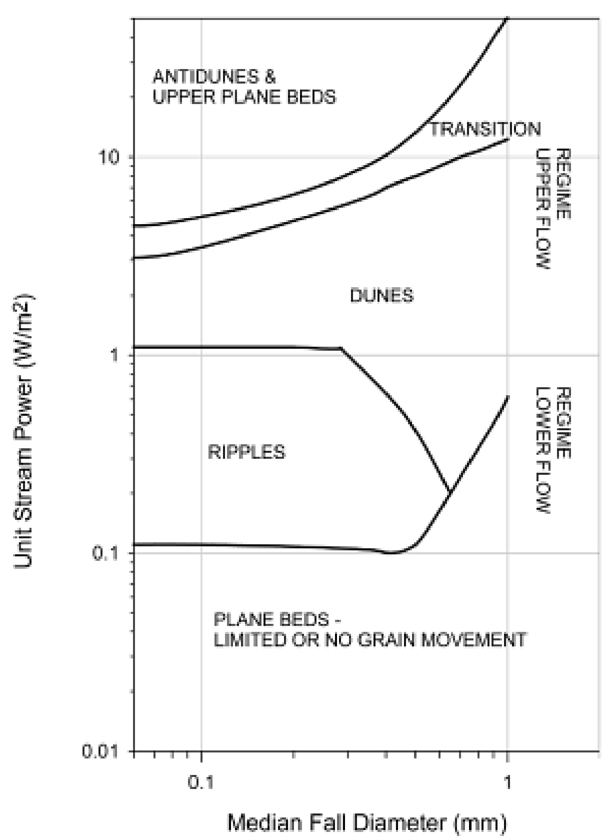


Exhibit B - Simons and Richardson (1966) relationship between grain diameter and stream power in the fluvial sedimentation process and the bedforms that are developed

These processes affect where erosion and deposition is occurring within the river system with the velocity and associated turbulence ultimately defining the grain size of any sediment being deposited in a section of river. In meandering river systems major differences in velocity are observed across the river, with the majority of the deposition or accretion occurring at the point-bar or the "curving inward" side of the meander where velocities are slower. On the outside of the meander (the "curving outward" side), higher velocities are observed with greater potential for erosion and any deposition that may be occurring dominated by coarser grained materials. The higher velocities and erosion on the outside of the meanders facilitate lateral migration of the meander bend (where banks are not engineered or otherwise configured to prevent lateral erosion and associated and associated lateral river channel migration or have been incised into bedrock) and progressive accumulation of sediments will occur on the inside of the meander. This process of accumulation of sediments on the inside of the meander is called lateral accretion (refer to Exhibit C).

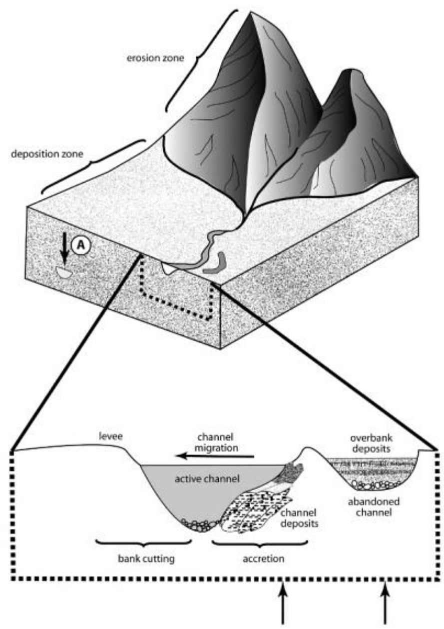


Exhibit C - Meandering River and Schematic of Lateral Accretion from Payne et al. (2008)

During flood events when the water level rises above the river channel banks, sediments (primarily silts and clays) are deposited in the adjacent flood plains; these are referred to as overbank deposits. The sediment size deposited will vary with distance from the river channel. Fine-grained sands and silts will be deposited adjacent to the river while silt and clays deposit at distal points due to the stream power dissipating rapidly away from the channel. This transition from gravel and sand at the point bar, to finer sand during proximal overbank deposition, to silt and clay during distal deposition is called vertical accretion for this fining-upward sequence. Exhibit D illustrates an idealized vertical accretion of the fining upward of the sequence.

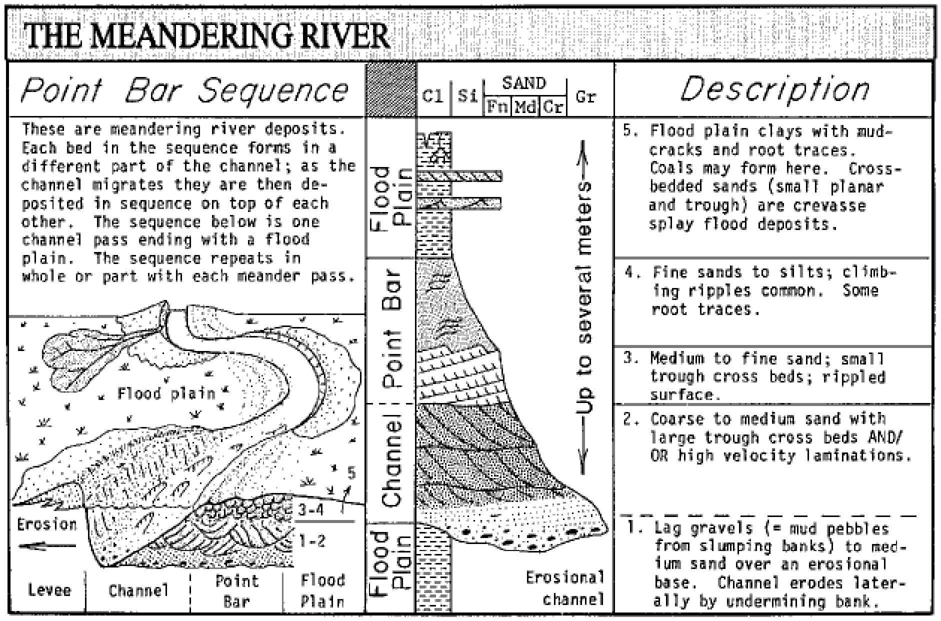


Exhibit D - Schematic for Vertical Accretion
http://www.seddepseq.co.uk/depositional_env/fluvial/meander/meander.htm

These classical patterns of erosion and deposition are observed in the fluvial environment of the Hudson River, where a regime of lower flow, which consists of plane beds and ripples, are formed in the curving inward side of the meander. As noted above high velocity sections of the Hudson River (for example adjacent to the site and downstream of Bakers Falls Dam) are dominated by riffle flow and limited deposition is expected, while in low velocity segments on the inside of very dominant river meanders and in large pools behind the dam structures, extensive deposition of fine-grained sediment are expected.

3.0 ASSESSMENT OF HUDSON RIVER HYDROLOGY AND GEOMORPHOLOGY

An extensive program of hydrologic and geomorphologic data collection and sediment quality testing has been conducted by USEPA and GE and contractors working for both parties in the Hudson River. These assessments have led to a comprehensive understanding of the hydrology and geomorphology of the river, and the sediment deposits, and this has been used by GE to refine and develop their sediment type classifications and mapping for the 40-mile stretch of River that comprises the PCB Superfund site.

It should be noted that much of the work conducted by GE built on original assessments of river geomorphology and hydrology conducted by USEPA, which incorporated available data and studies by others including the NYSDEC and the National Oceanographic and Atmospheric Administration (NOAA). The following sections provide a chronological review of sediment geomorphology assessments conducted within the Hudson River. The original assessment and validation of assessment methods was conducted by USEPA with GE undertaking subsequent assessments which refined the understanding of sediment geomorphology and contaminant distribution.

3.1 Overview of GE Assessment of Hydrology and Geomorphology

The Upper Hudson River (UHR) is freshwater and non-tidal. Downstream of Fort Edward, the river is joined by several tributaries, the largest of which are the Mohawk River, Batten Kill, Fish Creek and Hoosic River. The flow in the river is primarily controlled by several reservoirs above Glens Falls, including the Great Sacandaga Lake. The UHR has an average depth of less than 8 feet in the shoal areas and approximately18 feet in the channel, with a maximum depth of more than 45 feet. The NYSCC (NYS Canal Corp) navigation channel in the Hudson River is generally identified as being a minimum of 12 feet deep by design in the project area.

The Hudson River Superfund Site is spilt into the three sections: River Section 1 (from the former location of the Fort Edward Dam to Thompson Island Dam); River Section 2 (from Thompson Island Dam to Northumberland Dam); and River Section 3 (from Northumberland Dam to the Federal Dam at Troy). Key river features are illustrated on Figure 1.

As part of a comprehensive Sediment Sampling and Analysis Program (SSAP), the physical and chemical characteristics of river sediment were assessed by GE. The focus of the activities was to evaluate the nature and extent of PCB impacted sediment and facilitate targeted PCB mass removal. The program of works conducted over more than 10 years included infrastructure documentation, debris/obstruction surveys, select geophysical studies (e.g., magnetometer, multi-beam bathymetry, acoustic Doppler [river velocity]), geochronology studies of sediment deposition, geotechnical studies in certain areas (e.g., test borings, cone penetrometer), and collection of sediment samples. These data sets were then evaluated to define dredge areas (dredge prisms) for future sediment remediation activities.

The majority of the data was collected between 2002 through 2004 and is summarized in the 2005 *Phase 1 Dredge Area Delineation Report* and the 2005 *Supplemental Delineation Sampling Program Data Summary Report*. Subsequent data collection was performed in 2006 in areas designated for Phase 2 of the dredging/remediation operations which USEPA identified as requiring additional information. This data was reported in the 2007 Phase 2 Dredge Area Delineation Report. Sampling stations were designated within each area. The following parameters were collected as part of the 2002 through 2004 field activities:

- Mass per Unit Area (MPA) of PCBs with three or more chlorine atoms (referred to as Tri+ PCB or PCB3+);
- Surficial sediment PCB concentrations (Tri+ PCB and Total PCB);
- Depth of PCB-containing sediments;
- Sediment texture;
- Sediment stratigraphy, including location of underlying rock or gravel, when encountered;
- River bathymetry; and,
- Profile of PCB concentration (Tri+ PCB and Total PCB) and sediment type with depth.

The focus of the investigations from 2002 through 2004 was on the top 12-inches of the sediment and PCB concentrations in these materials. In addition a broad range of other chemicals of potential concern (including metals) were analyzed for and detected in sediment. These delineation reports also utilized data from previous USEPA investigations (as described below) particularly building on the remote sensing techniques developed by USEPA to determine the nature of sediment characteristics. Key information sources identified within the data collected by GE to understand the hydrology and geomorphology within the river included:

- Additional Side Scan Sonar (SSS) Surveys and other remote sensing techniques conducted along the Hudson River
- The Hydraulic flow analysis that was conducted on discrete cross sections at specific locations on the Hudson River;
- Physical characterization of sediments within the Hudson River; and,
- Hydrodynamic modelling conducted to assess the stability of sediment within the river under different flow regimes

Each of these key study components are described in the sections below.

Consistent with the approach employed by USEPA, sediment type mapping was conducted by GE using SSS acoustic methods. Sediment probing, confirmatory grain-size analysis, and visual textural classification of surficial 2-inch sediment samples at each Sediment Sampling and Analysis Program (SSAP) core was used to validate the results. The SSS acoustic results were presented in the *2003 Supplemental Field Sampling Program* document for River Sections 1 and 3 and the *2003 Side Scan Sonar Data Interpretation Report* for River Section 2. A previous survey was conducted using SSS in 1991 and 1992 but no information was available in the reports obtained for review from EPA or public sources.

The SSS surveys were performed as part of the SSAP to map the river bottom. The resolution of the data collected by GE was higher than that collected by USEPA, and was used to classify the surficial sediment into five types, as follows:

- Type I (clay, silt, fine sands): smooth, generally featureless bottom; principally composed of soft silty sediments.
- Type II (sands): smooth to mottled bottom; principally composed of semi-compact to compact sand deposits.
- Type III (coarse gravel and sand mixtures): irregular bottom; principally composed of compact gravel and cobble deposits intermixed with sand.
- Type IV (mixed sediments): smooth and irregular bottom; a varying assemblage of sediments typically associated with Types I, II, and III.
- Type V (rocky): extremely irregular bottom; principally composed of bedrock, cobbles, and/or boulders that are often overlain by a variable thickness of unconsolidated sediments.

3.1.1 1993 Geomorphological Assessment

The USEPA assessment (1997), which is described in the subsequent sections below, provided a detailed review of the findings from a 1993 report on geomorphological data by R.D. Flood of SUNY-Stony Brook that included evaluation of sonar maps, sub-bottom profiles, and sediment samples to assess the character of the Hudson River bed and the nature of the sedimentary processes.

Though the referenced R.D. Flood report was not available for review, the integrated interpretation of the sonar mosaics and other results presented in the report was reported by USEPA (1997) to show the following (direct quotes from the report are provided in italics below):

- *Analysis of the side-scan sonar 500 kHz signal and the 1984 NYSDEC sediment PCB survey indicated that the acoustic signal could effectively identify areas of fine-grained sediments and be used to predict the level of sediment PCB contamination given the strong relationship between PCB concentrations and silt/clay fractions.*
- *The pool above Bakers Falls dam is primarily underlain by exposed rocks, although some sediment is observed near the base of the present dam and near the river edge. Much of the riverbed in the region between Bakers Falls and Rogers Island dam is rocky, although some sediments are found on the riverbed. Several mounds resembling remnant deposit material are present on the riverbed towards the southern end of the remnant deposit area.*
- *South of Fort Edward, the sonar images can be quantified in terms of sediment grain size. Comparisons between sediment grain size analysis and the digital acoustic signal values, i.e., DN, of the 500 kHz sonar images suggests that, in areas where the sonar image is uniform, coarser sediments are more reflective (lighter) and finer sediments are less reflective (darker). Areas with DN less than 40 probably have mean grain diameters less than 4 phi (less than 63 μm; i.e., predominantly silts and clays), areas with DN greater than 60 probably have mean grain diameters in the sand- and gravel-size range (greater than 4 phi or 63 μm).*

- *Evaluation of the sonar images and other data suggests that sediment distribution patterns are locally complex. Basement rocks, cut away to form the Champlain Canal, are exposed in some areas while lacustrine silts and clays of glacial age are exposed in other areas. Coarser-grained sediments are often observed in the channel while finer sediments are more common in shallow water. In some areas, an irregular lineation pattern is observed on the sonar records that suggests past river-bed erosion. Downriver of these areas of irregular lineations, increased levels of wood chunks and wood chips are present in surface sediments. Sediment mounds, probably created by disposal of dredged sediment in the river, are also observed in a number of areas. Fine-grained sediment has accumulated in the lee (downriver) side of these mounds in most areas where mounds are observed.*
- *Local sediment distribution patterns depend on riverbed geometry and downriver changes in sediment sources. Rock outcrops can provide sheltered areas where fine-grained sediment accumulate or can limit bed-load transport by presenting an obstacle to bed-load movement. The corners of dredged channels, depending on average current velocity, also provide sites where sediments can accumulate. Changing morphology of the river because of islands, entering creeks, geologic structures, e.g., rocky shorelines, and man-made structures, dredge mounds, cribs, canal structures, and dams, change the cross-sectional area of the river and create areas of reduced velocity where finer sediments tend to accumulate. Some structures, especially dams, also affect upriver and downriver sedimentation and erosion patterns. Flow in the river is three-dimensional and some effects, such as the tendency for higher velocities near the outsides of river bends, even when the dredged channel is in the inside of the bend, help to control sedimentation and erosion patterns.*
- *Lacustrine silts and clays of glacial age underlie several portions of the river and also exist in portions of the watershed drained by tributaries to this section of the river. Although these deposits represent fine-grained sediments, they can be considered essentially free of PCB contamination due to their age. These deposits affect river sedimentation in several ways. Where exposed, these sediments appear to have been eroded, thereby increasing river cross-sectional area and supplying uncontaminated, fine-grained sediments to the water column. Deformed layering within these sediments is also observed. These deformed layers suggest that the stability of these sediments needs to be understood should large volumes of overlying sediments be removed.*
- *Comparisons between along-river changes in current velocity provide insights into factors that control sites of sediment accumulation. In the Thompson Island Pool, finer-grained sediments and sediments with higher total PCB inventories are more common in areas where mean velocities decrease because of increased river cross-section. In particular, sections of the river near NYSDEC Hot Spots 15 and 16 (about RM 189.4) and near Hot Spots 12, 13 and 14 (about RM 190.1) have generally lower average velocities because of increased cross-section. However, erosional patterns are also observed in both these areas, demonstrating local sediment deposition variability. Finer-grained sediments along the east side near RM 189.4 appear to be shielded by rock outcrops, while those near the center of the river at about RM 190.1 have experienced some erosion. The portion of the river near mile 189.9, where Zimmie (1985) suggests the maximum potential for long-term erosion exists, is in part rocky, and PCB concentrations appear generally low, suggesting that the potential for PCB resuspension is actually reduced rather than enhanced here.*
- *Preliminary analysis of changes in river velocity characteristics undertaken using the more detailed Phase 2 river cross-sections in the Thompson Island Pool and in the other surveyed portions of the river more clearly defines areas where the most significant concentrations of PCBs may exist and where sediments are most susceptible to erosion. Precise sites of PCB accumulation and resuspension within those sections of the river are controlled by the details of*

riverbed geometry and three-dimensional flow patterns within the river. The sonar images help to identify areas of finer-grained sediment accumulation and sites of past erosion.

- *Comparing sonar signal strength with total PCB measurements made for surface sediment samples collected in 1984 from the Thompson Island Pool suggests that the surficial PCB concentrations greater than 50 ppm are found where the 500 kHz median DN is less than 45 to 60. This corresponds to the sonar DN range for finer sediments (mean size less than 4 phi). This comparison, in conjunction with along-river changes in cross-sectional area, is used to determine the likely distribution of contaminated sediments within the region of the river surveyed.*

3.1.2 USEPA Evaluation of Sediment Characterization

USEPA conducted an evaluation of sediment characterization by acoustic techniques in their February 1997 Phase 2 Report Further Site Characterization and Analysis Volume 2C-Data Evaluation and Interpretation Report (herein called the 1997 USEPA report). The evaluation focused on an area from immediately above Bakers Falls to Lock 5 above Schuylerville (a distance of approximately 15 River Miles). As stated by USEPA, *"The primary goal of sediment characterization for this project was to provide detailed knowledge of the nature of the bed of the UHR through geophysical techniques, specifically acoustic imaging, of the river bed supplemented by limited sediment sampling. Acoustic imaging of the river bed through the use of side-scan sonar for river bottom character, high frequency echo sounding for bathymetry, and low frequency acoustic sub-bottom profiling for river bed structure, combined with limited discrete sediment sampling, provides information on river bed character and river bed sediments at a resolution not obtainable from discrete sampling alone. Integration of results of sonar, bathymetric, sub-bottom and sediment sampling studies provides new insights into sediment distribution patterns and the processes responsible for that distribution."*

3.1.3 Evaluation through Acoustic Techniques from the 1997 USEPA Report

As part of the assessment USEPA sought to *"define the current distribution of river sediment type and to correlate this information with previous sediment PCB inventory measurements completed by NYSDEC"* and "*aid in completing the feasibility study and as a general guide for the selection of low resolution coring sites."*

USEPA recognized that SSS and sub-bottom profiling techniques provided a powerful tool for characterization of sediment along large reaches of the Hudson River. Remote sensing techniques were identified as providing the ability to identify *"along the length of the area large areas of fine-grained sediments (i.e., silts and clays) where suspended matter with high affinity for PCBs was present…In addition to examining areas of potentially high PCB levels, the geophysical investigation was also intended to define those areas where PCB contamination is likely to be minimal, i.e., exposed bedrock, glacial-age deposits and coarse-grained sediment*". As described in the geochemical assessment of river sediment (upcoming EHS Support, 2015 document), the high affinity of inorganics for silt/clay and organic matter make areas of silts and clay key areas of interest in the assessment of potential metal impacts in sediment.

To support the calibration of the acoustic geophysical data, USEPA collected discrete sediment samples from a number of different locations to calibrate the acoustic data. Highlights of the Confirmatory Sampling Program included:

- *Collection of samples from 178 sites in the geophysical study areas (roughly half coring sites and half grab sampling sites), both from cross-river transects and from selected sonar targets;*

- *Collection of samples in areas of fine-grained sediments by co-located manual push coring, one core sliced into three four-inch sections horizontally for grain-size and chemical analysis, the second core used for X-radiographic analysis to determine sediment structures;*
- *Collection of grab samples in areas of coarser-grained sediments where hand coring was unsuccessful, with the entire sample retained for grain-size and chemical analysis;*
- *Geotechnical and chemical (non-PCB) analysis of a total of 333 samples (219 core slice samples and 114 grab samples, including duplicates); and*
- *Comparison of the grain-size results with the texture and density information provided by the X-radiography in order to assist interpretation of geophysical investigation results.*"

In the assessment of the relationship of sonar image data and sediment characteristics USEPA found that the remote sensing data exhibited high reliability in identifying sediment type. USEPA noted that the sonar data can be influenced by multiple variables; however, USEPA noted that "*processing of the sonar data has reduced instrumental artifacts in order to provide a sonar image that describes the riverbed in a qualitative fashion. Riverbed characteristics that may affect the sonar character include bottom type (sediment, rock outcrop, vegetation), sediment size (gravel, sand, silt, clay), small-scale roughness (ripples, lineations, rock layering or fracture pattern, mounds created by animals), sediment layering (buried but near-surface sand or gravel layers), larger discrete features (trees, large chunks of sawn wood, docks, other large debris, and shadows cast by those features), bottom slope (flat-lying, sloping away from the sonar instrument, or sloping toward the sonar instrument), and the shoreline (riprap, marsh, sediment). The effects of some of these environmental factors on the sonar image is clear. For example, when the bottom slopes towards the sonar instrument, signal strengths are enhanced; whereas when the bottom slopes away from the sonar instrument, signal strengths are reduced and there may even be large regions in shadow.*

To ascertain the potential impacts of environmental factors, discrete surficial grain size measurements were conducted on confirmation samples and 400-pixel by 400-pixel reduced images from areas corresponding to the sample were prepared to study the relationships between image digital value (DN) and sediment grain size for both the 100 kHz and 500 kHz images. According to the USEPA:

Using visual and computer analysis, 113 of the original 155 grain size analysis were classified as being in uniform areas of the sonar mosaic. This subset of grain-size analyses and DNs was analyzed by linear regression to determine possible relationships between grain-size parameters and image values (*Table 4-1 and Figures 4-3 through 4-6*). *As noted by USEPA, a "positive correlation" was used to indicate that image value increases as grain size increases. However, since grain size is measured on a phi scale (size [μm] = 2[-phi]), larger grain sizes have a smaller phi value. Thus, the slope of a correlation curve between the phi value and DN will be negative for a positive correlation between DN and grain size. The best correlation between grain size parameters and image values were found for the 50-ft diameter circles. Figure 4-3 shows the relationship between the DN for the 10- and 50-ft circles. The remainder of the grain size analysis presented here deals only with the 50-ft circle results.*

Table 4-1

Results of Linear Regression Study -- Grain Size Parameter vs Image DN[a]

Reduced 500 kHz Images

	Median Digital Number			Median Digital Number			Standard Deviation Digital number		
Grain Size Parameter[b]	Slope	Intercept	r-Squared	Slope	Intercept	r-Squared	Slope	Intercept	r-Squared
d(15)	-6.713	60.450	0.529	-6.788	61.838	0.526	-1.334	15.428	0.256
d(40)	-5.992	66.337	0.500	-6.073	67.813	0.499	-1.236	16.669	0.261
d(50)	-5.834	68.785	0.484	-5.924	70.315	0.484	-1.245	17.259	0.270
d(70)	-6.128	76.216	0.497	-6.231	77.892	0.499	-1.357	19.001	0.299
d(85)	-6.297	83.653	0.518	-6.403	85.454	0.520	-1.404	20.686	0.315
d(90)	-6.197	86.599	0.498	-6.300	88.443	0.500	-1.379	21.332	0.302
% gravel	0.387	52.458	0.148	0.391	53.757	0.147	0.059	14.042	0.042
% sand	0.404	34.207	0.271	0.412	35.107	0.274	0.109	8.617	0.241
% mud	-0.502	73.154	0.529	-0.511	74.774	0.531	-0.114	18.413	0.334
mean	-6.798	74.409	0.539	-6.896	76.010	0.539	-1.438	18.425	0.295
std. dev.	5.185	47.310	0.013	4.942	49.109	0.012	-0.301	15.278	0.001

Reduced 100 kHz Images

	Median Digital Number			Median Digital Number			Standard Deviation Digital number		
Grain Size Parameter[b]	Slope	Intercept	r-Squared	Slope	Intercept	r-Squared	Slope	Intercept	r-Squared
d(15)	-5.490	52.442	0.325	-5.387	55.219	0.310	-1.004	19.327	0.091
d(40)	-4.994	57.404	0.319	-4.901	60.090	0.304	-0.900	20.212	0.087
d(50)	-4.704	59.120	0.289	-4.617	61.775	0.275	-0.846	20.519	0.078
d(70)	-4.472	63.635	0.243	-4.381	66.180	0.231	-0.795	21.301	0.064
d(85)	-4.343	67.988	0.227	-4.251	70.430	0.215	-0.784	22.127	0.062
d(90)	-4.267	69.989	0.217	-4.175	72.379	0.205	-0.769	22.481	0.059
% gravel	0.510	43.686	0.236	0.489	46.762	0.214	0.061	18.099	0.028
% sand	0.111	43.312	0.019	0.120	45.605	0.022	0.054	15.735	0.038
% mud	-0.328	60.145	0.207	-0.325	62.900	0.202	-0.072	21.117	0.083
mean	-5.231	63.012	0.293	-5.126	65.574	0.279	-0.941	21.220	0.080
std. dev.	11.737	27.841	0.063	11.601	30.926	0.060	2.282	14.578	0.020

Notes:

a. DN= (grain size parameter) * (slope) + (intercept)

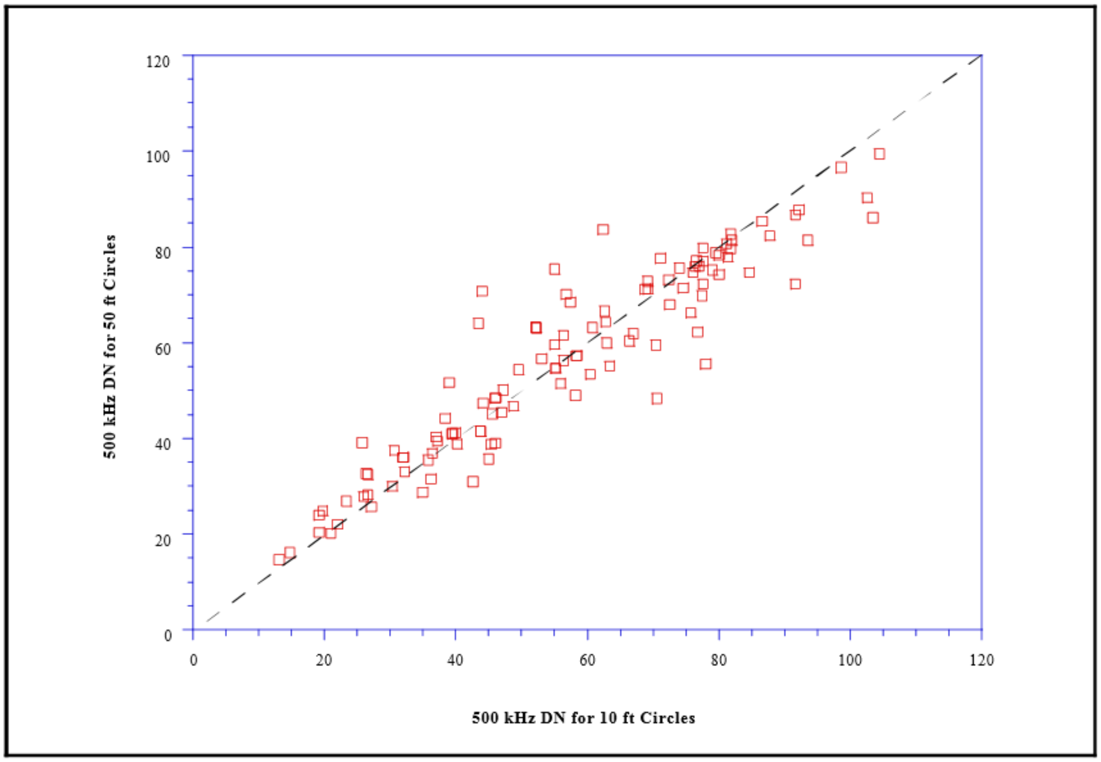
b. Correlation among the image digital number (DN) and D(15) to D(90), mean and standard deviation grain-size parameters

parameters are based on the phi scale $\left[\text{phi} = \frac{-\log(\text{diameter in mm})}{\log 2} \right]$

Source: TAMS/Gradient Database

TAMS/*Gradient*

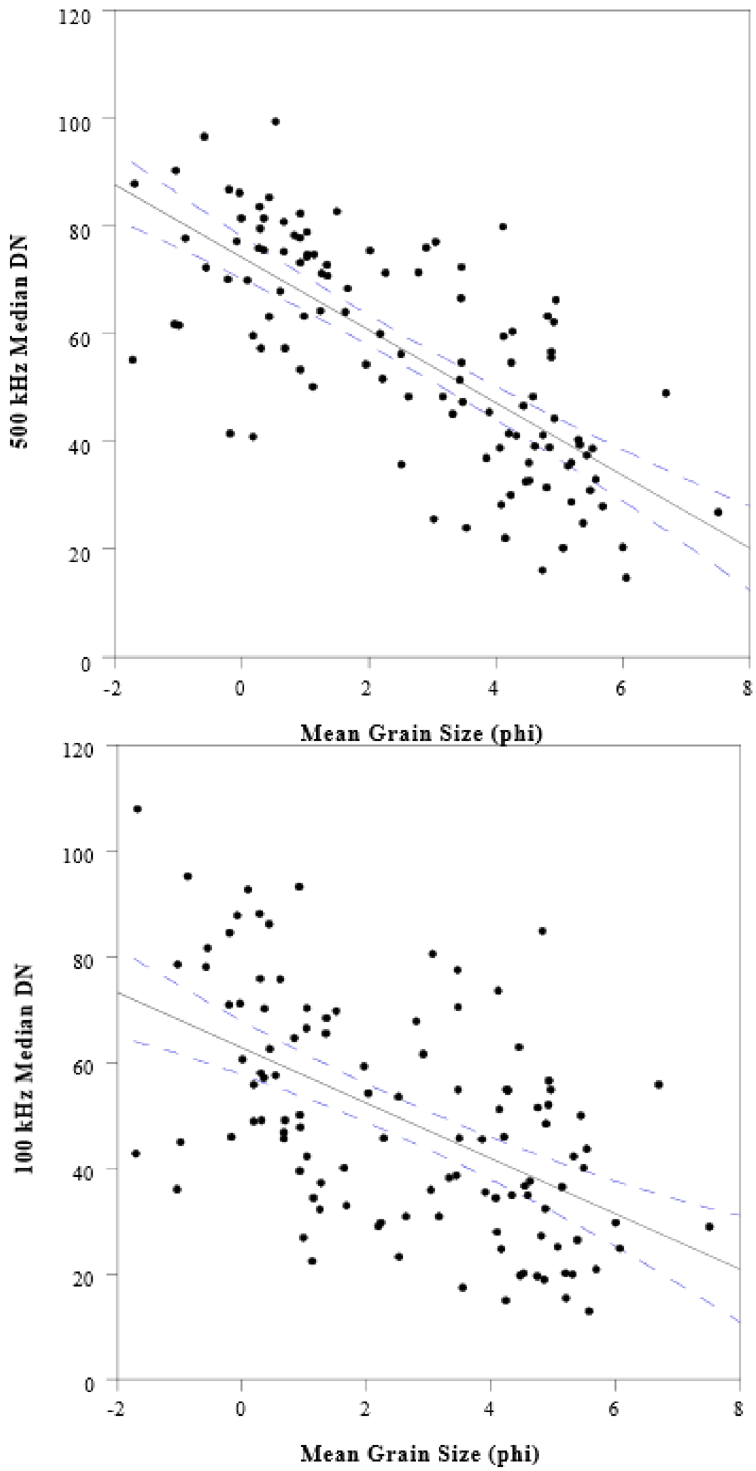
Exhibit E – Table 4-1 from USEPA 1997



Source: Phase 2 Side-Scan Sonar Images

Figure 4-3
Comparison of the DN Value for 10 ft and 50 ft Circles
at Confirmatory Sampling Sites

Exhibit F – Figure 4-3 from USEPA 1997



Note:
a. $phi = \frac{\log[\text{grain-size (mm)}]}{\log 2}$

Source: Phase 2 Side-Scan Sonar Images; TAMS/Gradient Database

Figure 4-4
Calibration Plots of DN vs. Grain-Size

Exhibit G – Figures 4-4 and 4-5 from USEPA 1997

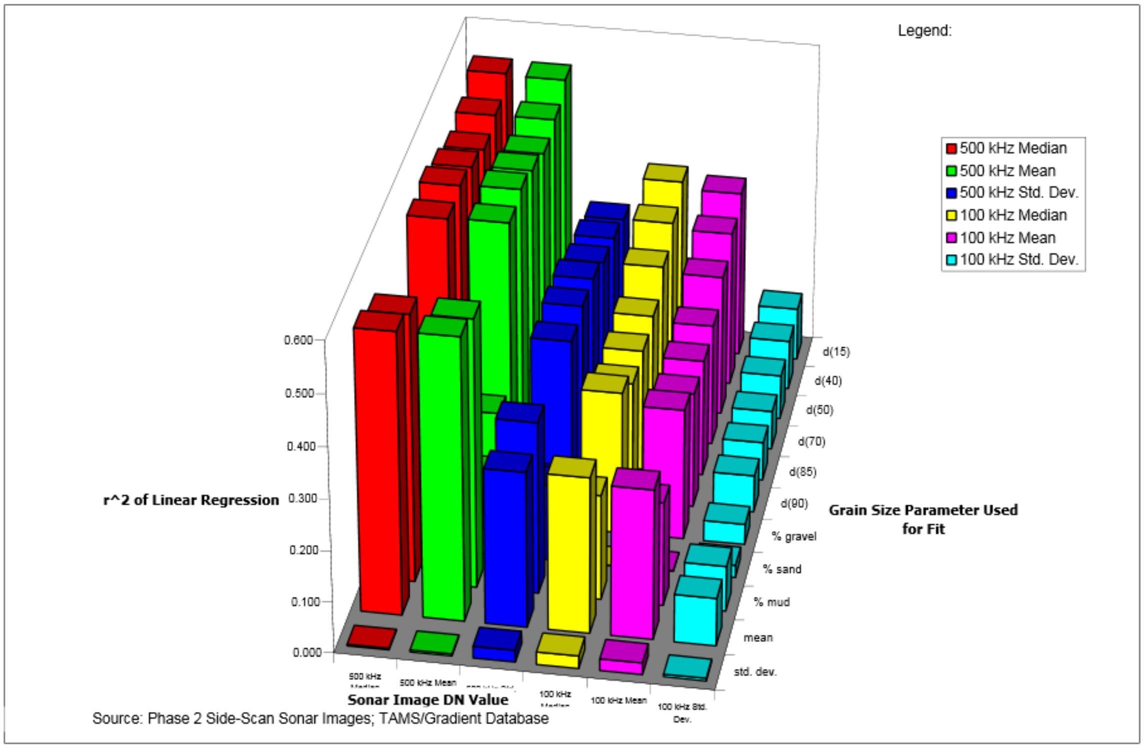


Figure 4-5
Three-Dimensional Correlation Plot of Digital Number vs Grain Size

Exhibit H – Figure 4-5 from USEPA 1997

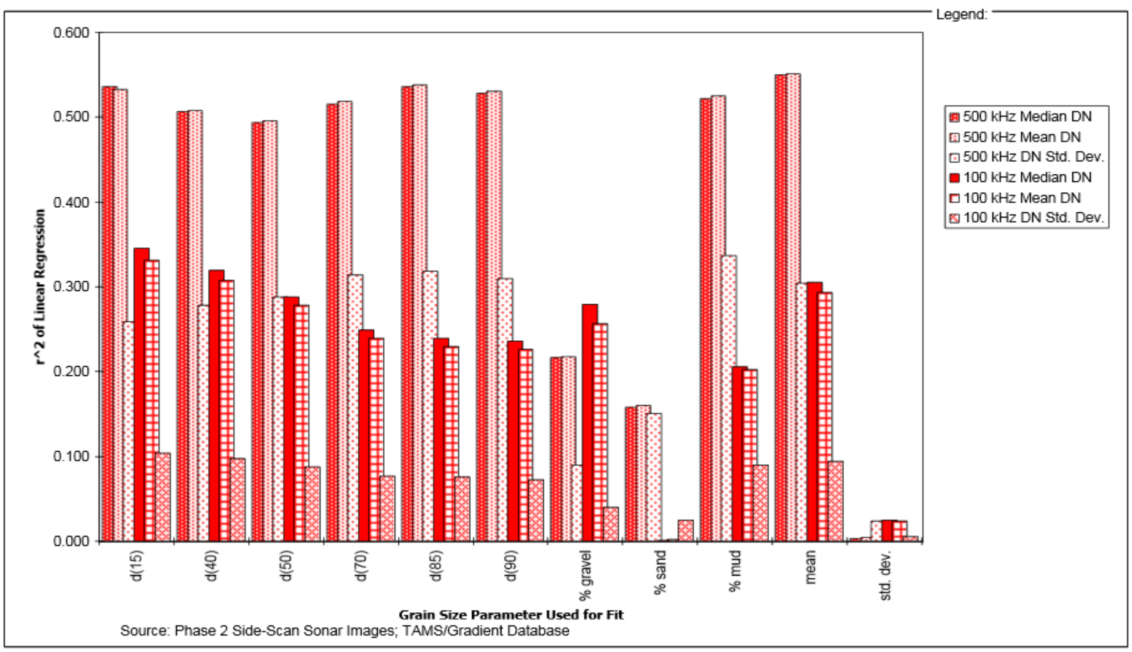
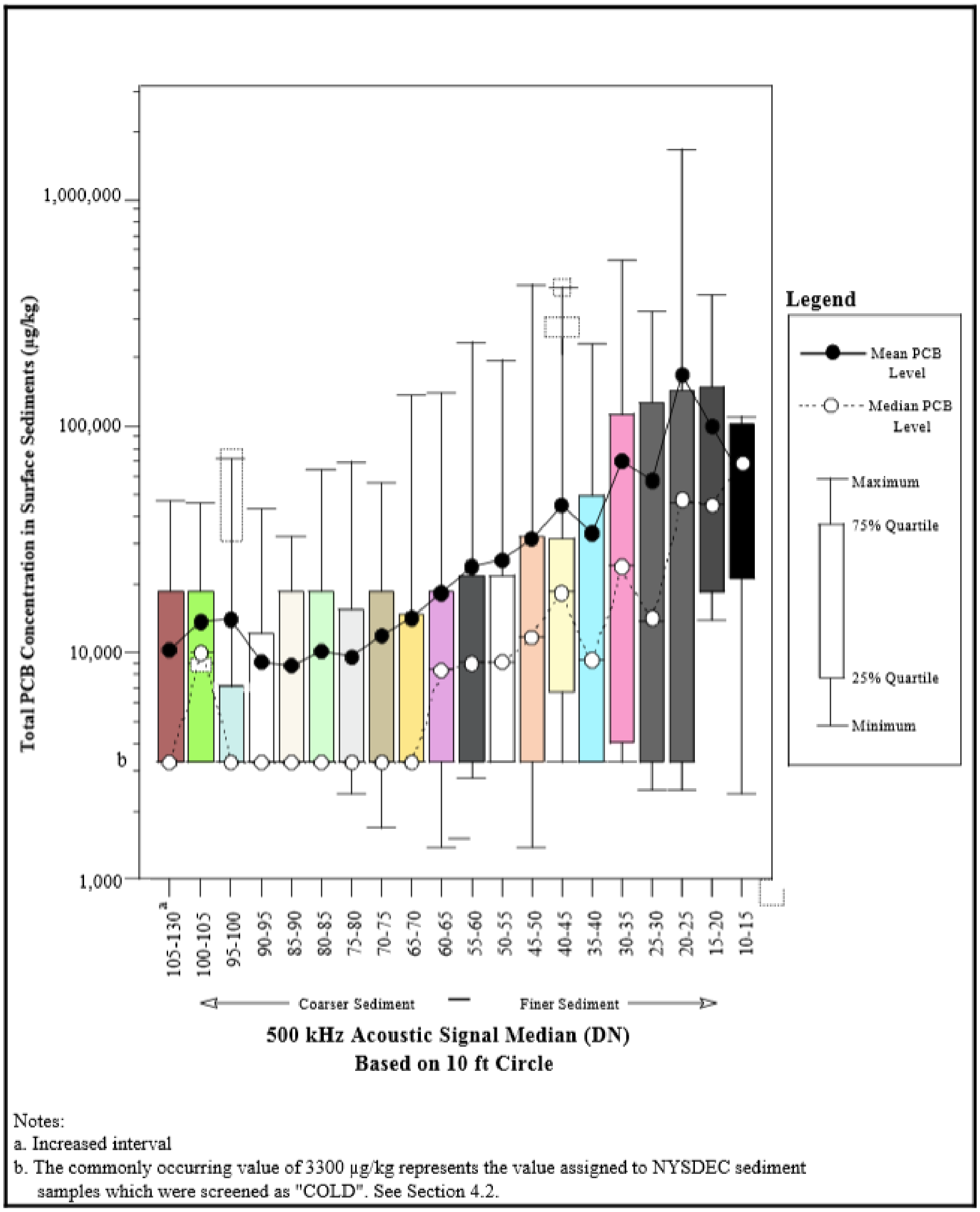


Figure 4-6

Two-Dimensional Correlation Plot of Digital Number vs Grain Size

Exhibit I – Figure 4-6 from USEPA 1997



Source: Phase 2 Side-Scan Sonar Images; Brown et al, 1988 TAMS/*Gradient*

Figure 4-7
Comparison of 500 kHz Acoustic Signal and 1984 NYSDEC
PCB Levels in Surface Sediments

Exhibit J – Figure 4-7 from USEPA 1997

USEPA noted that "t*he correlation between DN and grain size parameters was found by USEPA to be strongest for the 500 kHz median- and mean-image DNs and the mean grain size (r^2 = 0.54; Table 4-1). Similar correlations were observed for the six calculated percentiles, i.e., d(15) through d(90), and for percent mud (i.e., silt plus clay) with r2 in the range of 0.48 to 0.54 when correlated with the 500 kHz image. There was a poor correlation between image DN and percent gravel or percent sand (r^2 = 0.16 to 0.22). This is in part due to the non-linear relationship between grain size expressed as percent gravel or percent sand and the actual mean sediment grain size. For example, in a sample with 50 percent sand,* *there could also be 50 percent gravel, 50 percent mud, or 25 percent gravel plus 25 percent mud. Since each of these sediments would have a different mean grain size, one would expect a different image DN in each case, although percent sand remains constant. In general, the 500 kHz DN standard deviation image correlates less well with grain size parameters than the median or mean image DN (r2 in the range of 0.25 to 0.34), with the best correlations associated with percent mud, d(70), d(85), d(90) and mean size. This indicates that the uncertainties in the DN value are not strongly associated with the uncertainties or variability of the sediment grain size distribution.*

Based on the assessment of the correlations USEPA concluded that the most useful correlation was between the 500 kHz median image DN and mean grain size. In particular, low DN values (less than about 40) generally correspond to finer grain sizes (mean size less than 64 μm or 4 phi), while higher DN values generally correspond to coarser sediments (coarse sand, gravel). For the purpose of characterizing the sonar images, sediment type was described by USEPA as "finer" (DN less than 40), or as "coarse" or "coarser" (DN greater than 60) depending on a qualitative assessment of the DN value of the image. The terms "coarse" and "coarser" are both used where there is more than one region of distinctive high reflectivity in close proximity. Plate 4-3 shows how sediment characteristics have been assigned on the basis of the sonar mosaic for the area of NYSDEC Hot Spot 14. The areas of finer sediment shown in the plate are also areas expected to have elevated concentrations of PCBs."

It was noted by USEPA that there were possible reasons for the scatter observed in the correlation plots on Figure 4-4 (Exhibit G) including: *(1) the effects of bottom slope on image value as the bottom is not horizontal at all sample locations; (2) the sonar correction technique results in a different "calibration" for different water depths or slant ranges (3) there is variability in the sediments at a scale smaller than sonar can resolve, and not enough sediment samples have been recovered to adequately characterize the bottom at the scale of the sonar record; (4) standard grain size parameters may not be appropriate measures of bottom roughness to use for comparison to the sonar values; (5) small bubbles of gas attached to sediment particles could affect sonar reflectivity; (6) biota, e.g., shells or marsh grass, also affects sonar reflectivity in some areas; (7) in some areas a fine sediment veneer may overlie coarser sediments.* In addition to the above validation, USEPA also completed a comparison of the SSS interpretation with historical (1976 to 1978) sediment classification data collected by NYSDEC. This comparison was presented as an Appendix to the 1997 USEPA report and was titled a "*Comparison of 1976-1978 Sediment Classifications and the Side-Scan Sonar Interpretation.*" From the NYSDEC database, sediment classification data was available for 493 locations throughout the area of SSS coverage. These locations were obtained for both the Thompson Island Pool and for areas below the Thompson Island Dam.

The report concluded the following: "*Overall, the historical 1976-1978 NYSDEC grain-size distribution results appear quite consistent with the current Phase 2 side-scan sonar classifications and the Phase 2 sediment grain-size distribution results. Historical silt, fine-sand, and medium-to-coarse-sand samples all map onto the side-scan sonar classifications in a manner consistent with the low resolution core data. This result supports the contention that Hudson sediment classifications have remained relatively constant over the last 15 years for large areas of the river bottom. That is, large areas of fine-grained sediments as classified in 1976-1978 are still areas of fine-grained sediments. Similarly, large areas of coarse-grained sediments also remain as originally classified."*

3.1.4 Recent Validation of Side Scan Sonar (SSS) Data

The SSS Surveys have been conducted from 2002 through 2013 and these surveys have been periodically evaluated and confirmed using the data from sediment sampling and assessment activities as these data became available. These assessments have included the following.

2003: USEPA had concerns that the original interpretation from the SSS data may not have identified all of the fine-grained sediment deposits. Additional sediment collection and confirmatory grain-size sample were collected to confirm these findings in the 2003 *Summary of Supplemental Investigations Performed in 2003 to Address EPA Comments on the Year 1 Data Summary Report*.

This work also included probing (a steel rod was manually advanced into the sediments at each SSAP and Supplemental Delineation Sampling Program (SDSP) sampling location) to facilitate rapid sample collection. The sediments recovered were then interpreted by a geologist, using the USCS classification system, and also classified into the following "primary visual classifications": clay; silt and fine sand; medium sand, coarse sand; and gravel. This probing work "*aided in the siting of data gap cores, as wells as determination of sediment type and thickness in the vicinity of Type III and V boundaries*". Delineation by probing did not occur in areas mapped by the SSS as Type III (gravel) or Type IV (gravel), unless at least 6-inches of overlying finer sediments were present. These areas were excluded from sampling because these sediments rarely exceed the PCB threshold concentrations. GE collected 1656 sediment cores with a total of 9,620 samples visually characterized and analyzed. An additional 2,300 locations were push probed in 2002 and 2003.

Geotechnical samples were also collected during the 2003 assessments. A total of 166 sediment samples were analyzed for Atterberg Limits, 411 sediment samples were analyzed for grain size distribution, 8,099 sediment samples were analyzed for moisture content, and 425 sediment samples for specific gravity.

In 2003, sub-bottom tests were conducted in some of the areas using ground-penetrating radar to assess the nature of the deeper sediments. All this data was utilized to validate and verify the SSS data and has been integrated into the interpretation and definition of the different sediment types.

2004 and 2005: Additional probing as described above was performed to differentiate sediment Types I and II from sediment Types III and V. In the 2007 Phase 2 Dredge Analysis Report, QEA reported that the SSS was 81% correct for Types I and II sediments and 65% correct for Types III and V sediment based on the additional probing.

2006: The *2007 Phase 2 Supplemental Engineering Data Collection Data Summary Report* (SEDC) summarized the collection of data by the multi-beam bathymetric surveys and additional geotechnical data in both the Phase 2 areas and in the Northern Thompson Island Pool (NTIP) area. These geotechnical data included Standard Penetration Testing (SPT), split-spoon sampling, Cone Penetrometer Testing (CPT), as well as the same suite of geotechnical laboratory parameters that was collected in 2003. Using the different drilling techniques, geotechnical laboratory parameters were collected in 17 borings and data from 43 forty-foot deep SPT/CPT borings were collected. "N-values" that represented SPT resistances were also recorded from the number of blows in a particular resistive layer.

2010: The *2011 Phase 2 Supplemental Engineering Data Collection Data Summary Report* summarized the collection of additional sediment cores and acquisition of elevation data for the top of the sediment by conventional surveying. This data was used to "*refine the Phase 2 dredge prisms and to recommend appropriate coring techniques for the remainder of the dredging program.*" The investigation focused on data gaps while utilizing the Alternative Sampling Methods Pilot Test (ASMPT) to fill in some of those data gaps in a subset of Certification Units (CUs) of River Section 1 (CUs 09 to 16 and 19 to 30). These data gaps were targeted for resampling due to missing data or the analytical data did not identify the Depth of Contamination (DoC). Like the previous investigations, visual grain size comparison was utilized to classify the sediment type. The geotechnical laboratory parameters collected were 101 samples for bulk density and moisture content. The collection of the sediment cores were split into three groups.

There were 113 locations selected that were already identified with "*high confidence*" of an "*accurate DoC for dredge delineation*." In contrast, there was 124 locations selected that were of "low confidence" because the vertical limit of Total PCB concentrations above1 mg/kg was not identified. The last group of 138 locations were for missing data at locations that a particular bathymetric feature like a shoal, slope, or channel existed that lacked SSAP cores or areas of ½ acre or more with no previous SSAP cores acquired.

Ten locations were selected as representative of conditions that are challenging to core for the ASMPT. The ASMPT utilized the four following sampling techniques that are described further in the *2011 Phase 2 Supplemental Engineering Data Collection Data Summary Report* : Sonic Drilling; Vibracoring (Hudson River method); Vibracoring with core catchers; and, Vibracoring with core catchers (Fox River method). The sonic drilling method was the only technology to have >80% recovery at all 10 "*challenging to core*" locations.

2011: The *2012 Phase 2 Supplemental Engineering Data Collection Data Summary Report* summarized the "*collection of additional sediment cores to fill in data gaps affecting the design of dredge prisms for certain areas targeted for dredging in 2012*." The areas sampled were in River Sections 1 and 2 (see Section 3.1) for CUs 31 through 70. The focus of the investigation was similar to the 2010 investigation with sampling of "low confidence" locations and also resampling of 20% of the "high confidence" cores. An additional goal of the sampling was to achieve a sampling density of 80 feet on center in all areas proposed for dredging. Sediment probing of the river bed was also conducted at each sampling location during this phase of investigations. The investigation collected soil cores at 115 locations for the "high confidence" sampling, 297 locations for the "low confidence" sampling, and 165 locations for "missing data" locations. Sampling around the West Griffin Island Area (WGIA) was hampered by both low water levels and high water levels. Also, no geotechnical laboratory parameters were collected at the WGIA however sediment samples were still visually characterized.

2012: The *2012 Phase 2 Supplemental Engineering Data Collection Data Summary Report* summarized the "*collection of additional sediment cores to fill in data gaps affecting the design of dredge prisms for certain areas targeted for dredging in 2013*." The areas sampled were in River Sections 2 and 3 for CUs 71 through 100. The focus was the same as in 2010 and 2011 with the low and high confidence sampling approach. Sediment probing of the river bed was also conducted during this investigation for sampling locations that were located near the boundary between two sediment types as defined previously by the SSS. The investigation collected soil cores at 24 locations for the "high confidence" sampling, 313 locations for the "low confidence" sampling, and 201 locations for "missing data" locations. No geotechnical laboratory parameters were collected.

Also in 2012, GE submitted a *Deposition Study Report* evaluating if there was measureable impact of PCB on the surface of the sediments rom the pre-remedy sampling to 2011 for River Section 1. They concluded that overall the PCB concentrations on the surface have been decreasing over time for this section of the river. At the time, USEPA was planning for a similar study for River Sections 2 and 3 to be conducted.

3.2 Bathymetric Surveys/River Hydraulics

To support the development of dredging plans, GE collected riverbed elevation data through bathymetric surveys. The bathymetric surveys tried to identify steep slopes, shoals, and the channel in the river. GE determined that "*sediment and PCB accumulation is likely to vary among these different physical conditions and their delineation can guide the location of dredge boundaries in a manner similar to that of the sediment type boundaries*." This data was also used as boundaries for the individual 80 foot or 160 foot grids used for the dredging because the edge of the point bar deposits were identified using this data.

The original bathymetric surveys were collected around the NTIP and East Griffin Island Area (EGIA) in 2001. These transects were collected every 100 feet and contoured at 1–foot intervals. This data also was used as an indicator of the location of the current navigational channel.

Single- beam bathymetry surveys of the Phase 2 areas were conducted in 2001, 2003, 2004, 2005, 2006, and 2007. The data that was collected in 2001 and 2003 were reprocessed. Multi-beam data was collected in 2005.Data from River Section 3 from 2006 and 2007 was not reprocessed.

Multi-beam bathymetry survey was collected in the winter 2006 for the area between Snook Kill (NTIP) to the Thompson Island Dam "*to obtain the river bed elevation data necessary for completing the dredging prism.*" River velocity data was also collected on three separate occasions during the summer of 2006 at seven transects between River Mile 178 (south of Schuylerville) and River Mile 158 (south of Lock 1) under various flow conditions when comparing to long temporal record for the USGS gauging station at Fort Edward. These velocity measurements used an Acoustic Doppler Current Profiler (ADCP) for measurement of velocity and utilized bathymetric cross-sectional data to allow for estimation of flow.

Multi-beam bathymetric studies were also completed for CUs 67 to 70 in 2006 and CU71 to CU78 in 2011. This data was collected to supplement the single beam studies and are summarized in the 2013 *Phase 2 Final Design Report for 2013*. The report also included a calculation of the velocities 100-year flow event in the grid cells of the hydrodynamic model developed for design of the isolation caps. They found that the vast majority of the grid cells had a velocity ranged between 0 and 5 feet per second (fps). Only a small portion of the river had river velocities greater than 5 fps within the water column.

GE conducted additional bathymetry surveys in 2012 and 2013 in Reach 3 (CU 85 to CU 96) to "*support the development of the design, update, volume calculations, and verify the location of the delineated shoreline.*" These results were reported in the June 2014 *Phase 2 Final Design Report for CU85 through CU96* report. This multi-beam bathymetric survey supplemented the 2003, 2004, and 2006 single-beam data set. The report included a calculation of the velocities for a 100-year flow event in the grid cells of the hydrodynamic model for design of the isolation caps. Similarly as described above for CUs 67 to 70, they found that the vast majority of the grid cells had a velocity ranged between 0 and 5 fps. Only a small portion of the river had river velocities greater than 5 fps.

As noted above, a number of multibeam bathymetric studies were conducted to assess the depth of sediment and flow conditions within the river. These studies indicated that the majority of flow within the river was less than 5 fps under the conditions assessed. In the 2007 *Phase 2 Supplemental Engineering Data Collection Data Summary Report*, seven transects were performed between the NTIP to the Thompson Island Dam (refer figures in Attachment C for locations). GE's contractor, Ocean Survey's Inc., conducted both multi-beam bathymetry survey and acoustic velocity measurements at three different river conditions ("low-flow" in August 2006, "moderate-flow" in July 2006, and "high flow" in July 2006). The range of velocity measurements reported are provided in the table below (Exhibit K) using units of centimeters per second (cm/s) for comparison with the Hjulstrom-Sundborg Diagram).

Transect Number	Low Flow (Min-Max) (cm/sec)	Moderate Flow (Min-Max) (cm/sec)	High Flow (Min-Max) (cm/sec)
1	2.4-16.7	14.6-42.5	9.9-65.6
2	2.9-12.8	2.1-35.4	4.8-50.8
3	0.8-15.4	4.5-37.6	5.7-58.3
4	1.3-33.1	18.4-59.4	20.6-85.7
5	3.8-30.1	10-51.6	10.4-73.3
6	5-12.7	12.1-29.7	26.4-43.5
7	4-35.1	2.7-59.5	5.2-83.9

Exhibit K – Summary of 2006 Multi-beam Survey Acoustic Velocity Measurements (Arcadis, BBL 2007)

Consistent with the other bathymetry surveys, river velocities were less than 5 fps (150 cm/s) with maximum velocities less than 1.2 fps, 2 fps and 3.5 fps for low, moderate and high flow respectively. Consistent with the principles described above, the highest velocities were associated with the deepest portion of the river at the navigation channel. The lowest flow velocity was located closer to the shore.

In the *Phase 1 Intermediate Design Report* Attachment E, QEA presented their Dredge Resuspension Model which estimated river velocity in sections of the river associated with the measured flow rates at the USGS stream gauge at Fort Edwards. Exhibit L below presents the associated estimated flow rates for varying high-flow event return periods (flood-events) and the modeled average velocity.

Table E-3-2. Average TIP velocity for various high-flow conditions.

High-Flow Event Return Period (years)	Flow Rate (cfs)	Average Velocity (m/s)
2	23,000	0.71
5	30,000	0.86
10	34,500	0.95
20	38,000	1.01
50	44,000	1.11
100	47,300	1.17

Exhibit L – NTIP velocity data (QEA, 2007)

EHS Support utilized these velocities to ascertain the relationship of the river velocities and the depositional scheme. Exhibit M shows the lowest flow's velocity recorded by the gauging station from 2007 to 2015, the average flow's velocity from 2007 to 2015, QEA's modeled 2-year flood event river velocity, and QEA's modeled 10-year flood event river velocity with the Hjulstrom-Sundborg Diagram. As a point of reference the maximum velocities measured in a cross section of the river for low, medium and high flow events above are 0.36 m/s, 0.60 m/s and 0.93 m/s. Lower velocities were also recorded in these cross sections.

In concurrence with GE's conceptual model for the deposition and further discussed in documents like the *Phase 1 Intermediate Design Report*, erosion only occurs during flood events. Erosion can occur at the 2-year flood event for fine-grained sediments like clay and silts; however, it takes a 10-year flood event for the erosion of more coarse-grain sediments like sand and gravel. For average flow, there is predominately deposition of all the sediments with some minor transport of the ultra-fine sediments entrained in the water column, but no erosion of the bottom sediments.

Consistent with the hydraulic and fluvial geomorphology principles described above, velocities along and across the river bed will vary in response to variability in grade, water depth and the flow mechanics of meandering rivers. Greater velocities and potential erosion will occur on the outside of the meanders and in sections with steeper grades than reflected in these calculations. However the calculations could still be conservative with the resistance of the river bed resulting in peak velocities higher in the water column and major retardation of flow near the basal contact of the river.

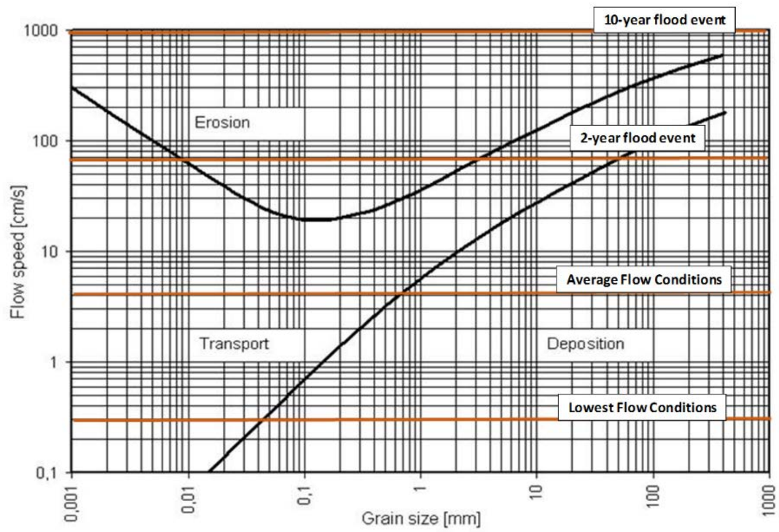


Exhibit M - Hjulstrom-Sundborg Diagram with Low, Average and modeled (2-year and 10-year flood) Velocities in Hudson River from the 2006 Acoustic Velocity Measurements (Arcadis, BBL 2007)

In reviewing GE's conceptual model and the river velocity data from the *Phase 1 Intermediate Design Report*, the erosion of sediments only has the probability to occur during flood events at a 2-year frequency for very fine-grained sediments to a 10-year frequency for coarser-grained sediments. The river bottom except during a major flood event has a very low probability of any erosion occurring of the sediments.

4.0 ASSESSMENT OF THE DISTRIBUTION OF FINE GRAINED SEDIMENTS

The February 1997 *Phase 2 Report Further Site Characterization and Analysis Volume 2C-Data Evaluation and Interpretation Report* discussed that the majority of the river bottom in the study area consists of fine sand that corresponds with SSS Types III and IV. The report also concluded that the sediments generally exhibit long-term stability. As mentioned in the 1997 USEPA report, the area between Glens Falls and north of Thompson Island is at a high river gradient and the bottom is predominately bedrock with sporadic sediments. The maps presented in the report show that the SSS Type I and II sediments are predominately associated with the inside of meanders in the river, in point bar deposits and where the water has been backed up by a dam or obstruction in the river.

Using the data collected by USEPA and higher resolution data collected by GE the SSS data has been refined and validated and maps of the sediment type in the study area are plotted and provided as Attachment A. These figures illustrate the distribution of the five types of surficial sediment identified by both the myriad of coring programs and the sonar collection.

The maps show a complex river system which is aligned with the hydrological principles described above with areas of fine grained materials (Type I and II sediments) identified in low velocity areas including ponded areas around dam and lock structures unless they are dredged regularly, the inside of stream meanders, immediately adjacent to the river bank and on the downstream side of point bars. This pattern is consistently observed throughout all river sections but has been modified by navigational dredging activities, which in many cases extended close to shore or dredged into underlying native materials.

The logical distribution of different sediment types as identified by SSS (and associated validation) within sections of the river supports the robustness of the SSS as a reliable method for characterizing sediment types. The distribution of the SSS sediment types are found where classic river bed geomorphology conceptual site models for meandering rivers are expected.

Further support for the reliability of the SSS data for identifying surficial sediment type is evidenced by assessment of the velocity data contained within the 2007 *Phase 2 Supplemental Engineering Data Collection Data Summary Report* (refer Exhibits K through M) and Bathymetric profiles (refer Attachment C), these assessment consisted of the collection velocity and bathymetric data at each cross section relative to sediment types observed was completed. The cross sections with the highest minimum and maximum velocities were cross sections 4, 5 and 7. In these cross sections, a greater proportion of coarse-grained Type III and V sediment was observed relative to the upstream cross sections 1 and 2 where Type I and Type II sediments dominated. Key observations in the area of these cross sections that support the robustness of the SSS data in characterizing the physical attributes of sediment include:

1. The detection of a coarser grained (Type III sediment) point bar on the upstream inside of the meander in the area of Cross Section 2. This point bar structure is consistent with the hydrological principles described earlier.
2. The absence of Type I sediment adjacent to Green Island in Cross Section 3 and the presence of large proportions of Type V sediment where flow is constricted and velocities are likely higher. In addition, Type I and II sediments deposition is observed downstream of Green Island where the river is wider and velocities are lower.
3. In cross section 4 where the river widens and deposition of Type III sediments is observed while upstream in faster flow sections this deposition is not observed.

4.1 Physical Testing of Sediment Characteristics

As part of the assessment activities conducted by GE physical testing of sediment samples was conducted. This testing included % fines analysis (silts and clays), % clay, and fraction of organic carbon (foc). As an additional validation of SSS data, EHS Support mapped the locations for each sample where physical testing data was available and assessed the attributes of the sediment relative to the sediment type indicated by SSS. It should be noted that in a number of locations, either at the edges of the river or on river banks, no SSS data was available. For data sets at these locations a zero was assigned for SSS type. For each sediment type, the number of samples and frequency of samples with %fines within the available data set are summarized in Exhibit N.

SSS Type	Number of Samples with % Fines	% of Samples with % Fines
Type I	1484	60.3%
Type II	295	12.0%
Type III	34	1.4%
Type IV	469	19.1%
Type V	6	0.2%
Unknown (Type 0)	171	7.0%
Total	2459	

Exhibit N – Frequency of % Fines in Sediment Data Set

Consistent with the anticipated properties of the different sediment types, higher percentages of fines, clays and organic carbon are observed in the Type I sediments relative to that observed for other sediment types. The distribution of these properties in the various sediment types are illustrated in the box and whisker plots presented as Exhibits O through Q below.

Type V sediments are not included in the plots as the available data set contained only six samples for Type V (rocky) sediment. The limited number of samples likely reflects the nature of the material and limited sediment present for sampling. The six samples show significant variability for % fines and % clays (7% to 98%), and likely reflect isolated silt and clay deposition observed within rocky outcrops. Given the limited sample set and nature of the Type V sediments (rock), the mean from the six samples probably does not represent the mean of the total population for Type V sediments; the population mean is likely much smaller.

As demonstrated in the box and whisper plots the Type I (clay, silt and fine sands) exhibit the highest mean (bold line) and highest lower quartile value (bottom of box) for fine percentage, clay percentage and organic carbon content compared to all other sediment types. The Type I sediments also exhibit the highest upper quartile values for fraction of organic carbon.

These results indicate that the SSS reliably identifies the areas of highest silt, clay and organic carbon content where organics and inorganics are likely to be preferentially distributed. Further the box and whisker plots present a clear indication of the correlations between fines content and clay and organic carbon fractions.

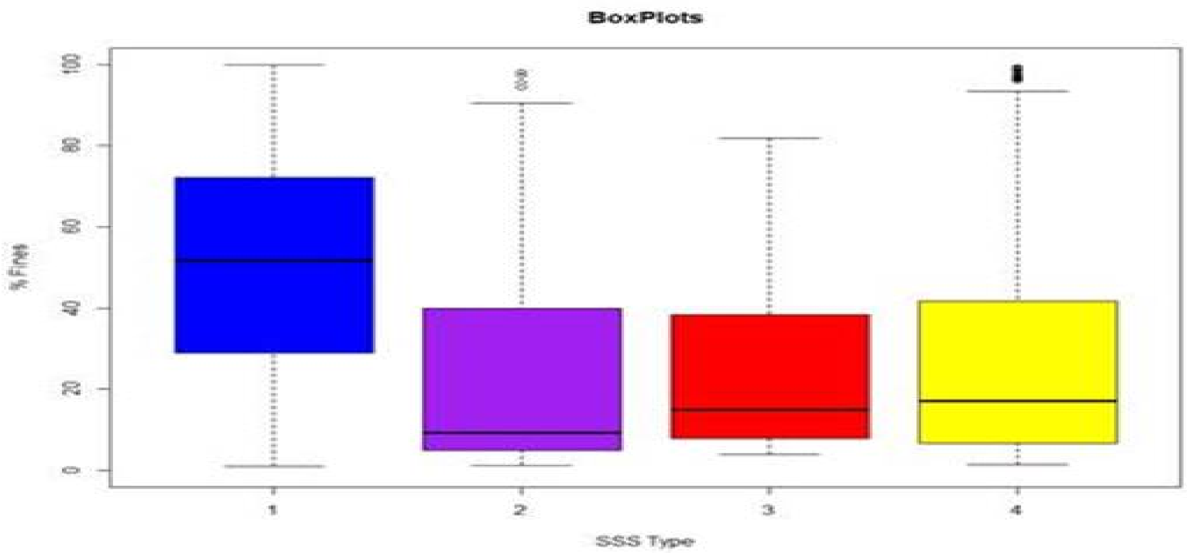


Exhibit O - Percent Fines in SSS Sediment Types

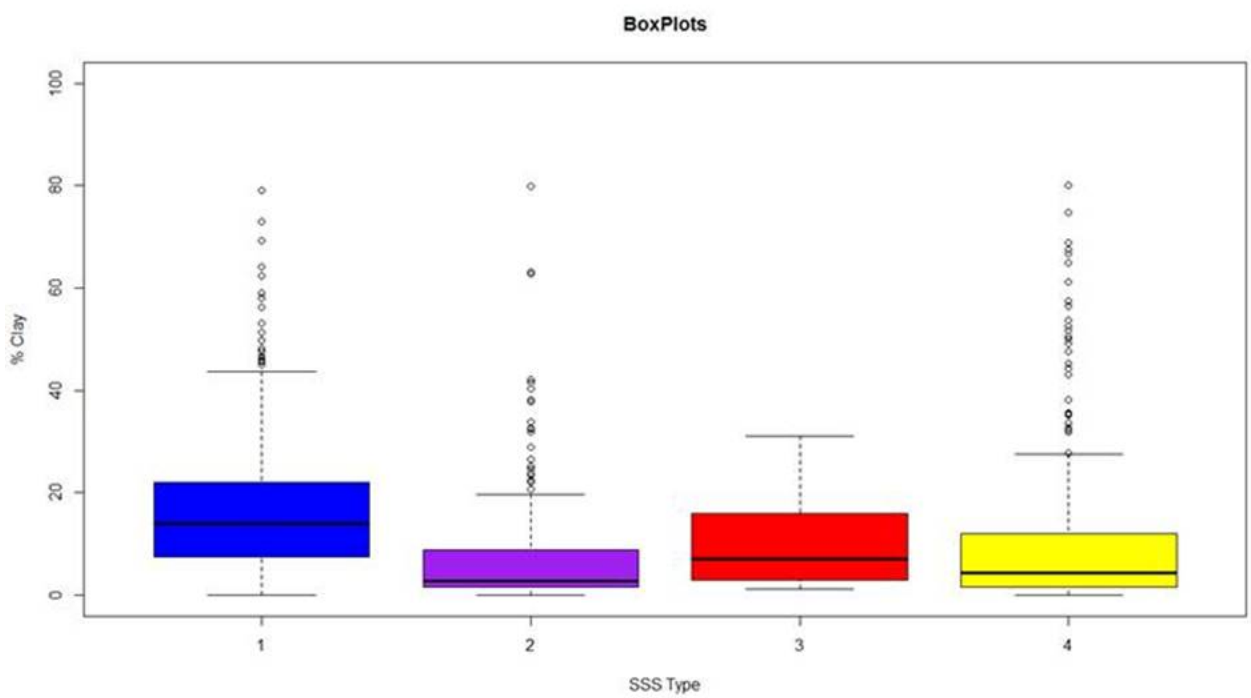


Exhibit P - Percent Clay in SSS Sediment Types

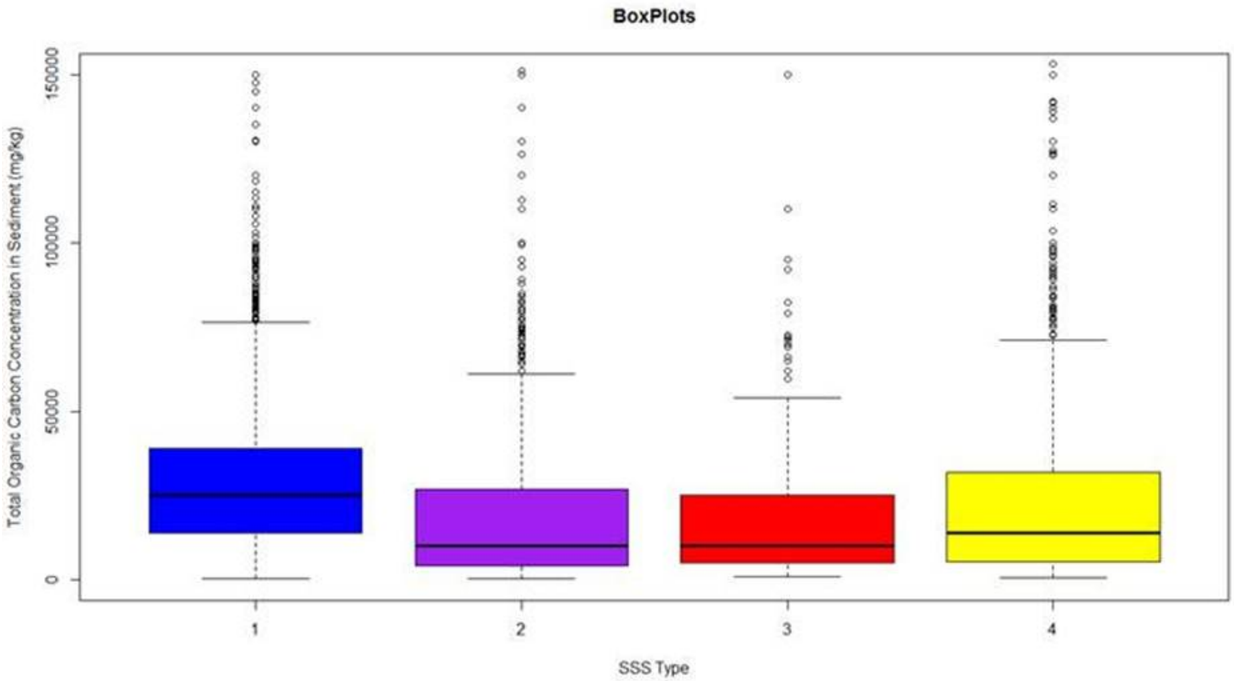


Exhibit Q - Total Organic Carbon in SSS Sediment Types

5.0 DREDGED AREAS IN THE RIVER STUDY AREA

The hydraulics and geomorphology of the Hudson River has been extensively modified by dredging and capping activities. These activities have included both routine navigation dredging as well as the work completed as part of the PCB Superfund project. GE completed an extensive program of dredging and capping works that extended downstream from Bakers Falls Dam (mile marker 197) to mile marker 180 below the Northumberland Dam/Lock 5 and further downstream. The majority of the GE dredging activities to date targeted Type I and II sediment areas but have in many areas involved bank to bank dredging of the Hudson River. Post dredging backfill and capping has also been completed in the immediate area downstream of Bakers Falls Dam and downstream of the former Fort Edwards Dam.

Navigation dredging within the Hudson River has been extensive and has generally been focused in and around locks and the navigation channels. An assessment of historical dredging activities (EHS Support 2015a) provides a detailed chronology of these dredging activities with millions of cubic yards of sediment removed from the river and placed in land based consolidation units. In addition to these activities the removal of the former Fort Edwards Dam (in 1973) saw a major reduction in river stage with exposed areas (remnant deposits) of PCB impacted sediment identified. In combination of dredging (remnant SSS type deposit 1 which was eroded and migrated downstream into the lock structures that are regularly dredged), the majority of remnant deposits (remnant SSS type deposits 2 through 5) were capped in place using a combination of geosynthetic clay liner, sand and fill, and rip rap stabilization systems (USEPA 2012). This resulted in some modification to the flow regime within the river that either slowed the velocity of the river by the dredging by increasing the cross-sectional area or made the river bottom surface less resistible to scouring during flood events.

The selected remedy for the remainder of the River is dredging and backfilling/capping pursuant to work plans and design documents developed by GE and approved by USEPA; implementation of this remedy is ongoing. The areas requiring sediments removal were designated as CUs. Phase 1 of the dredging works commenced in 2009 and focused in CUs surrounding Rogers Island. Following peer review of the Phase 1 work, supplemental assessments and final design plans for Phases 2 and 3 continued with dredging and capping works successively being implemented over the remainder of the PCB Superfund site.

Pursuant to the USEPA approved plans, three types of backfill and two types of caps were designed. The type of backfill to be placed was selected based on the surface water velocity regime for the given portion of River:

- Type I backfill (medium sand) is designed for placement in low velocity portions of the river (flow velocities <1.5 fps for 2-yr flood event).
- Type II backfill (gravel) is designed for areas of the river with moderate to high velocities (flow velocities >1.5 fps for 2-yr flood event). Type II was planned for all locations in the navigation channel - areas of the navigation channel dredged to depths of 15 feet or greater will include Type II backfill. Placement of backfill of any type will not occur in the navigation channel unless the post-dredge water depth is 15 feet or more.
- Type III backfill (medium sand amended with organics) is targeted for low velocity areas where planting or recolonization of aquatic vegetation would occur. Type III backfill comprises a combination of Type I backfill and topsoil resulting in a pre-placement TOC content of 2%.

After backfilling, a habitat replacement and reconstruction program was implemented comprising a combination of natural re-colonization and planting as specified by project requirements.

Where cap materials in addition to backfill would be placed, several design options were developed with the type of cap selected based on the PCB concentrations that remain in the sediment after dredging and the surface water velocities in that portion of the river. The cap designs developed are:

- “Type A” (isolation) caps designed for situations where the average Tri+ PCB concentration after dredging is less than or equal to 6 mg/kg and capping is necessary. Two Type A cap designs were developed, one for low velocity areas (below 1.5 fps) and one for areas with moderate to high flow velocities.(1.5 fps or greater based on a 10-year flow event).
- “Type B” (isolation) cap designed to be placed where the average Tri+ PCB concentration exceeds 6 mg/kg after dredging and GE and EPA have agreed that additional dredging is not required. Three options for Type B cap design were developed, one each for low, moderate, and high velocity areas.

Review of the certification documents (Forms 1 and 2 reports, including record drawings and data obtained from USEPA) show that a Type I and II sediments are approximately 50% of the river bottom from Fort Edwards to the Thompson Island Dam but 11% of the total area have been subject to dredging and backfilling/capping activities as part of the GE Hudson River Superfund project.

Areas backfilled and where additional cap materials were placed (cap boundaries) are shown on the SSS figures in Attachment A.

6.0 SUMMARY OF DATA REVIEW AND EVALUATION

A large volume of assessments have been conducted in the Hudson River by USEPA (which incorporated data collected by/on their behalf as well as data collected by other parties including the NYSDEC) and by GE to assess the hydrology and geomorphology of the Hudson River. The assessments were completed to enable assessment of fate and transport of chemical constituents (primarily PCBs) in the River and to support design of remedial dredging and restoration works completed by GE for the PCB Superfund project.

Based on review of the available information from these studies, and independent mapping of electronic study data obtained from USEPA's PCB Superfund database for verification and validation, EHS Support has found the following.

- Multiple assessments have been conducted to evaluate the geomorphology and hydrology of the Hudson River in the area downstream of the former Ciba-Geigy site. These data provide information that support assessment of river conditions and metals fate and transport in the river.
- The SSS data was collected by both the USEPA and GE on 80-foot grids to provide high spatial coverage of the areas for the river bottom between the Baker's Falls Dam to Troy, New York. USEPA also compared 1970s SSS data collected by the NYSDEC to the data collected by the USEPA to verify that the sediments are stable except during very low-frequency flood events. The SSS data for the Hudson River has undergone extensive and robust validation and verification by USEPA and GE, and was determined by USEPA to reliably represent sediment and flow conditions in the River.
- The SSS data is consistent with classical hydrological principles, and distribution of sediments/sediment type classifications assigned based on the SSS data is consistent with river conditions of flow, bathymetry/geomorphology, and results of confirmatory sampling.
- GE will be collecting additional data for assessments with their ongoing dredging and capping remedial activities so additional sections of the river will be impacted.
- Validation of the data using sediment sampling data indicates that consistent with the descriptor Type I sediments have higher fractions of fines, clay and organic carbon than other sediment types in the river. USEPA and GE datasets confirm association of metals and PCBs with the fine-grained sediments. The majority of Type I sediments between mile markers 197 and 180 have been subjected to dredging activities either as part of GE's remediation activities or navigation dredging. In addition large sections of the river have been backfilled and capped (refer Appendix A).
- In lower sections of the river (below mile marker 188) some areas sediments have not been dredged and backfilled/capped and considering the stability of sediment within the Hudson River the historic SSS data is considered representative of current sediment type distributions. On this basis, it is recommended that this data set be used to focus future investigation and fate and transport assessments outside of the already dredged and caped areas.
- On the basis of the extent of dredging and capping activities, the sediment type distributions within areas of remediation and navigation dredging activities are highly modified from the original sediment deposition. However in sections not affected by these remedial dredging and capping activities (and considering USEPAs and GE's finding that the sediment is relatively stable) this historical data provides with sufficient confidence in where fine-grained deposits formed and where they currently remain with the higher probability of metal accumulation

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FIGURES

FIGURE 1 - HUDSON RIVER FEATURES

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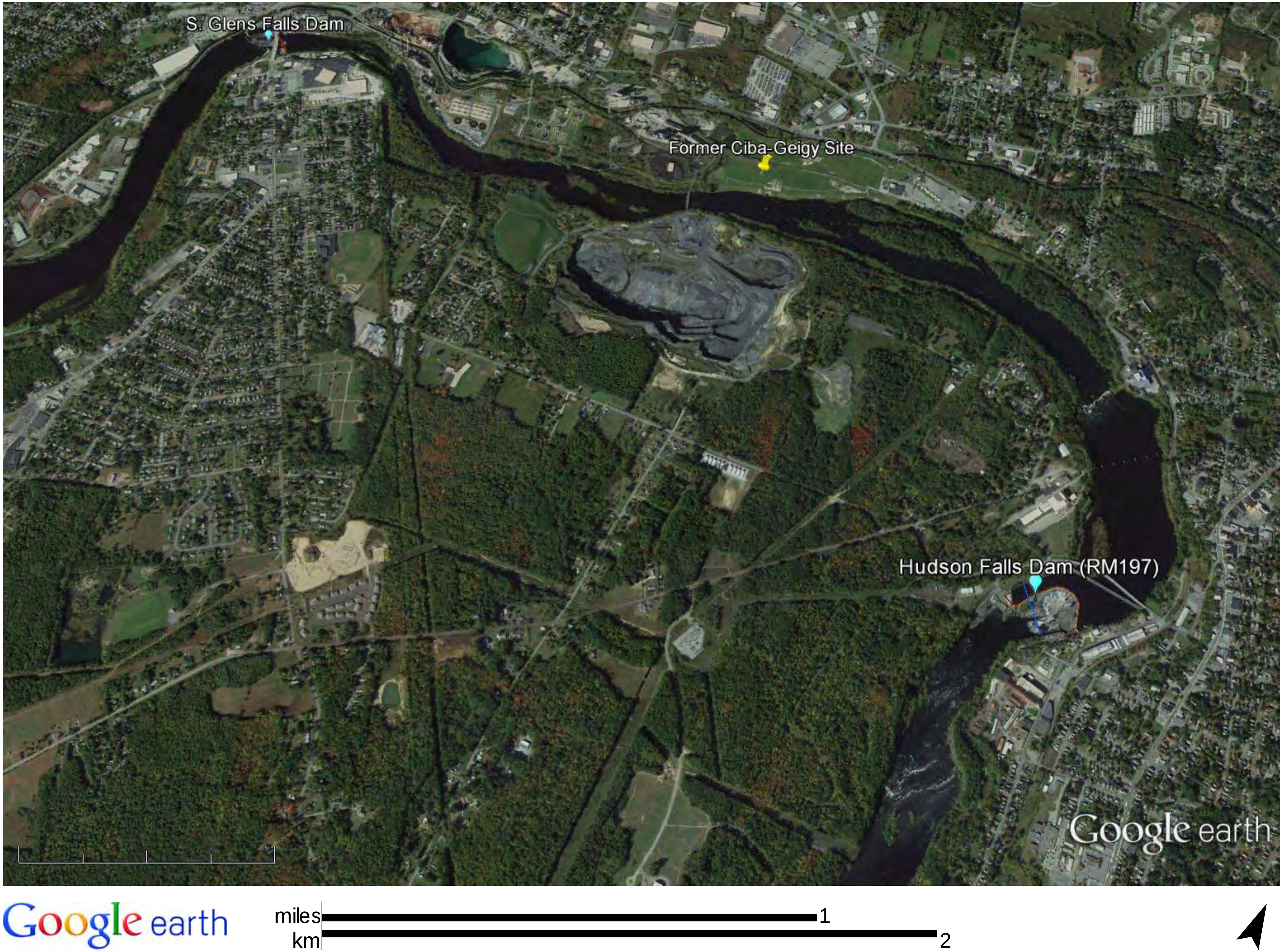

FIGURE 2 - HUDSON RIVER AERIAL MAP (RIVER MILES 196.5 - 201)

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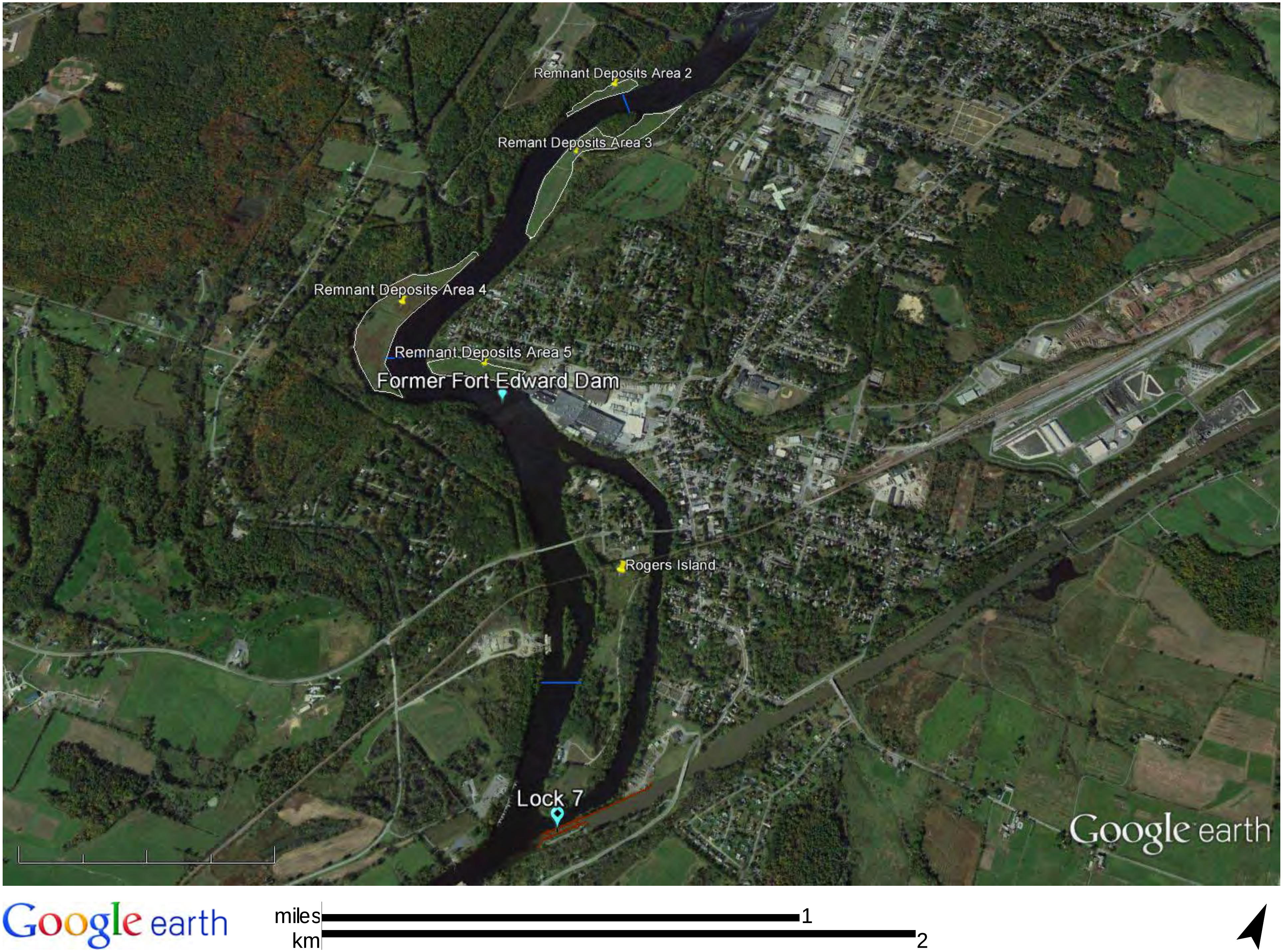

FIGURE 3 - HUDSON RIVER AERIAL MAP (RIVER MILES 193.5 - 196.5)

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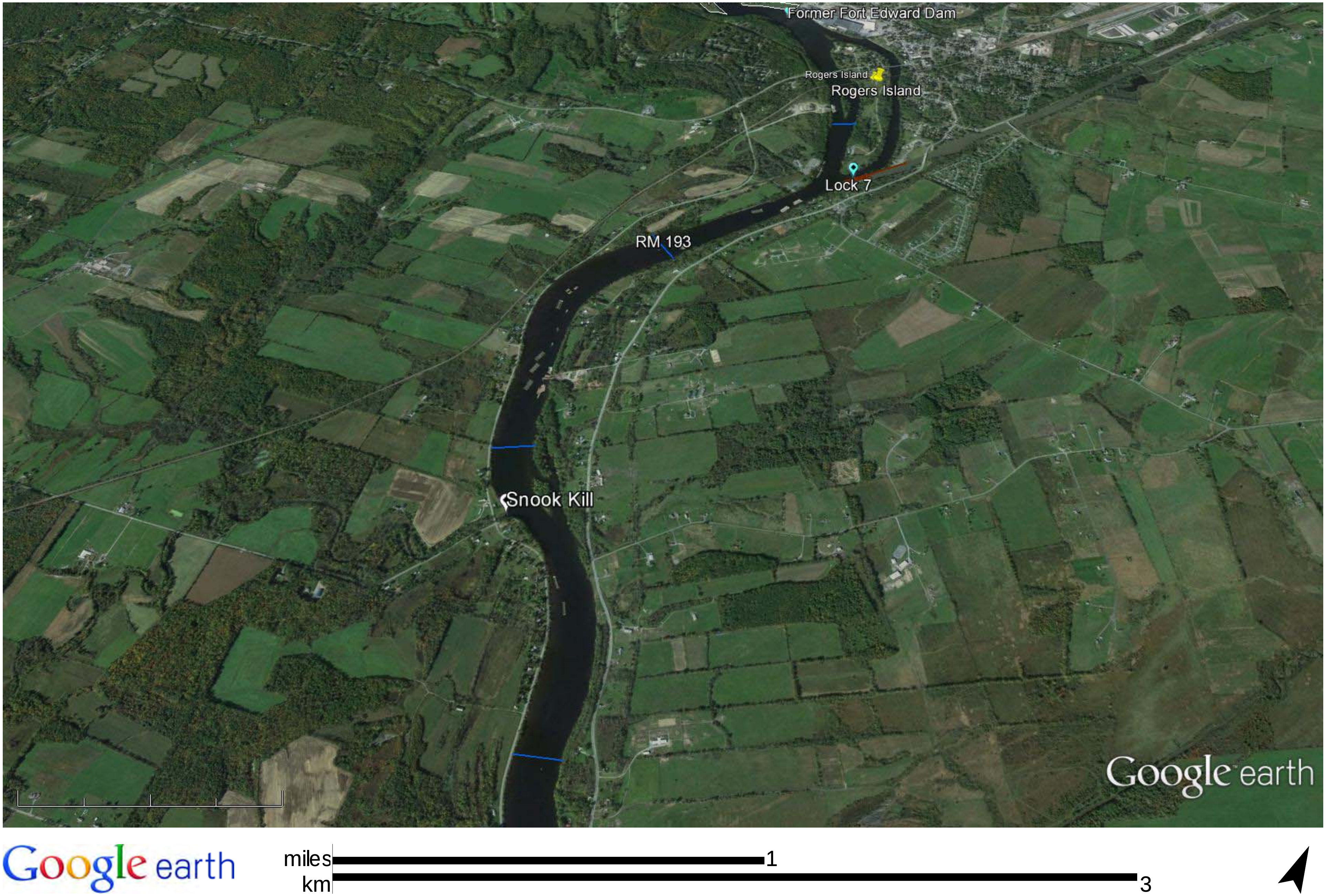

FIGURE 4 - HUDSON RIVER AERIAL MAP (RIVER MILES 191 - 194.5)

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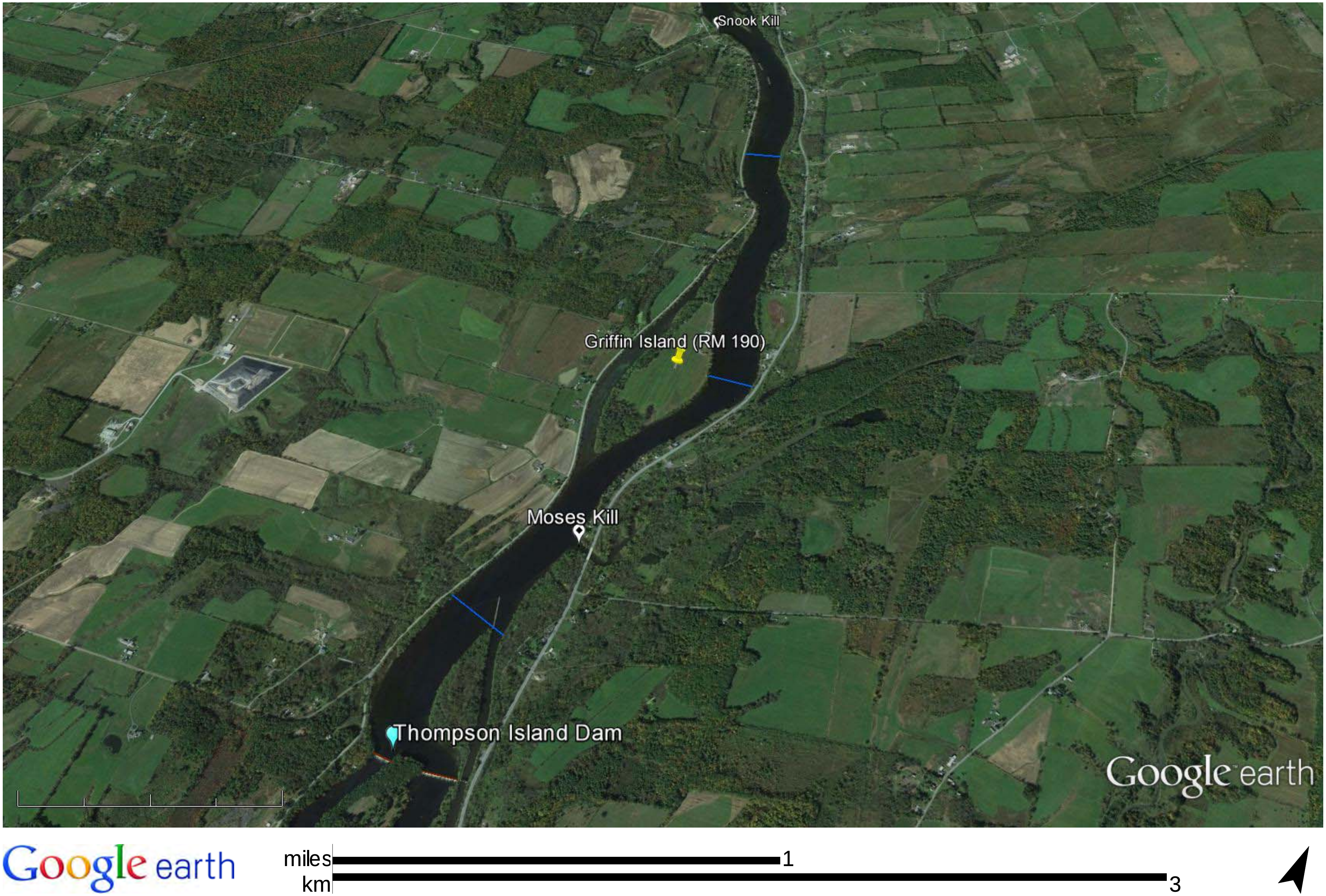


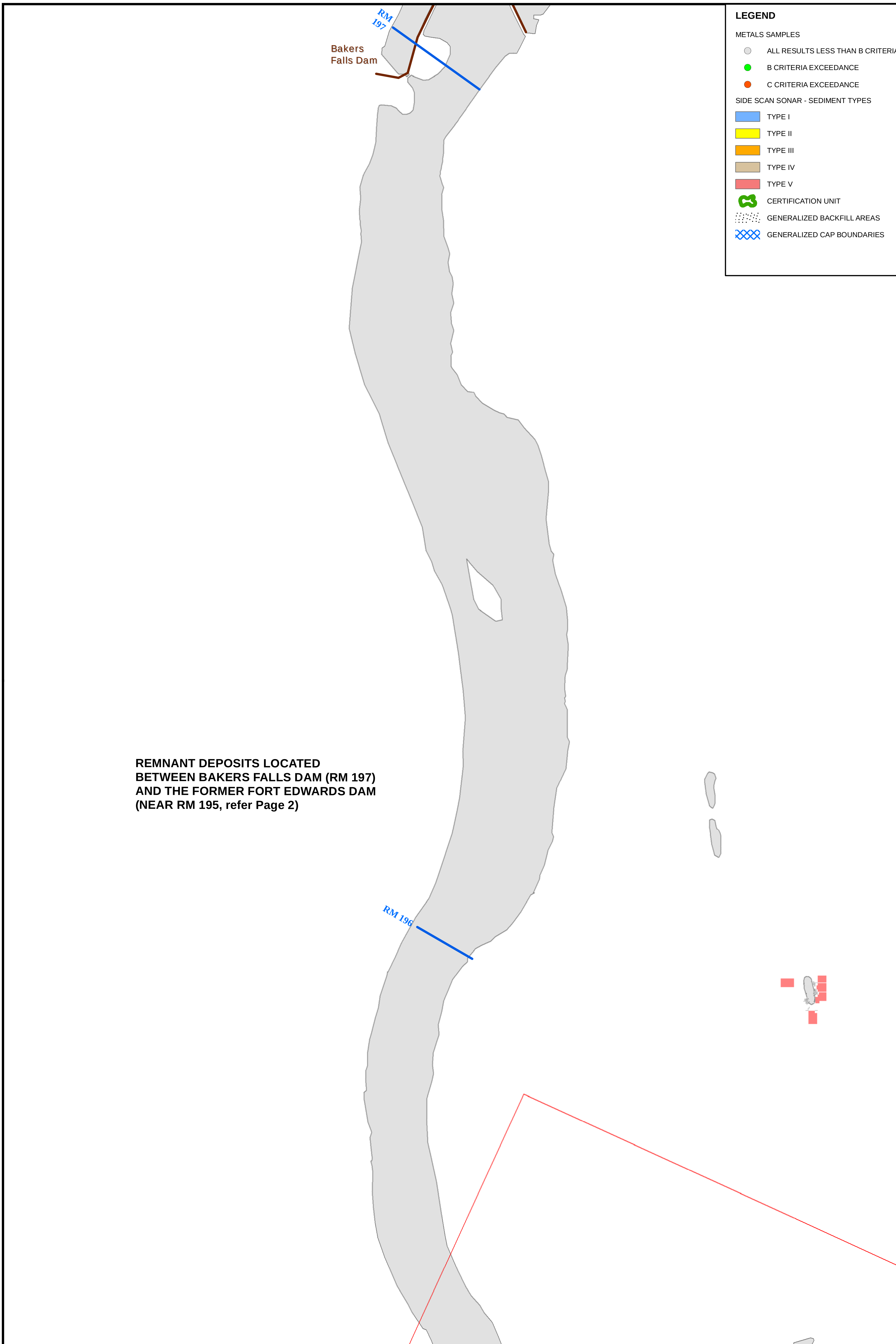
FIGURE 5 - HUDSON RIVER AERIAL MAP (RIVER MILES 188.5 - 192) **Imagery Date: 10/8/2011**

FIGURE 6 - HUDSON RIVER AERIAL MAP (RIVER MILES 185 - 188.5) **Imagery Date: 10/8/2011**

FIGURE 7 - HUDSON RIVER AERIAL MAP (RIVER MILES 181 - 185) **Imagery Date: 10/8/2011**

ATTACHMENT A

SSS Plots



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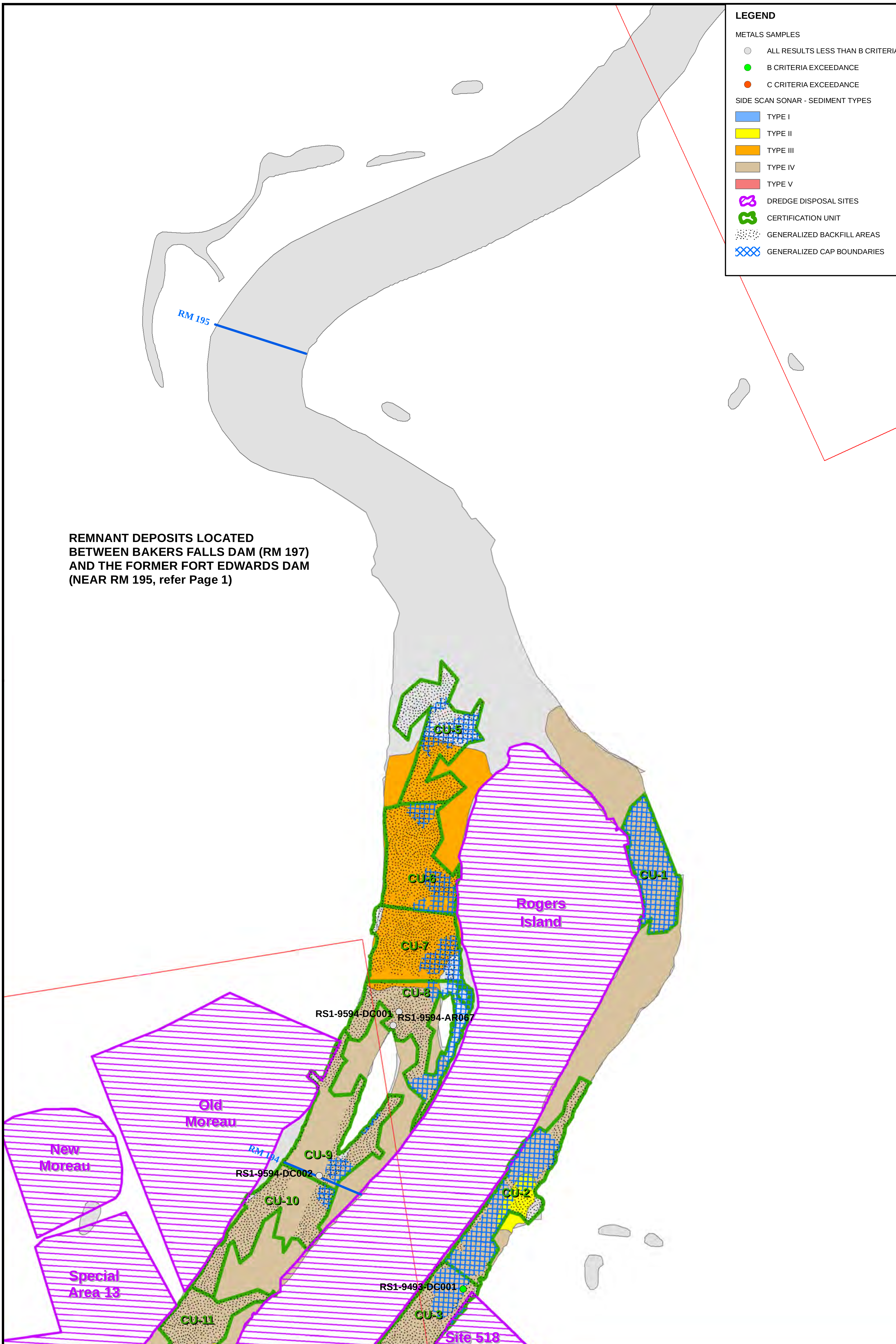

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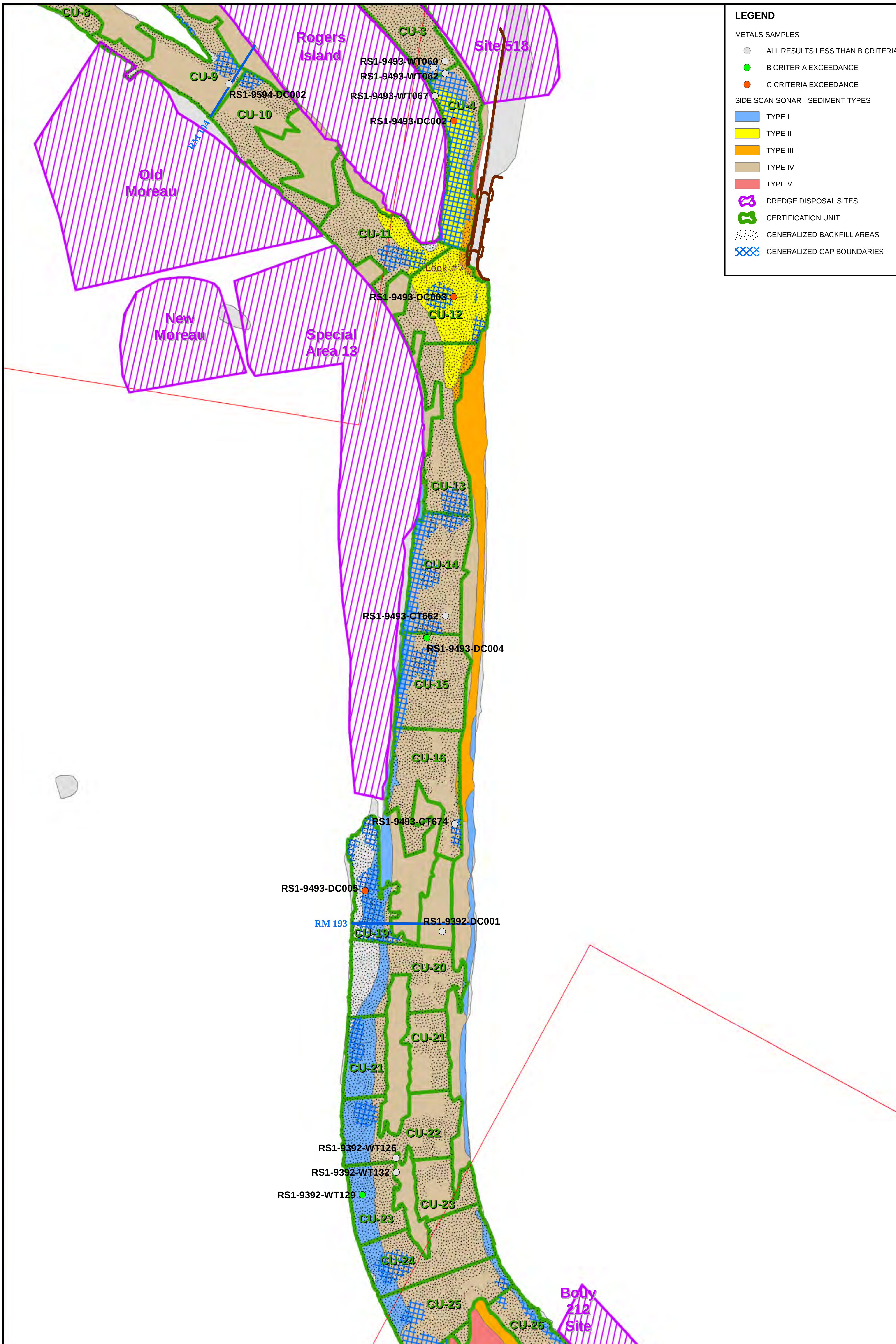

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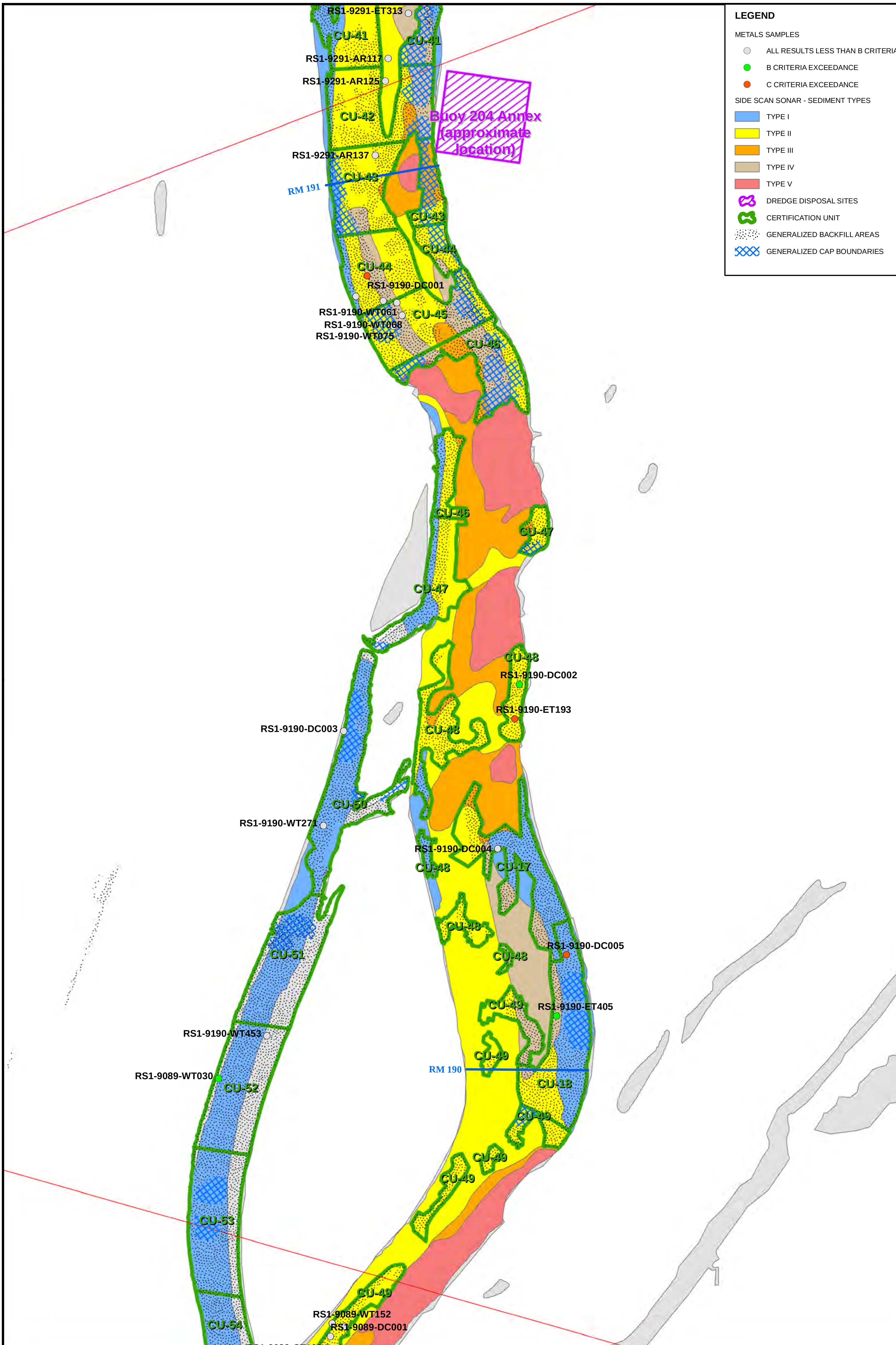

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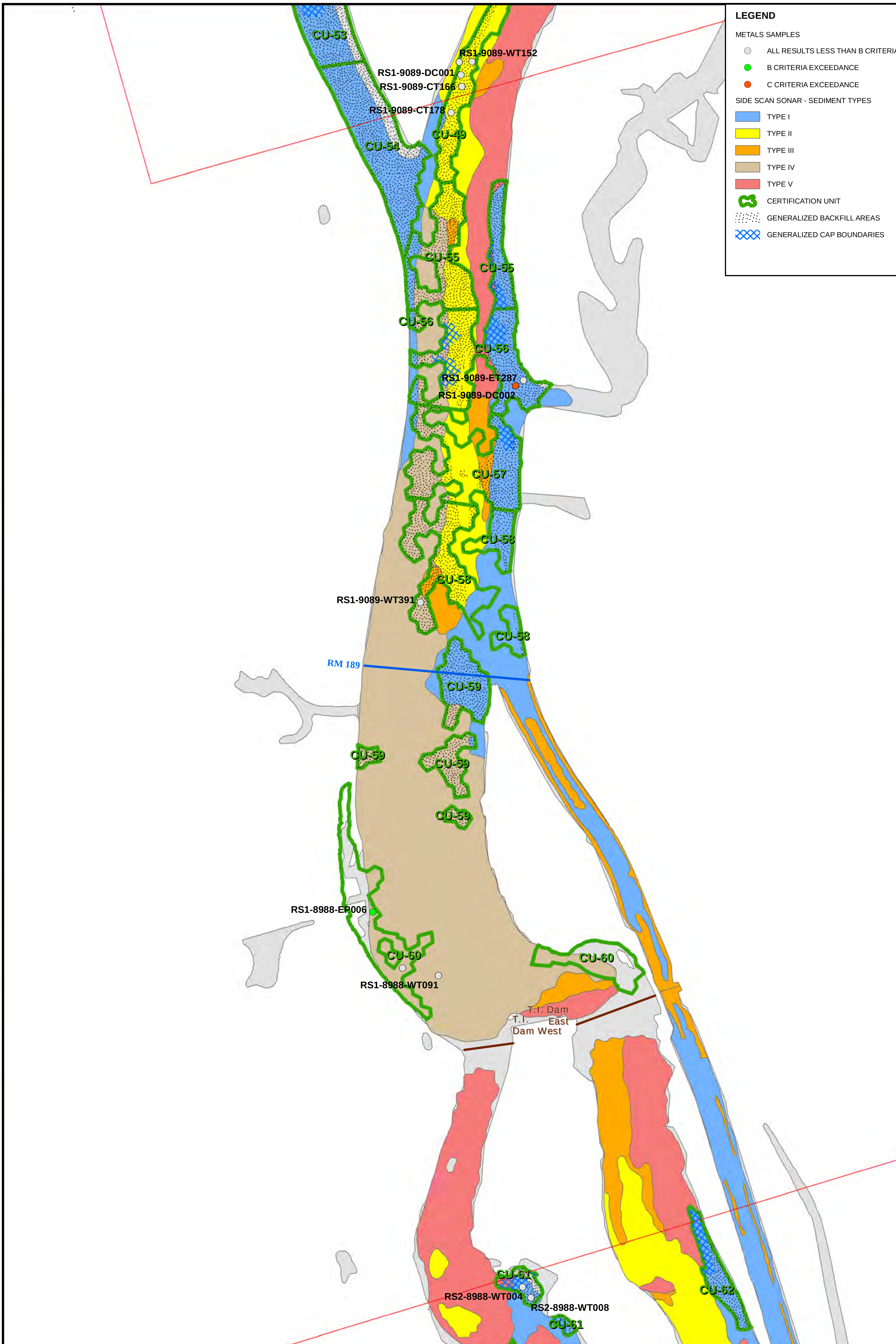

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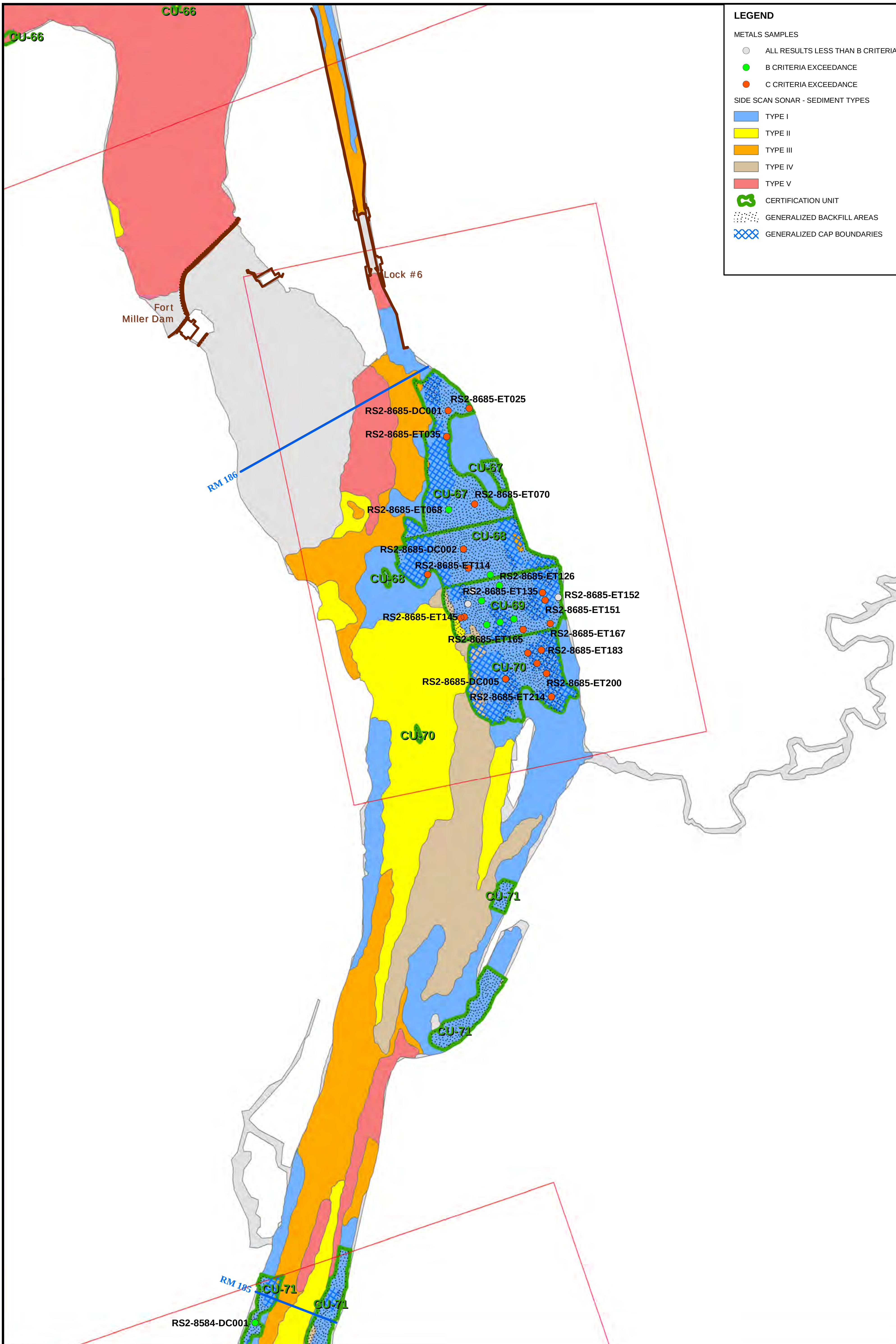

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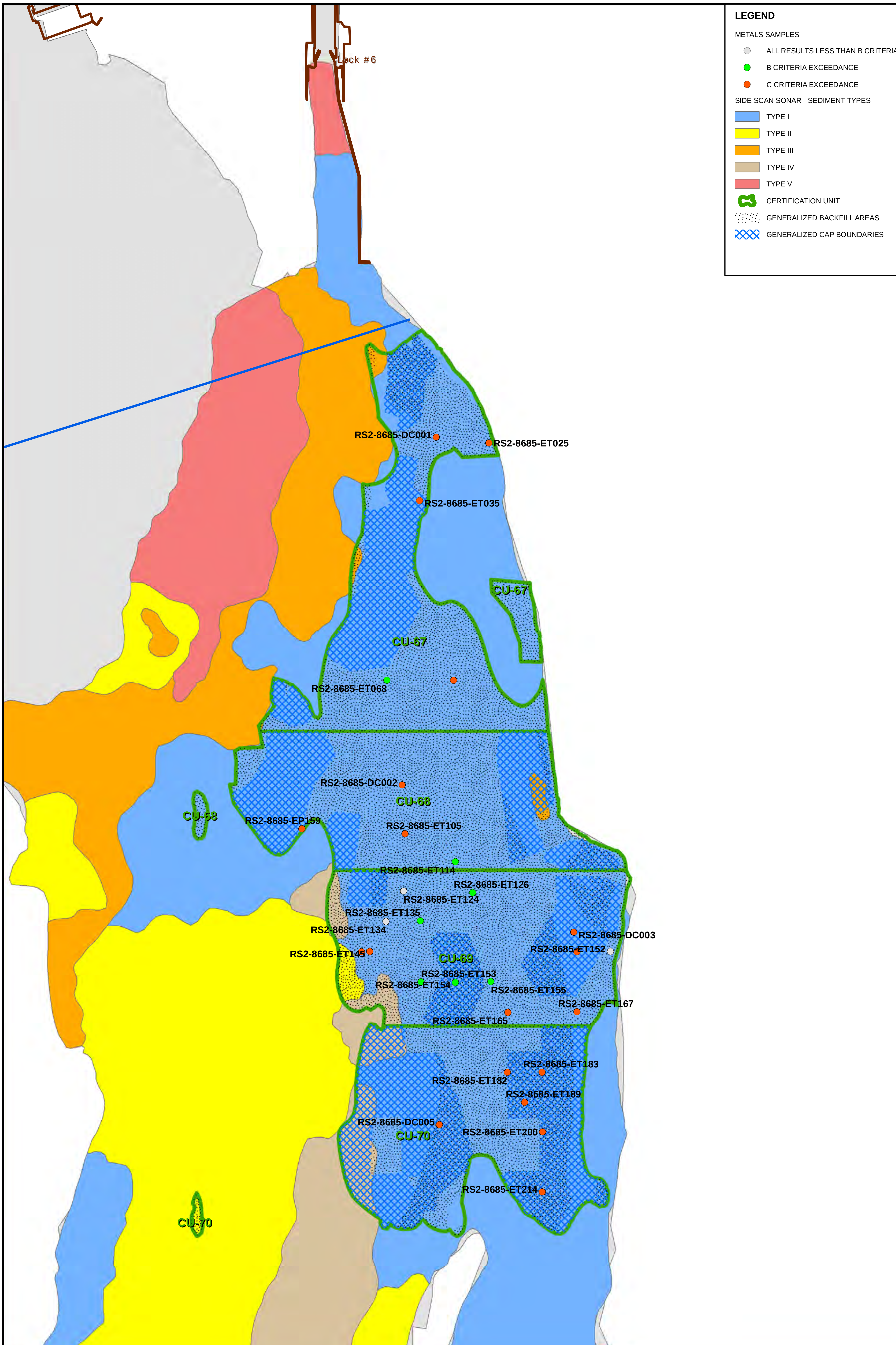

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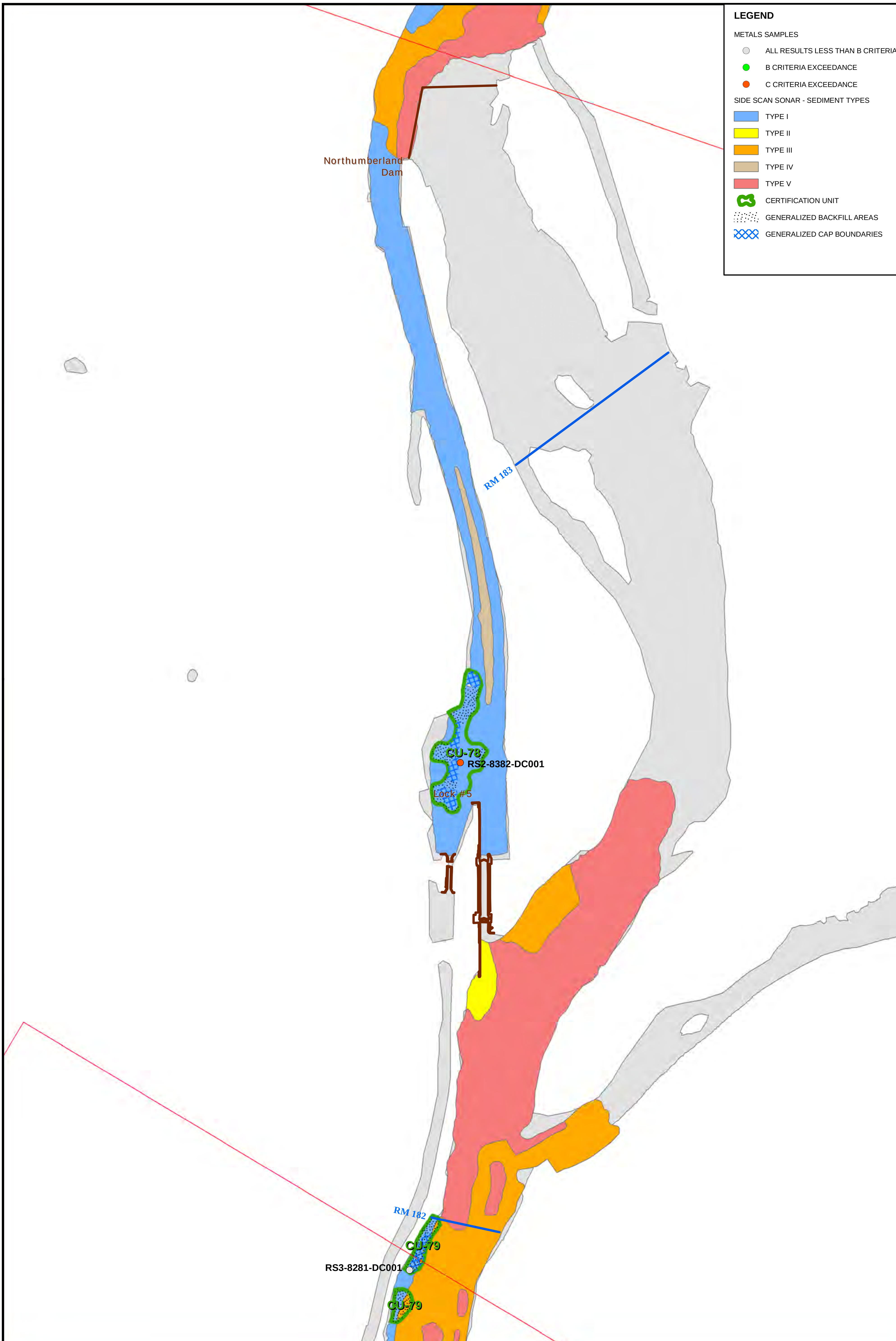

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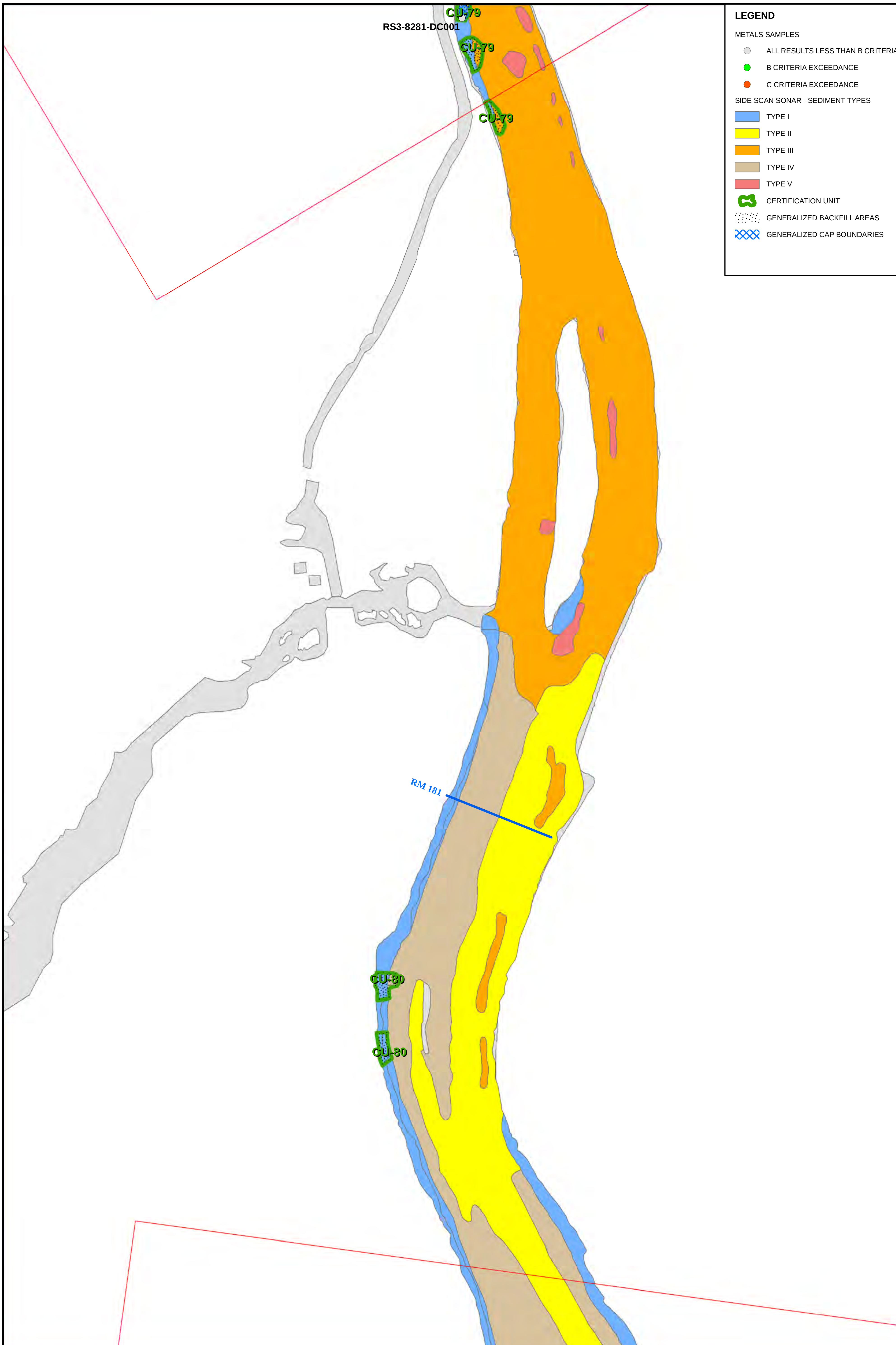

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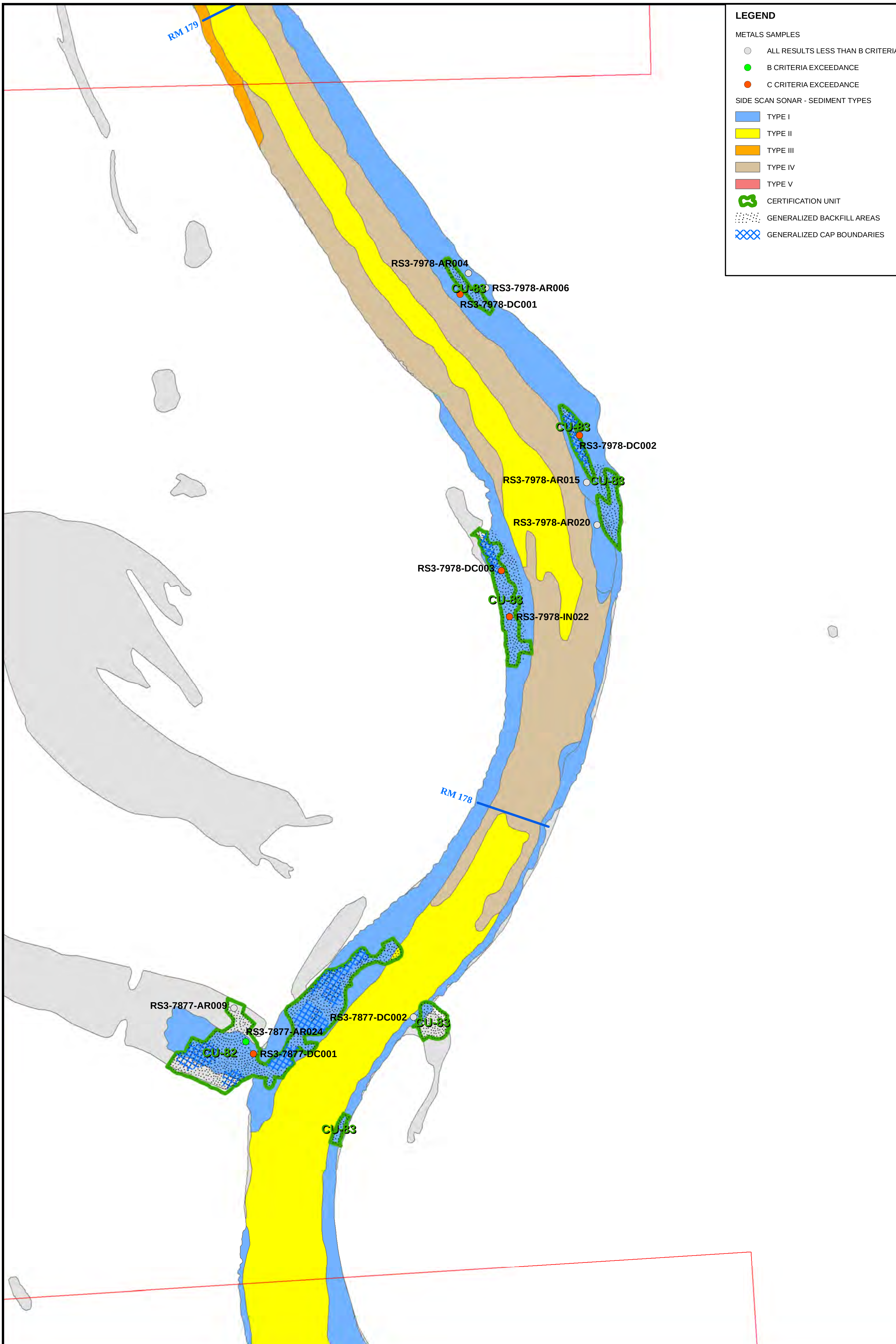

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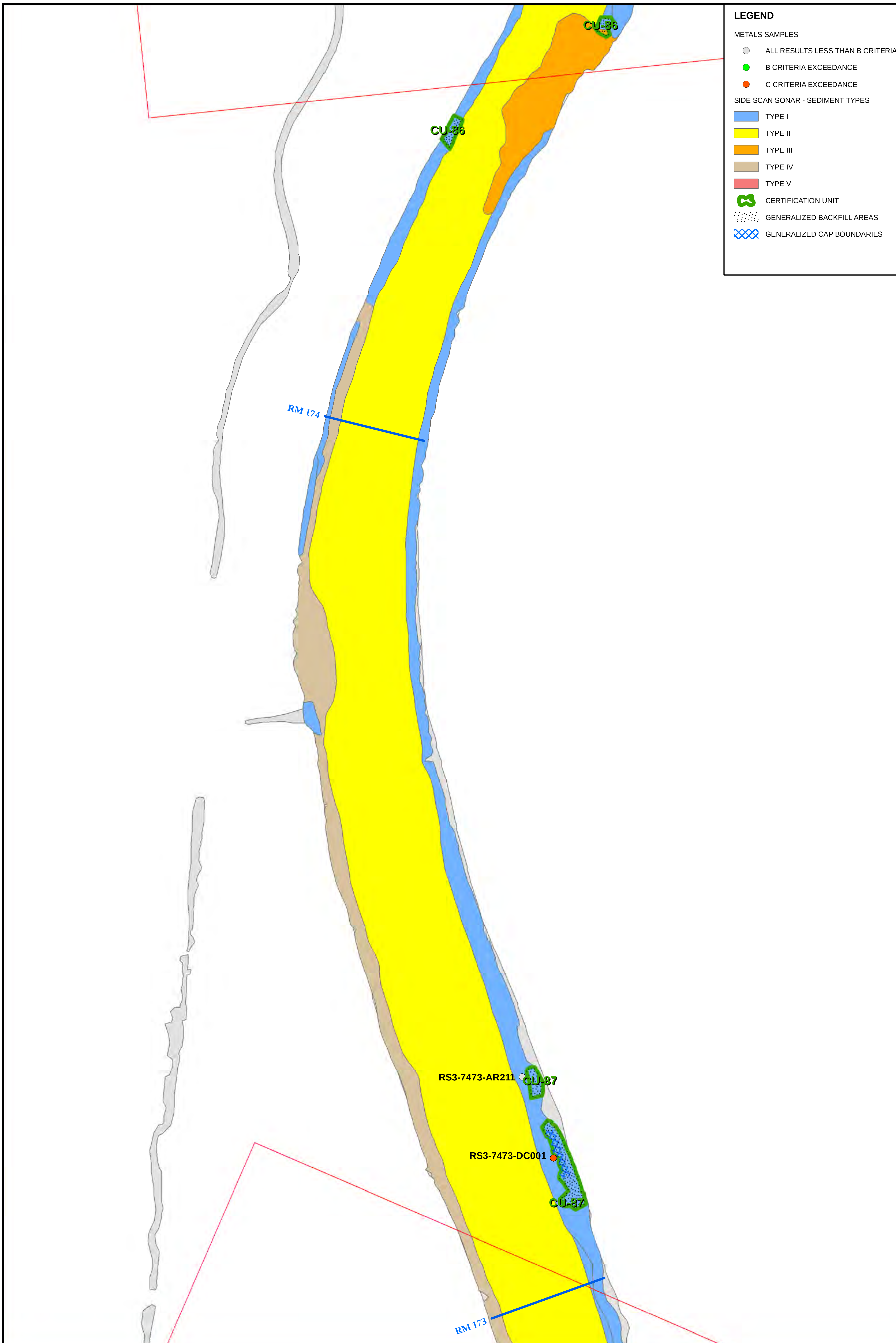

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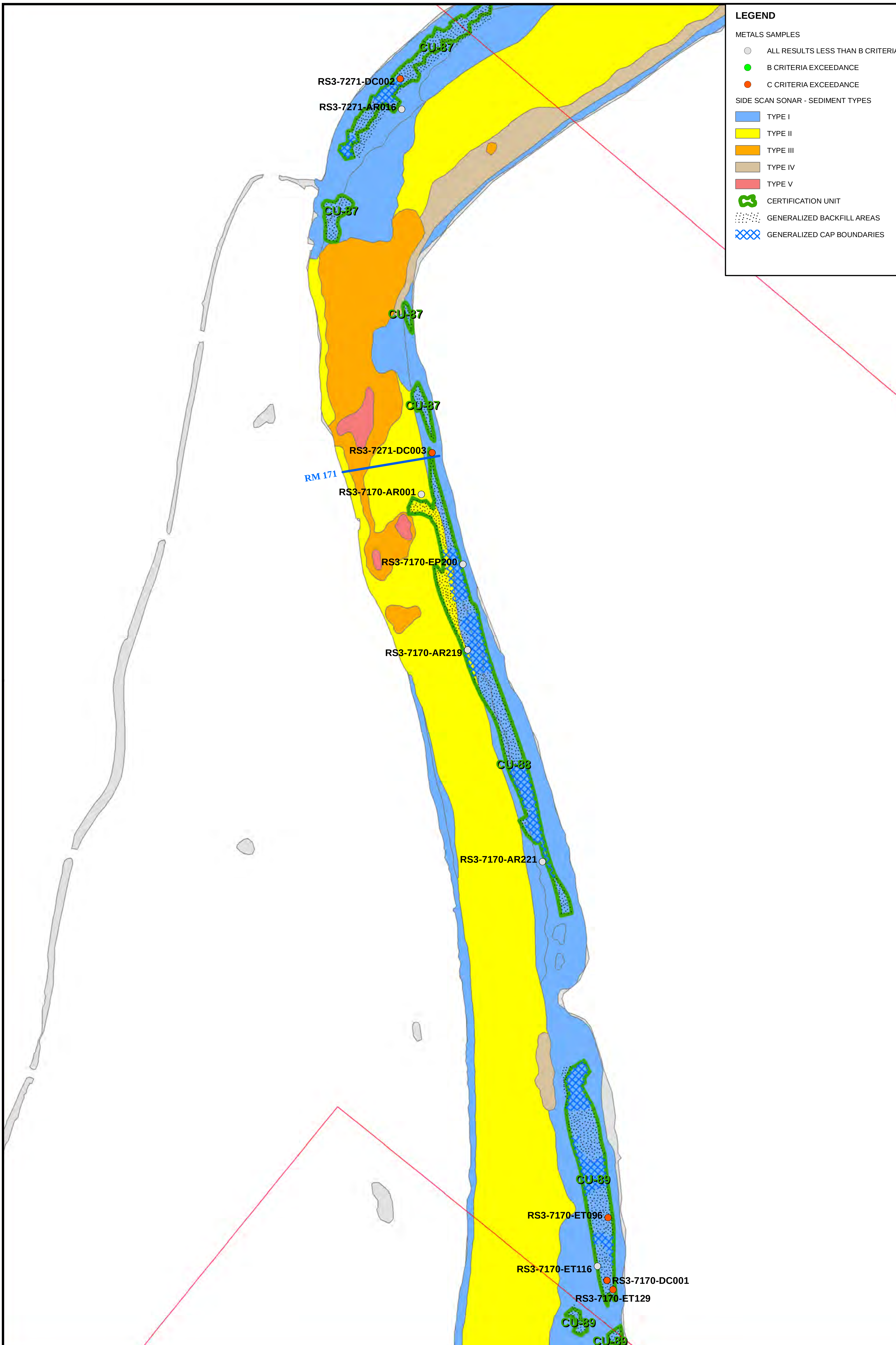

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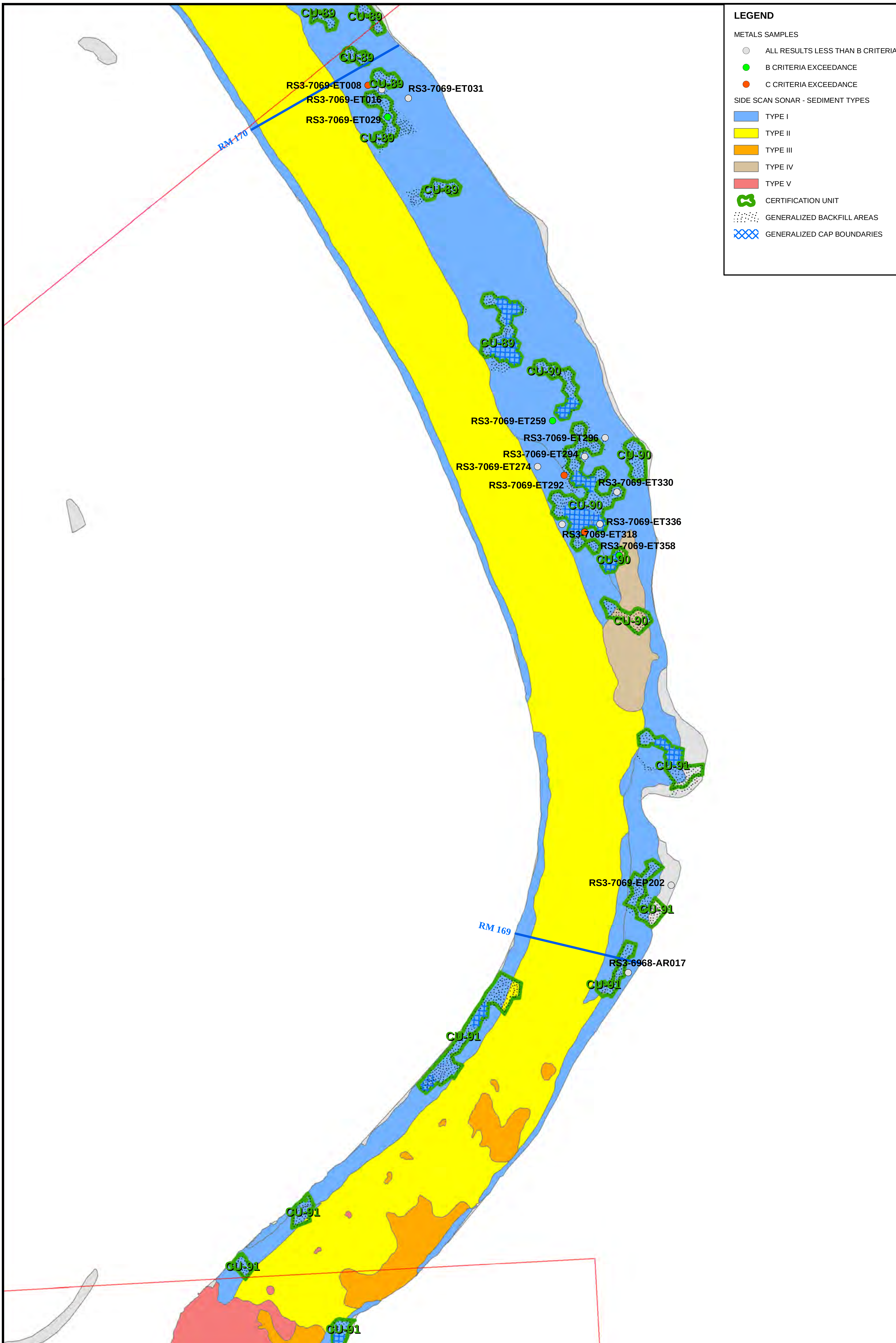

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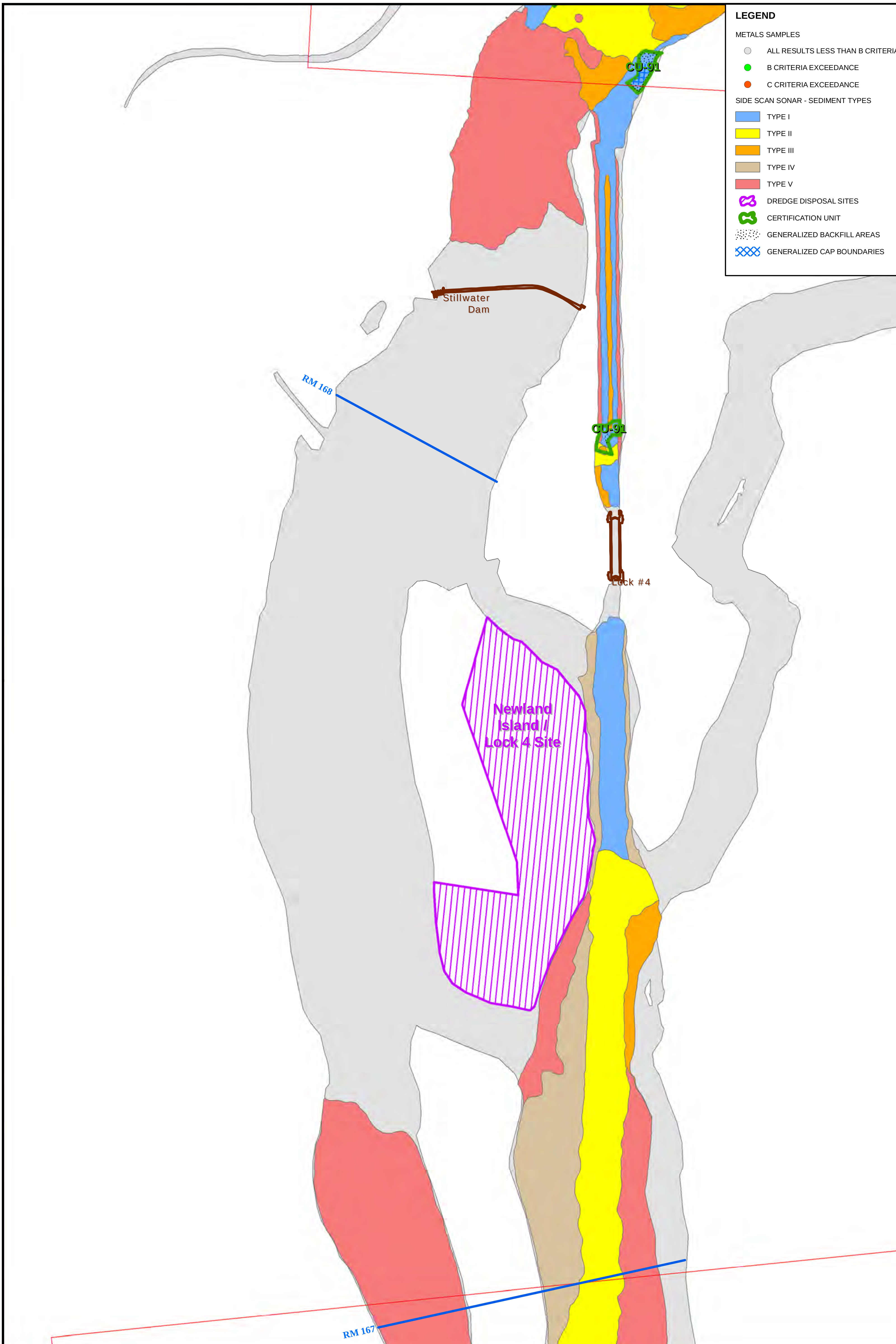

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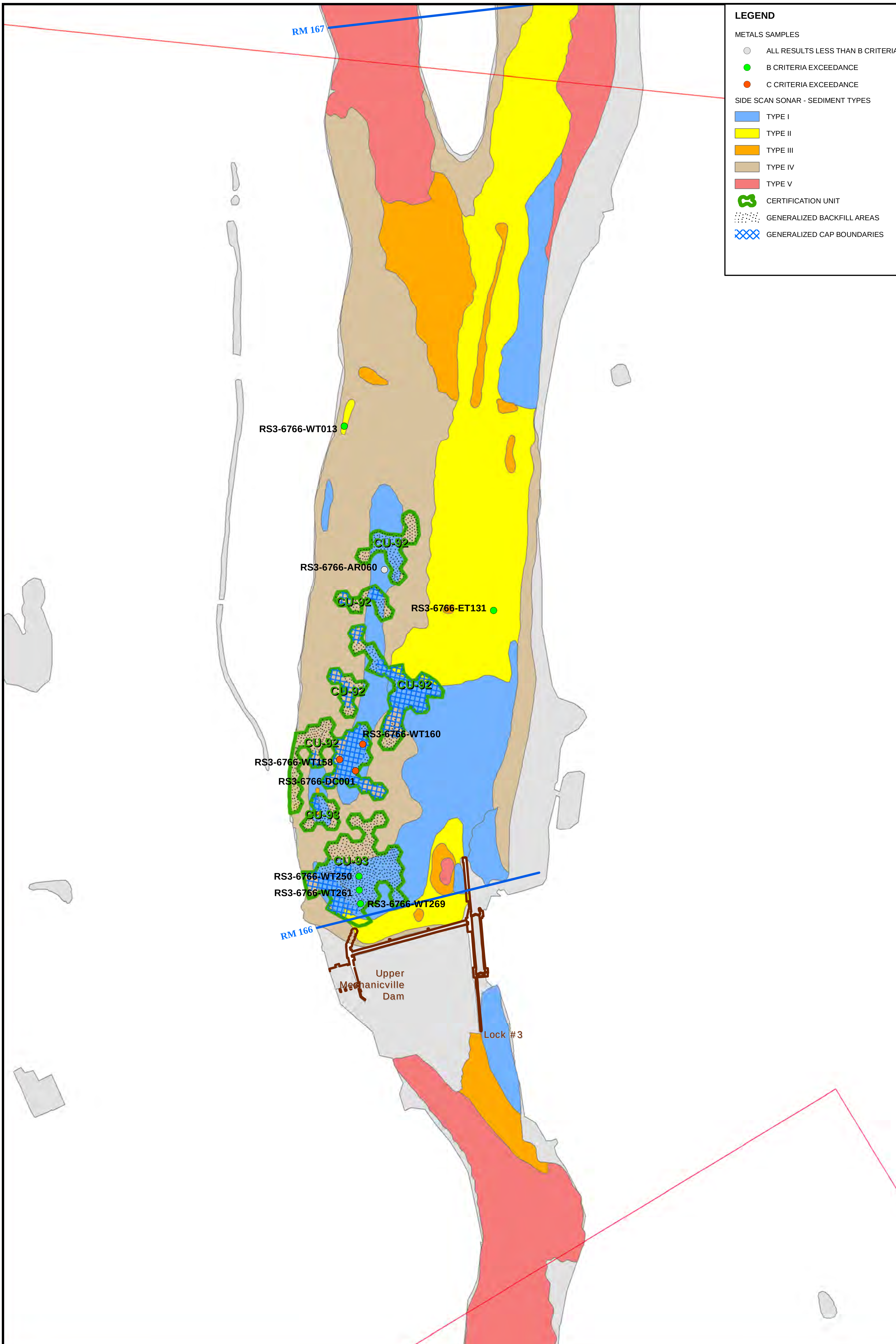

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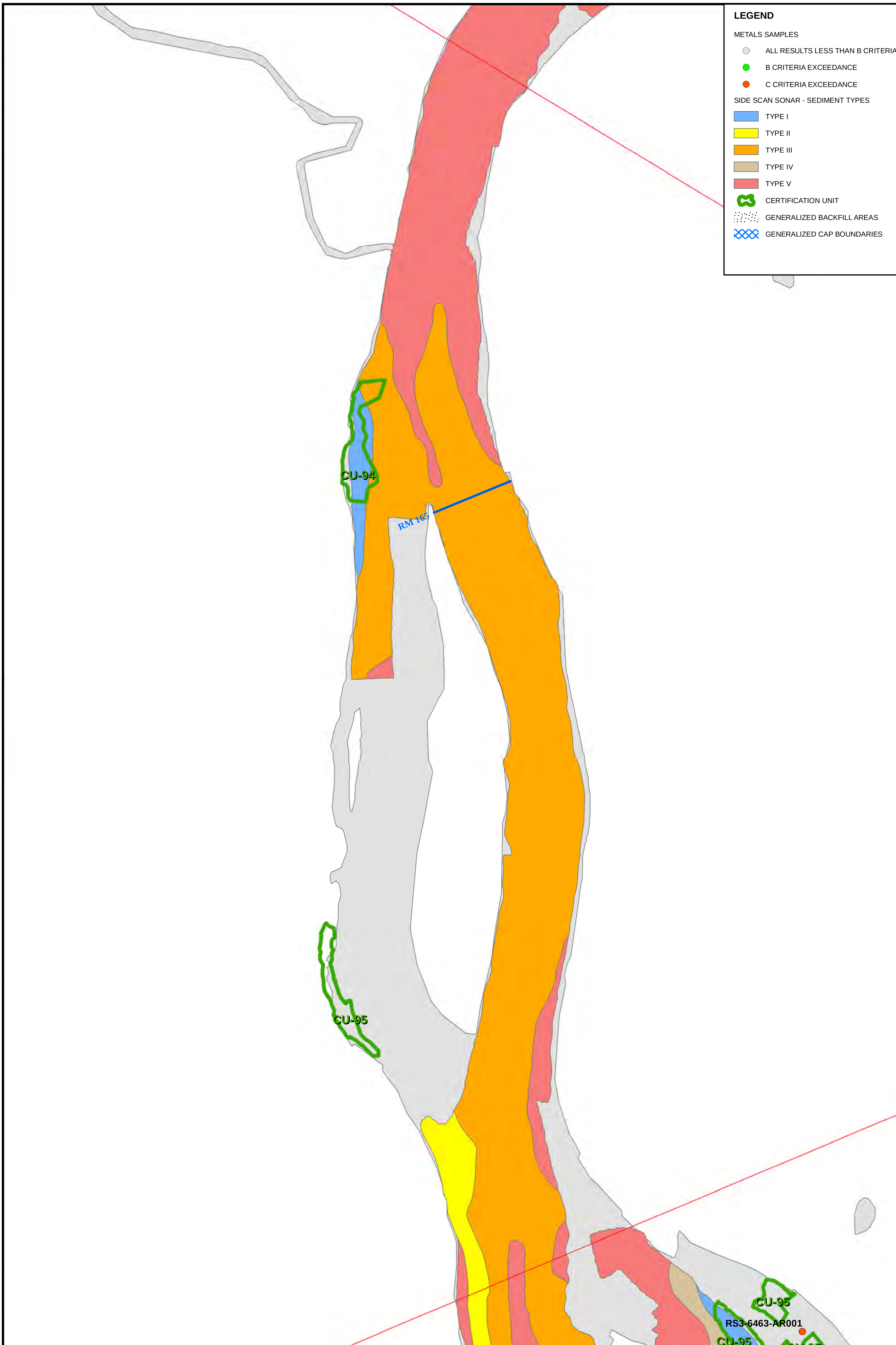

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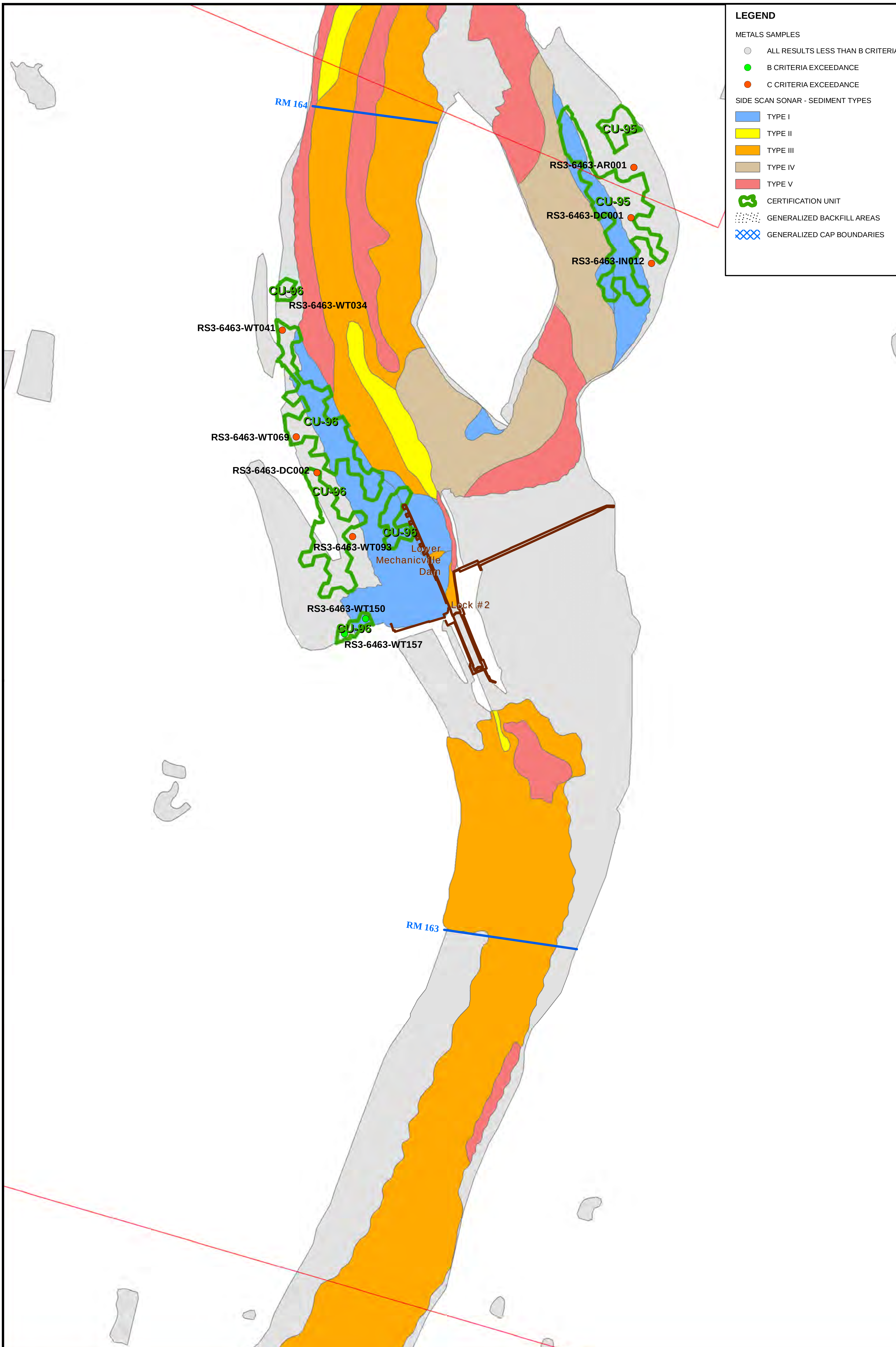

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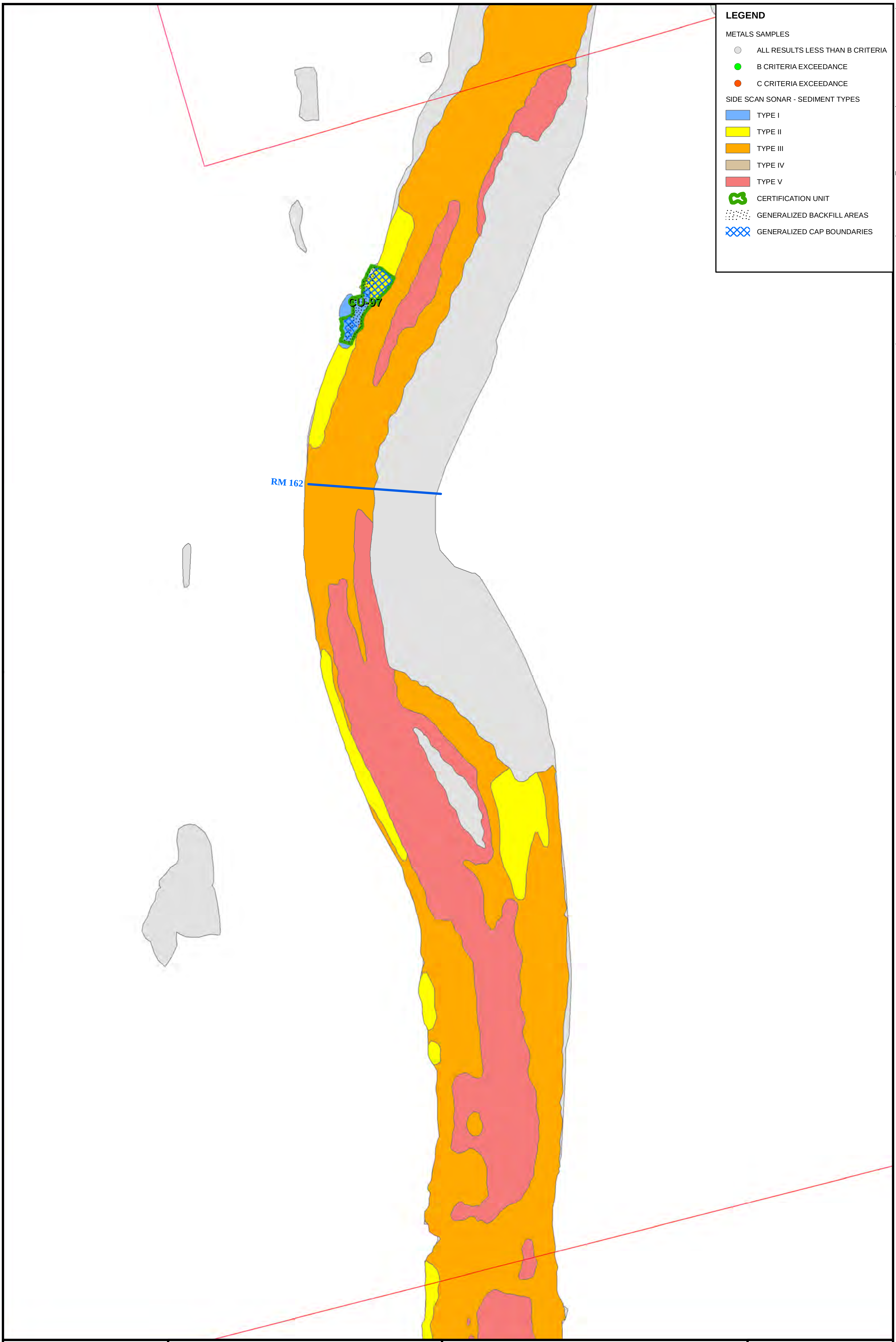

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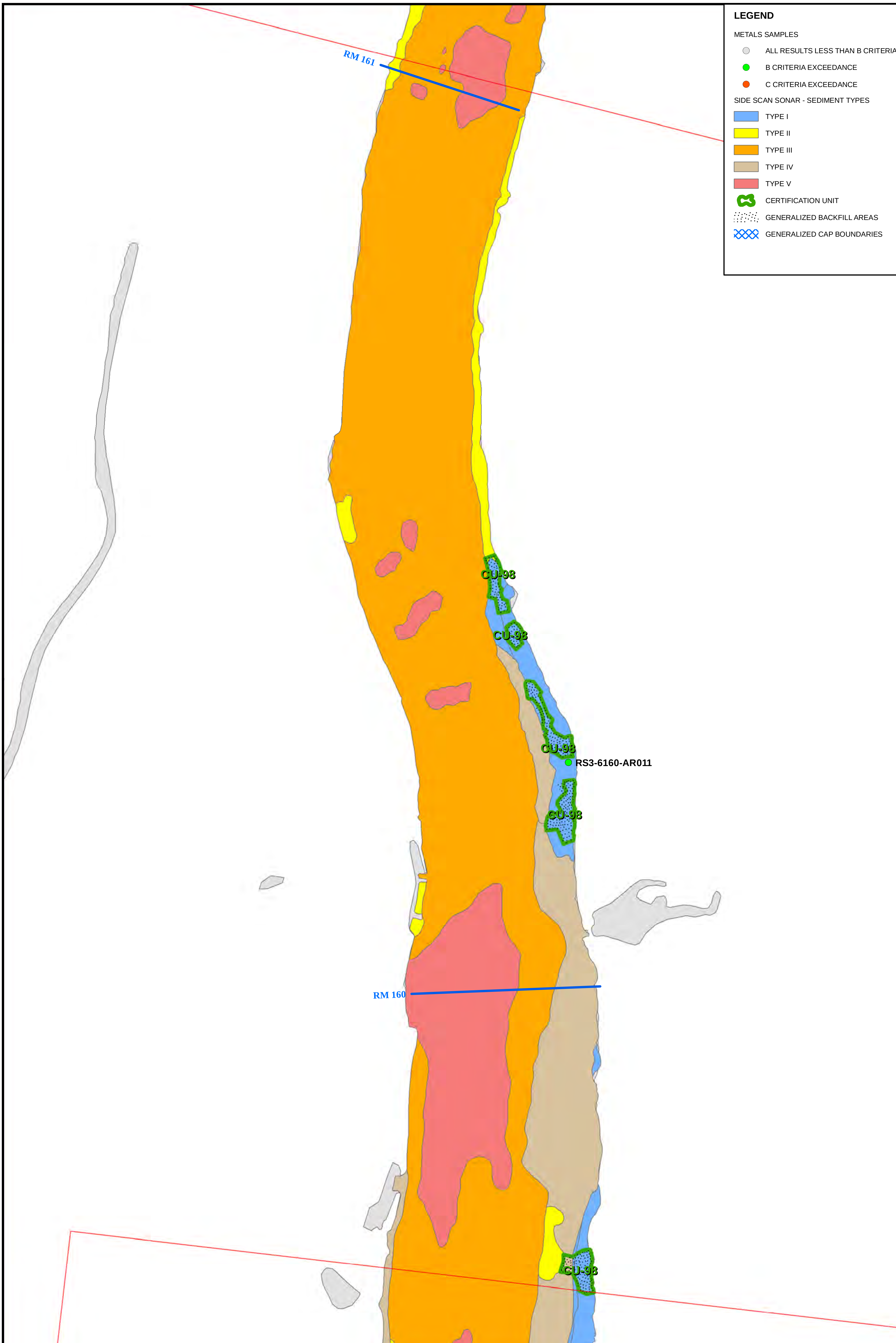

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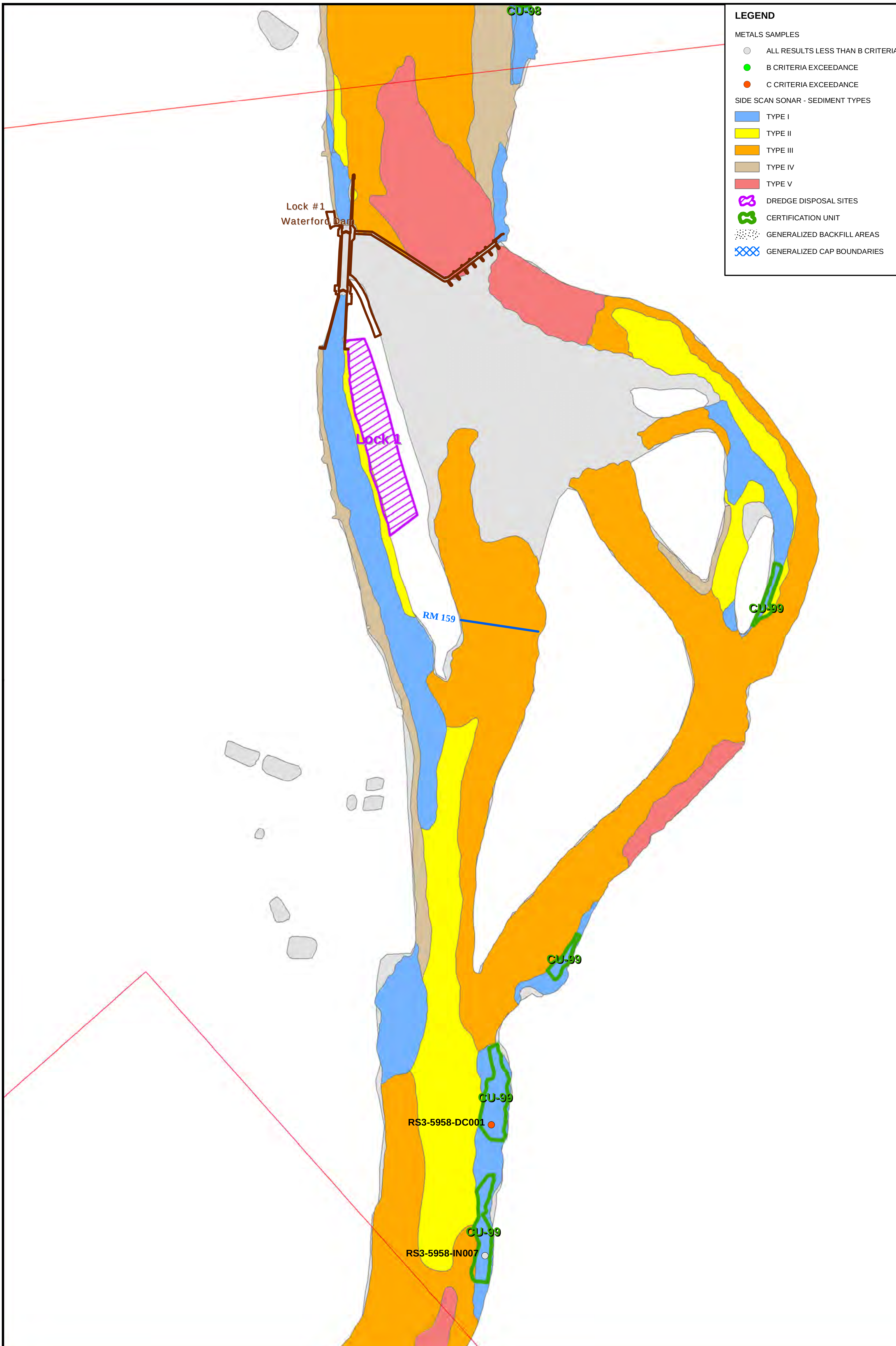

EHS Support consider it done

LOWER HUDSON RIVER

0 250 500
Feet

METALS RESULTS AND SIDE SCAN SONAR DERIVED \ SEDIMENT TYPES

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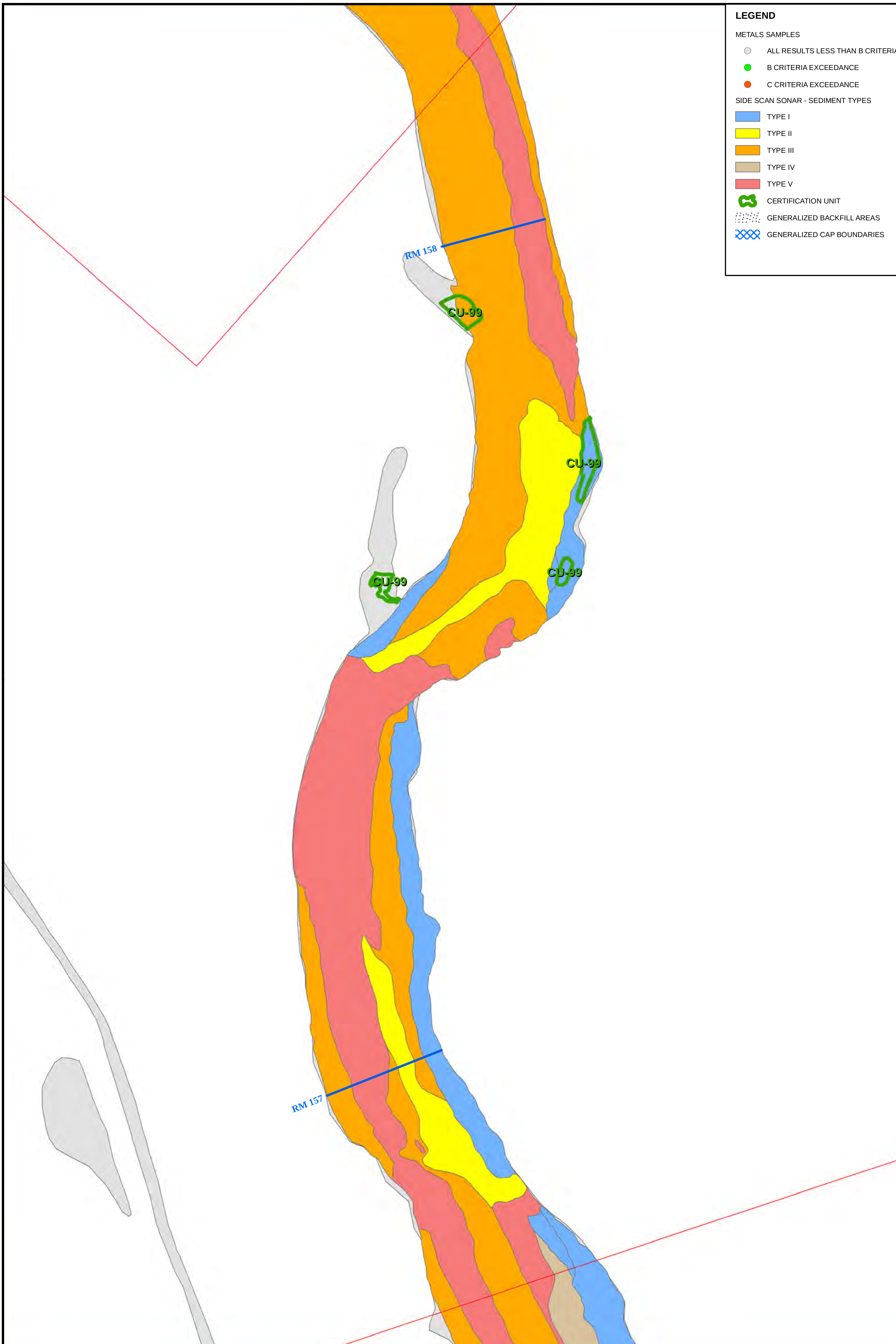

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LOWER HUDSON RIVER

METALS RESULTS AND SIDE SCAN SONAR DERIVED \ SEDIMENT TYPES

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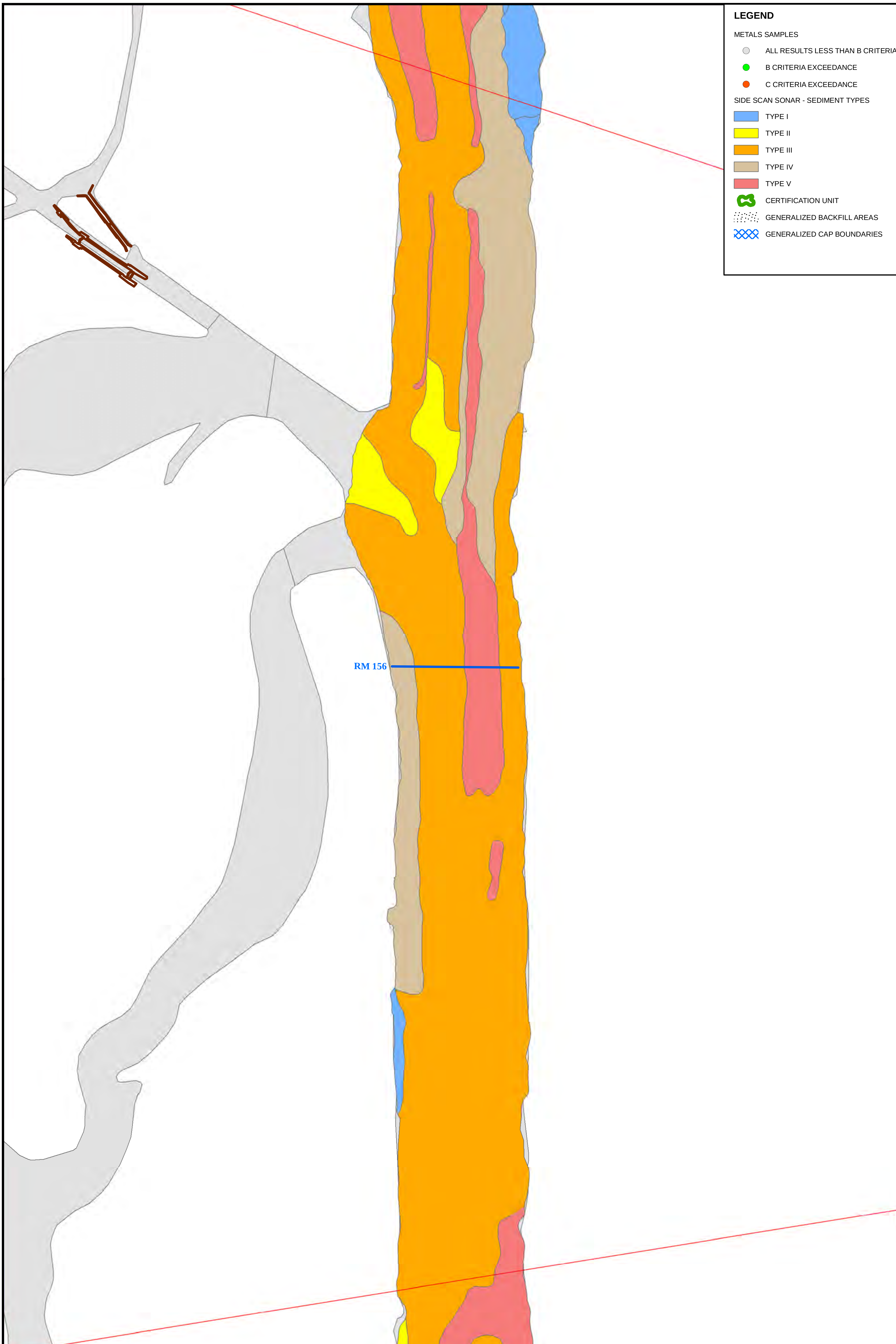

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LOWER HUDSON RIVER

METALS RESULTS AND SIDE SCAN SONAR DERIVED \ SEDIMENT TYPES

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LOWER HUDSON RIVER

0 250 500 Feet

METALS RESULTS AND SIDE SCAN SONAR DERIVED \ SEDIMENT TYPES

ATTACHMENT B

Aerial Imagery of River Features

FIGURE B1 - HUDSON RIVER IMMEDIATE SITE VICINITY - Imagery Date: 4/29/2004

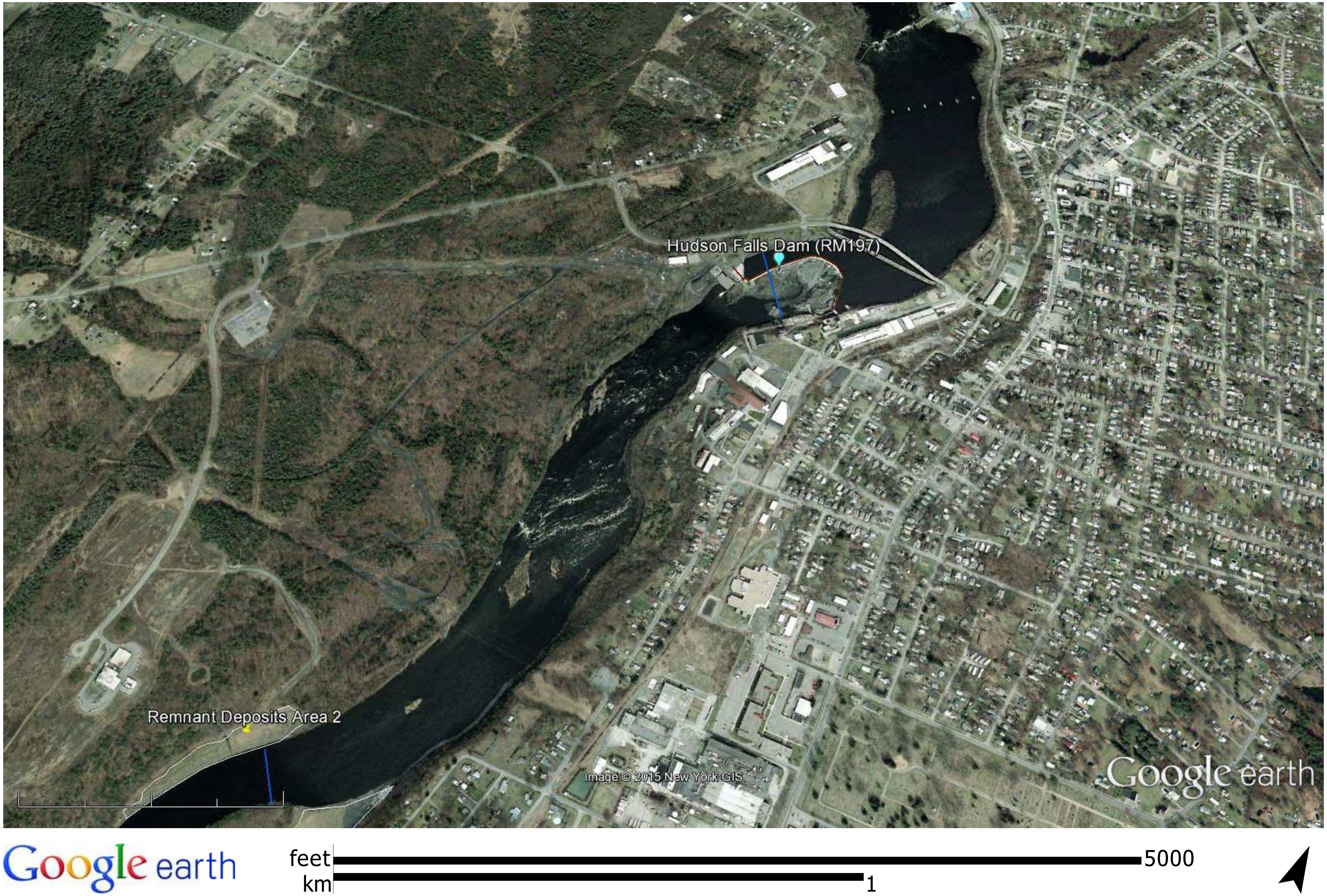


FIGURE B2 - HUDSON RIVER HUDSON FALLS DAM - Imagery Date: 4/29/2004

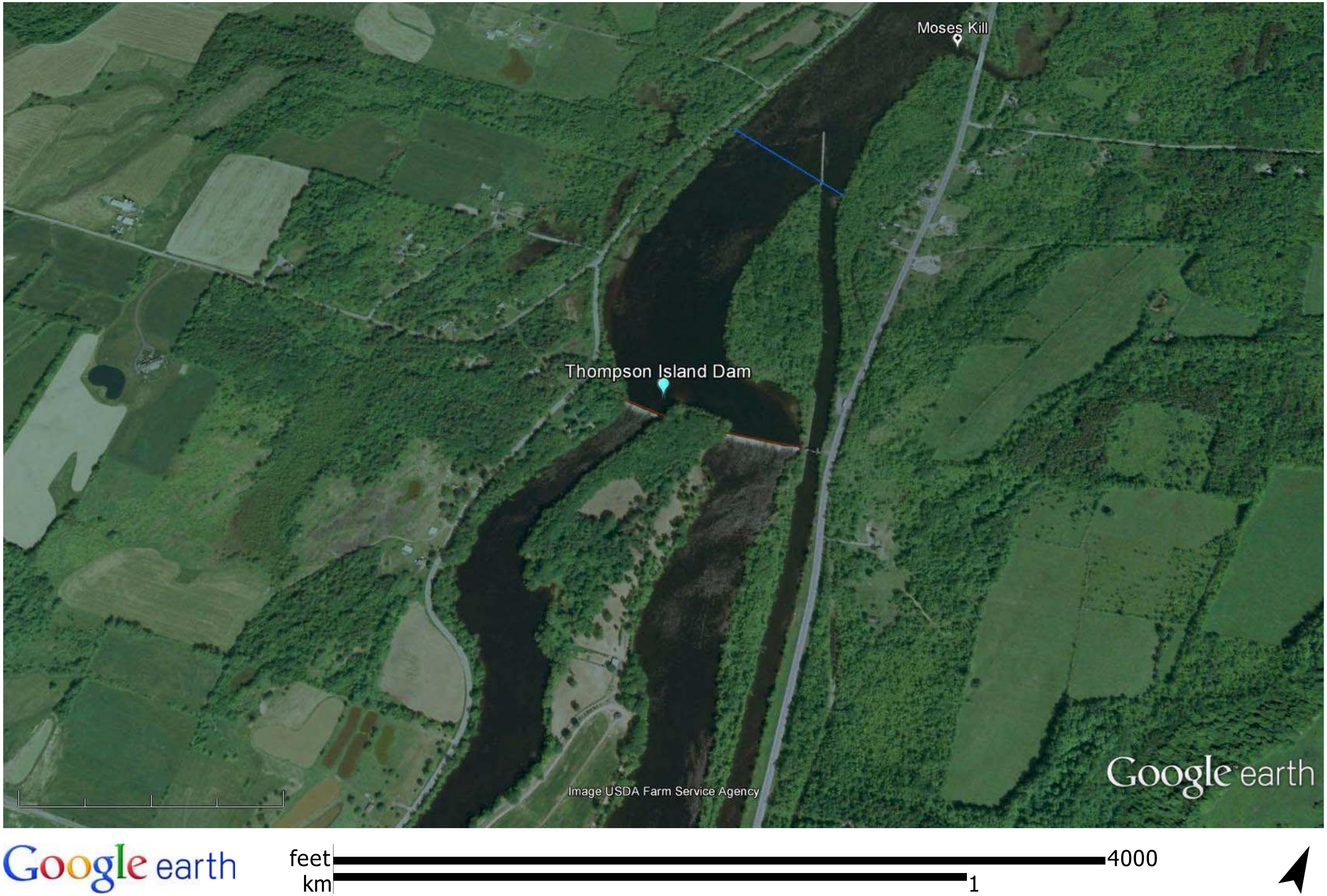


FIGURE B3 - HUDSON RIVER THOMPSON ISLAND DAM - Imagery Date: 9/5/2009

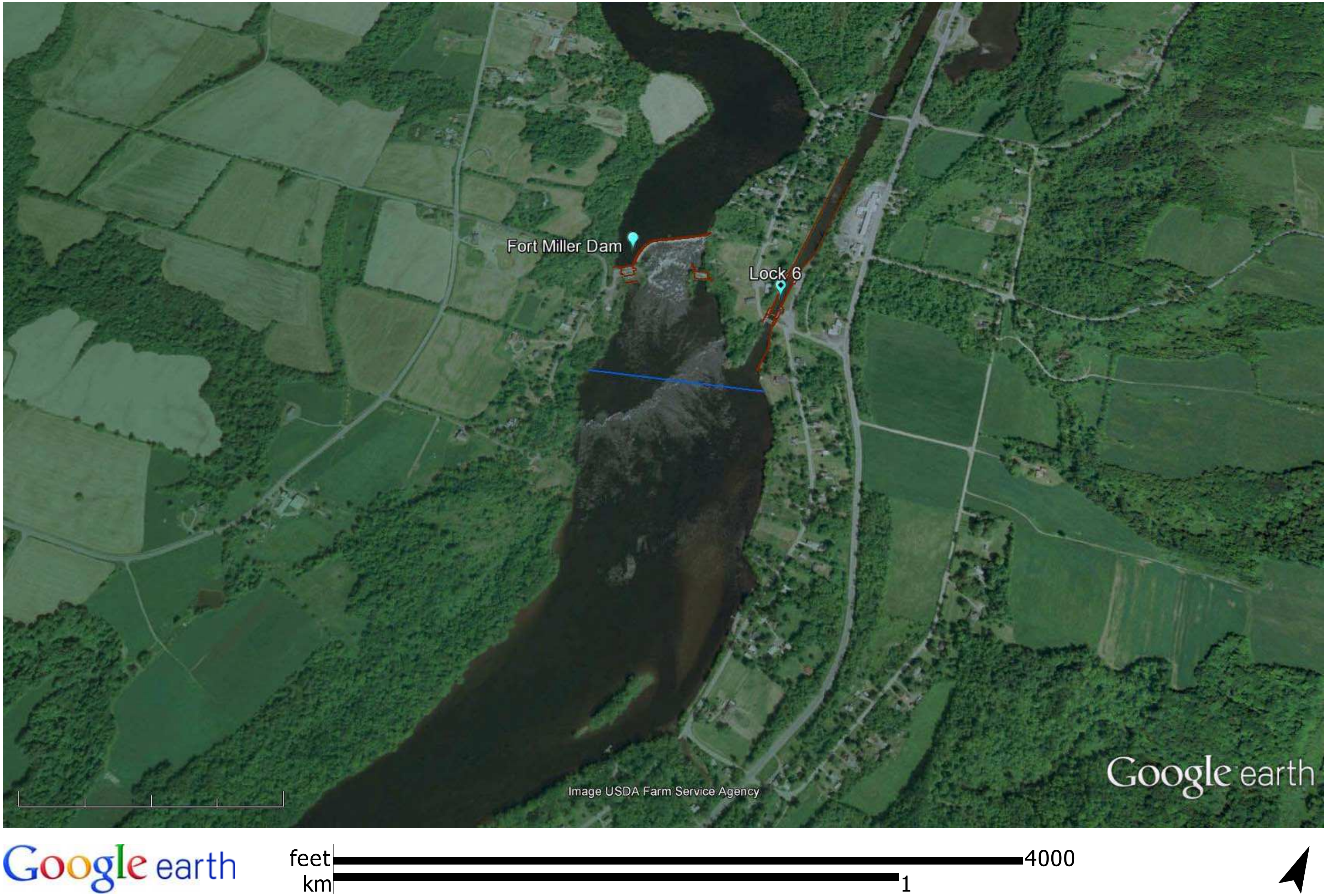


FIGURE B4 - HUDSON RIVER FORT MILLER DAM AND LOCK 6 - Imagery Date: 9/5/2009

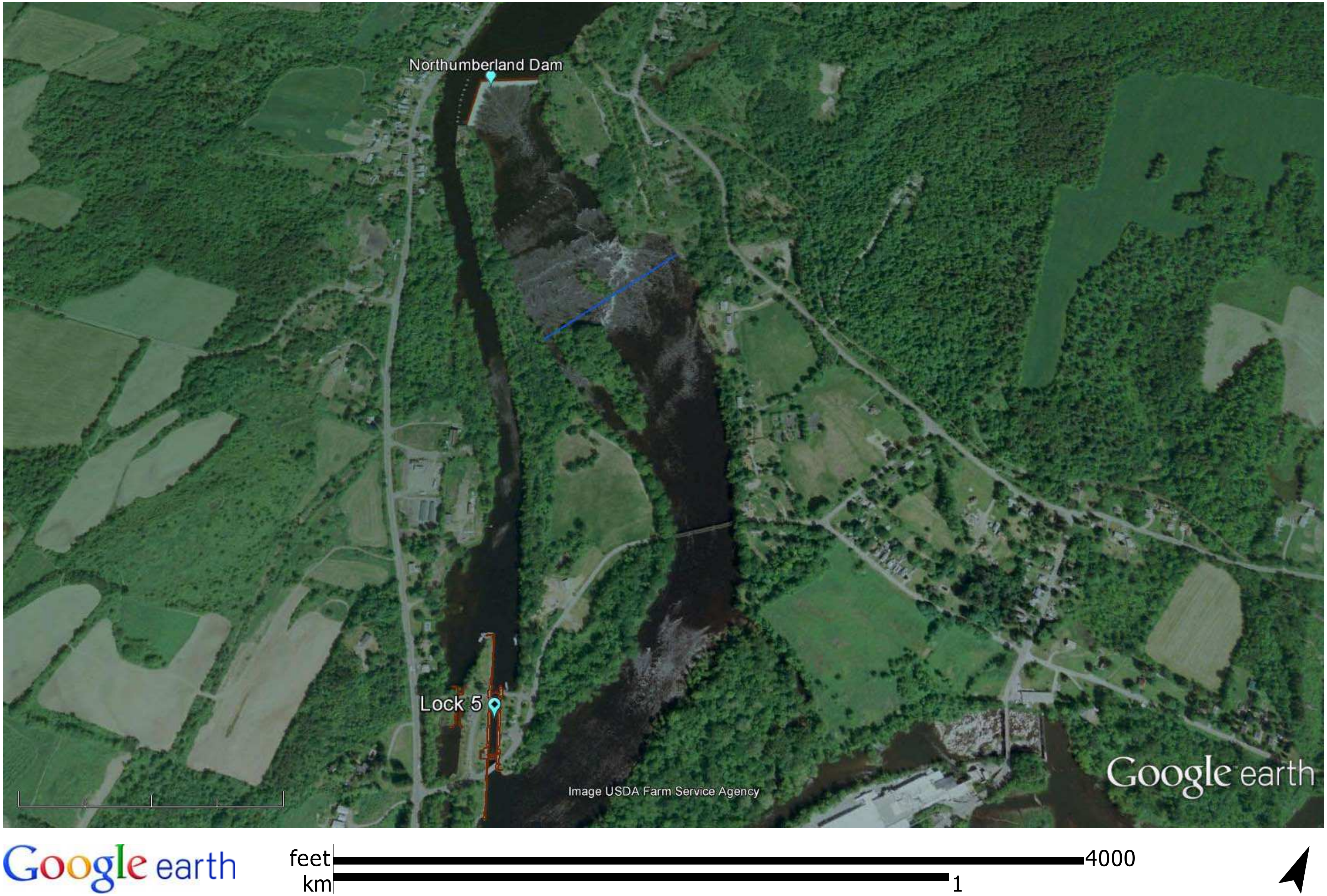
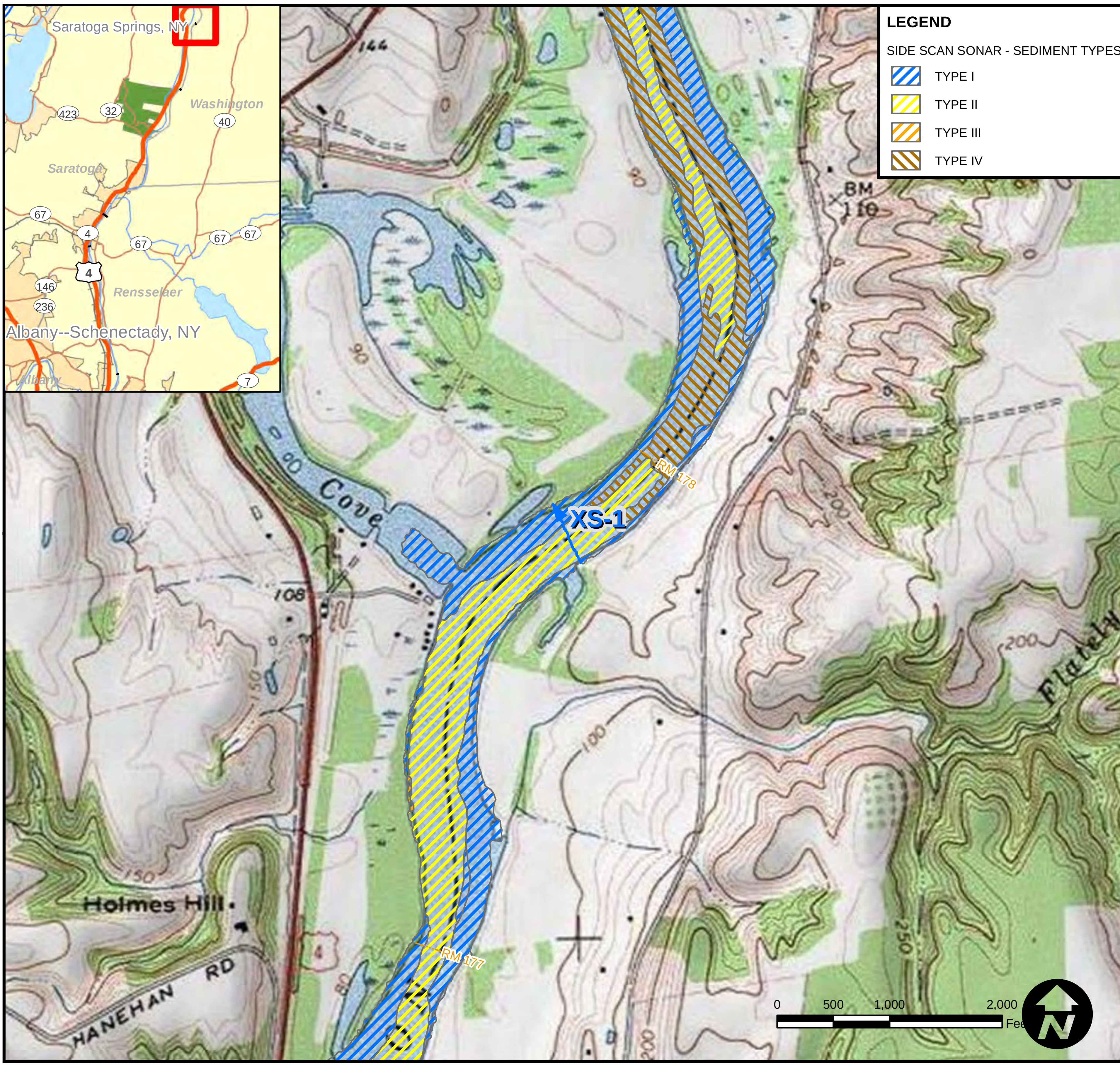
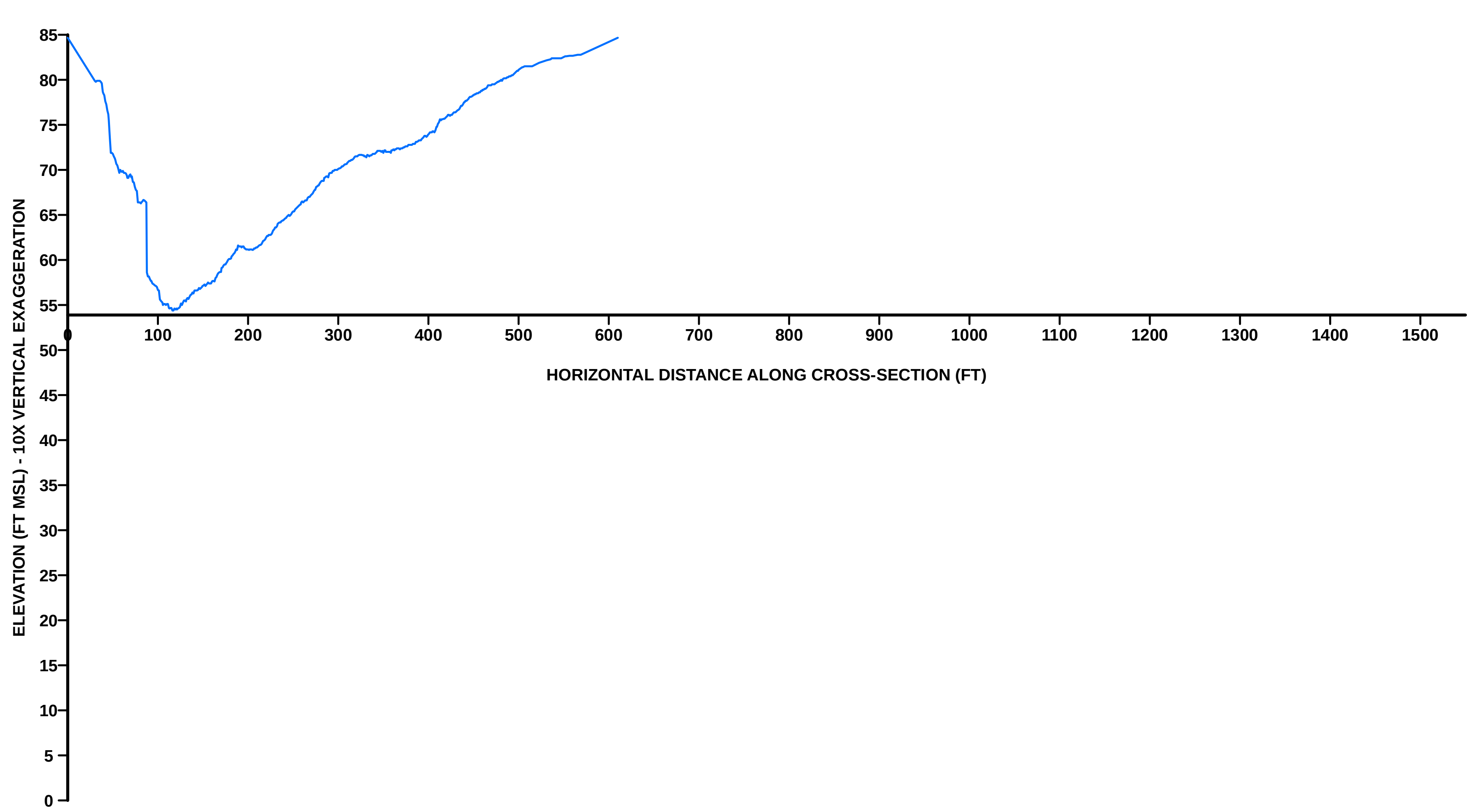


FIGURE B5 - HUDSON RIVER FORT MILLER DAM AND LOCK 6 - Imagery Date: 9/5/2009

ATTACHMENT C

Velocity Cross Section Locations





EHS Support consider it done	GLENS FALLS / LOWER HUDSON RIVER	VELOCITY CROSS SECTION 1	FIGURE 1

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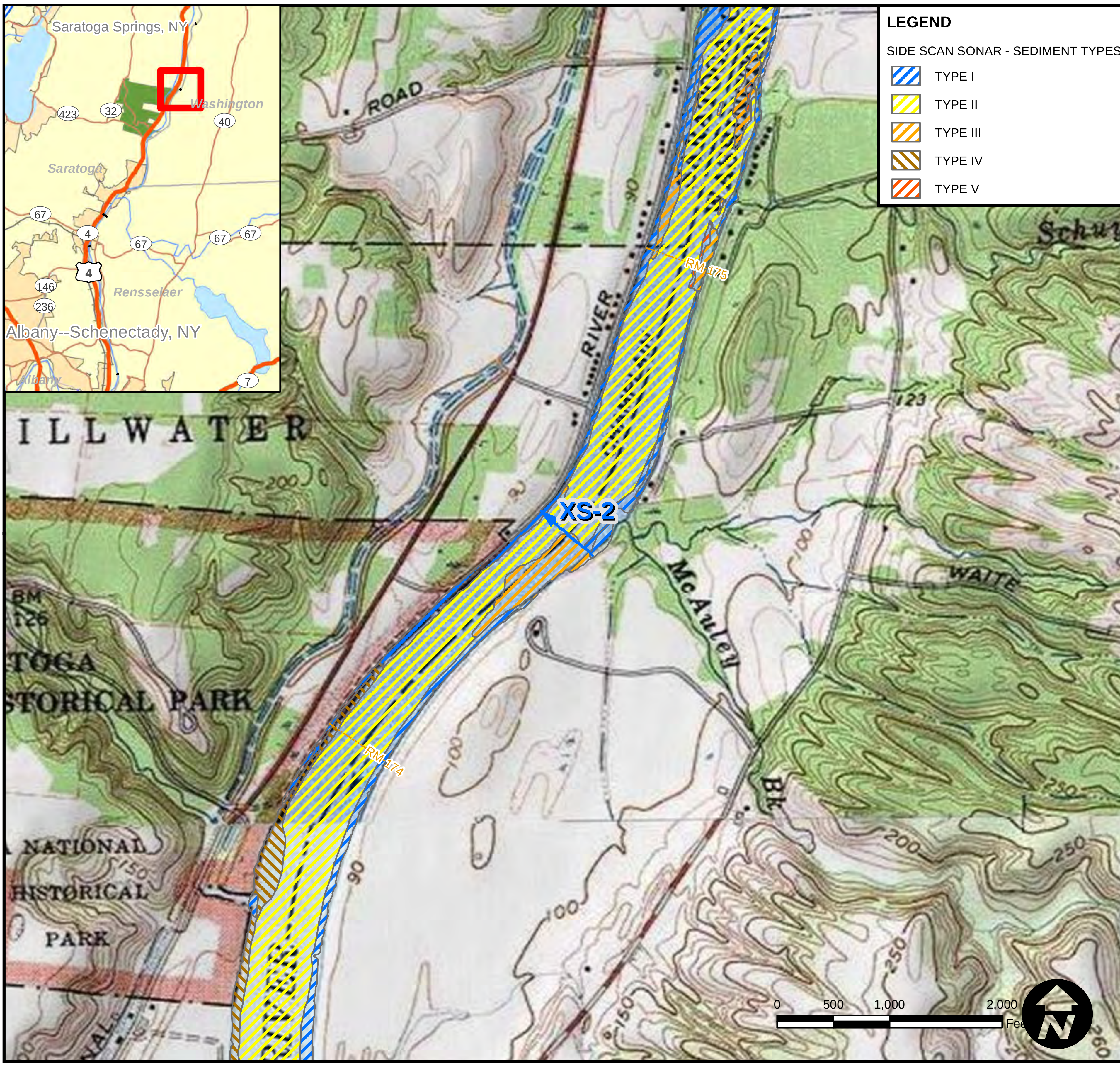

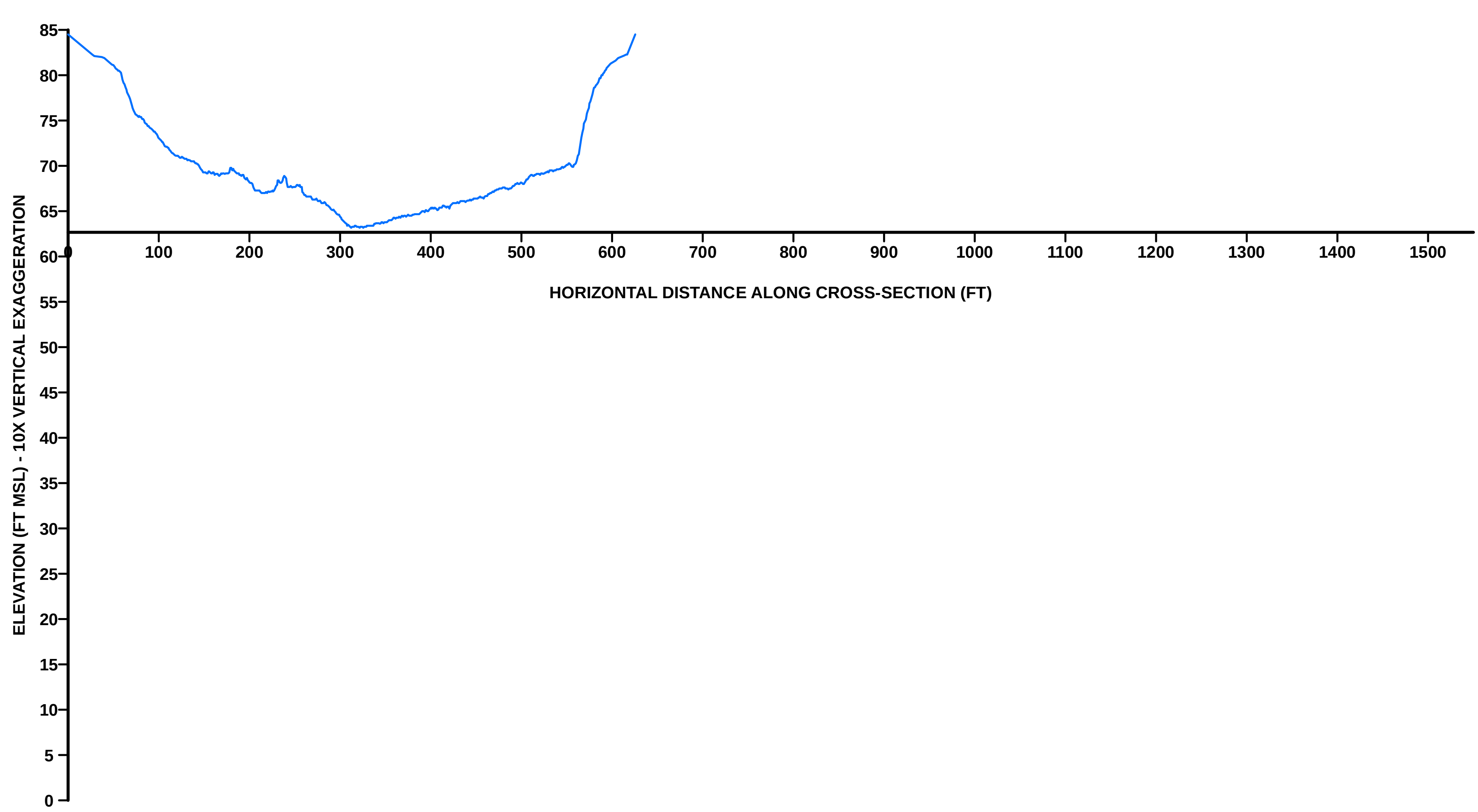

EHS Support consider it done	GLENS FALLS / LOWER HUDSON RIVER	VELOCITY CROSS SECTION 2	FIGURE 2

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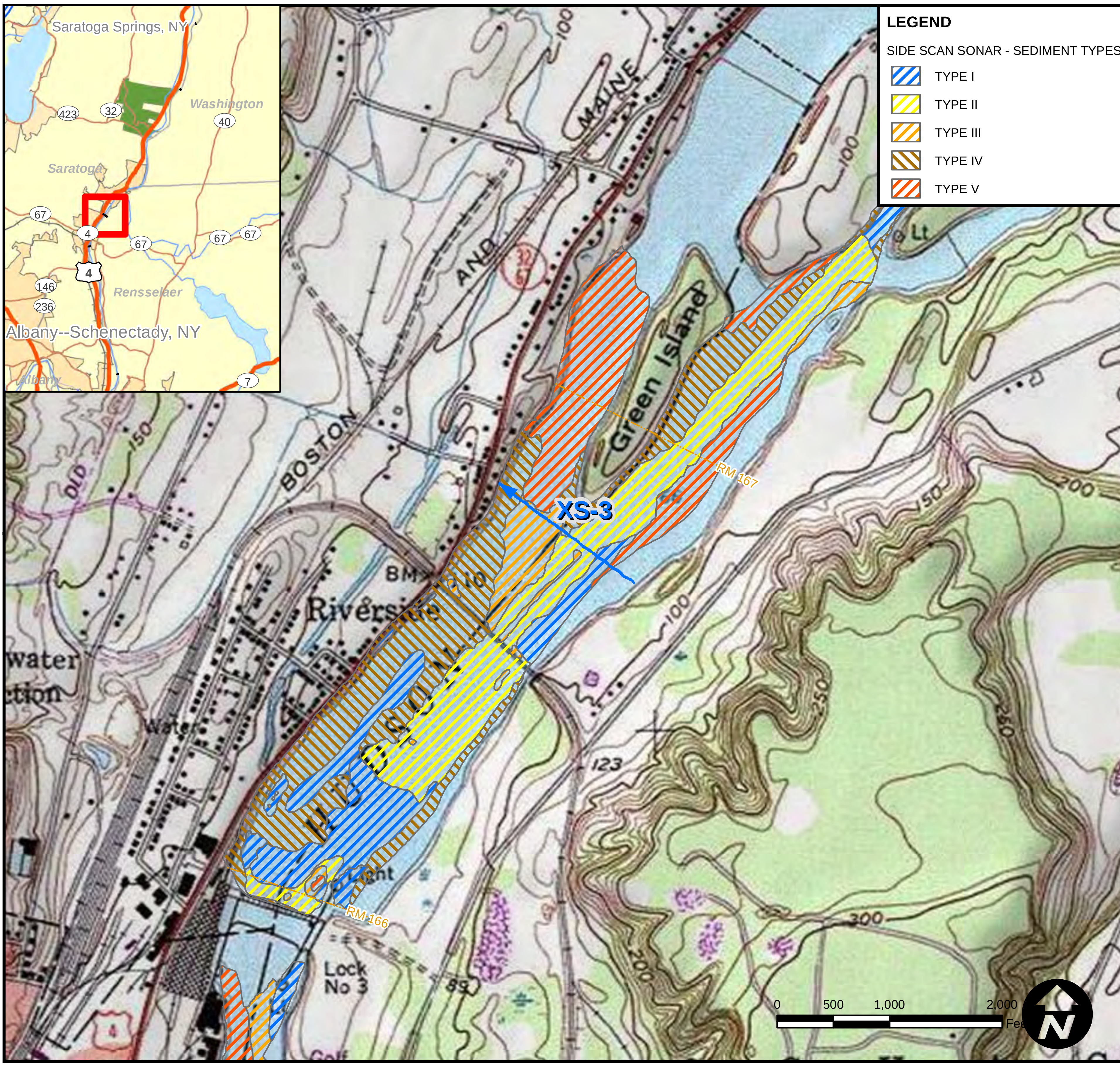

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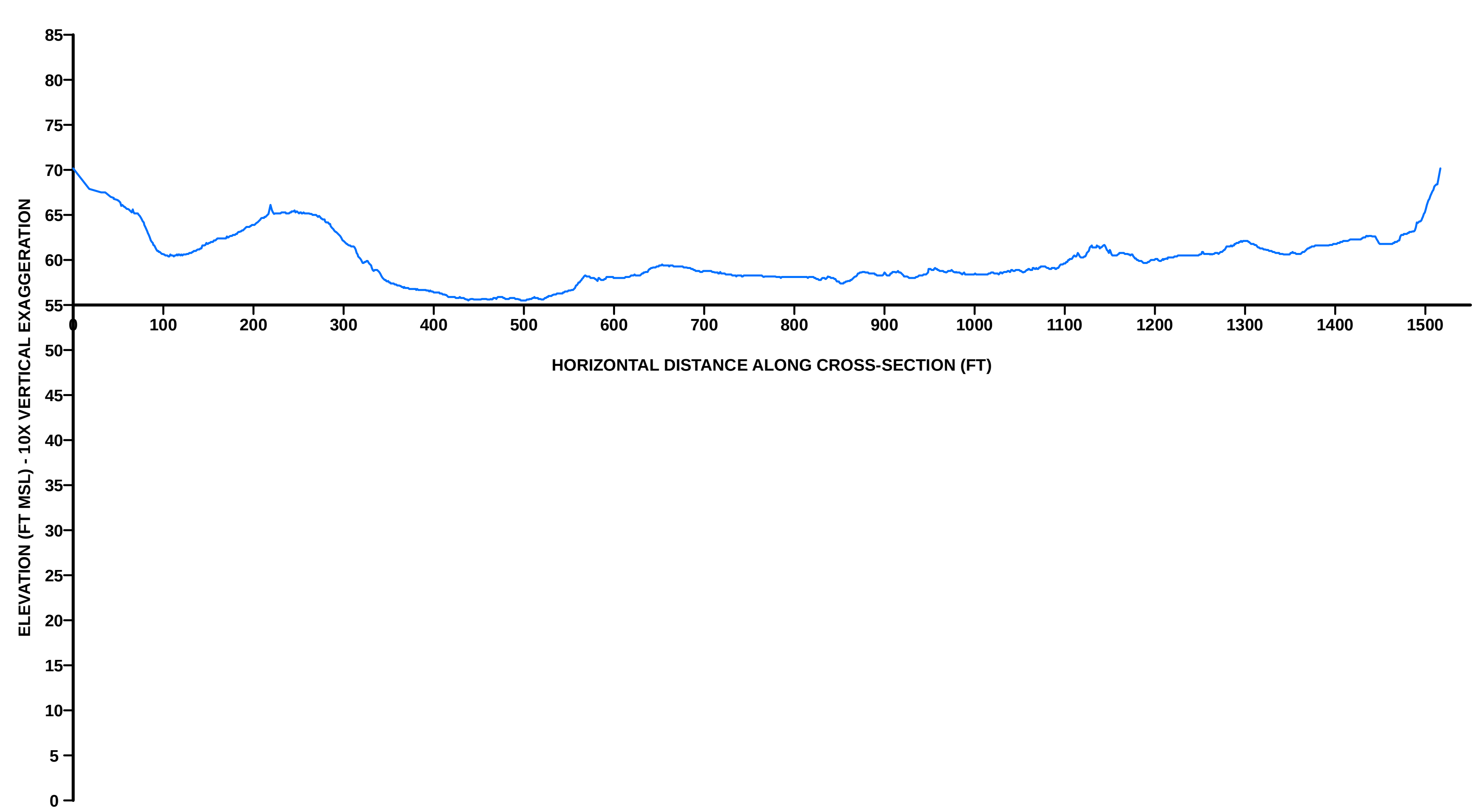
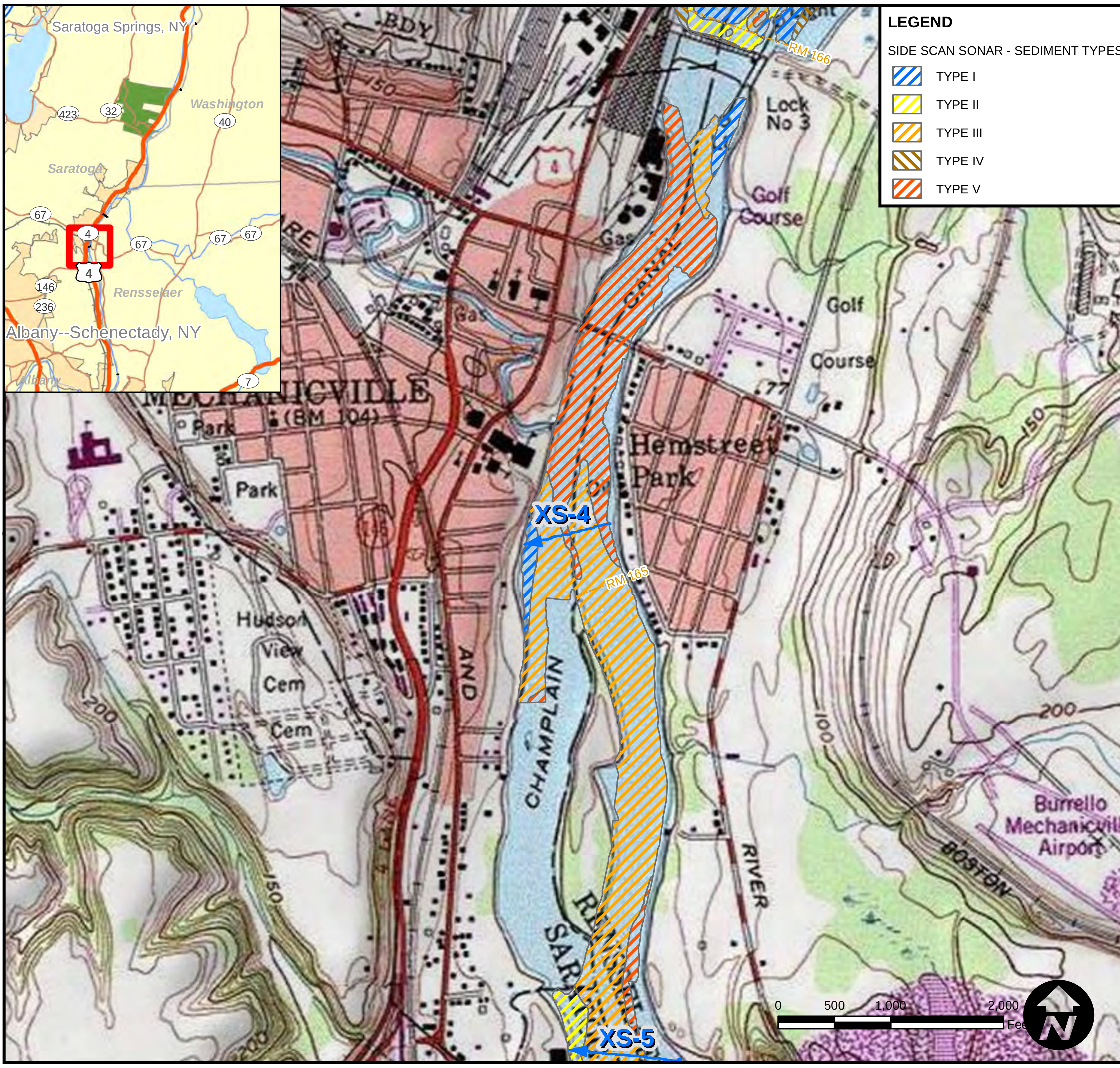
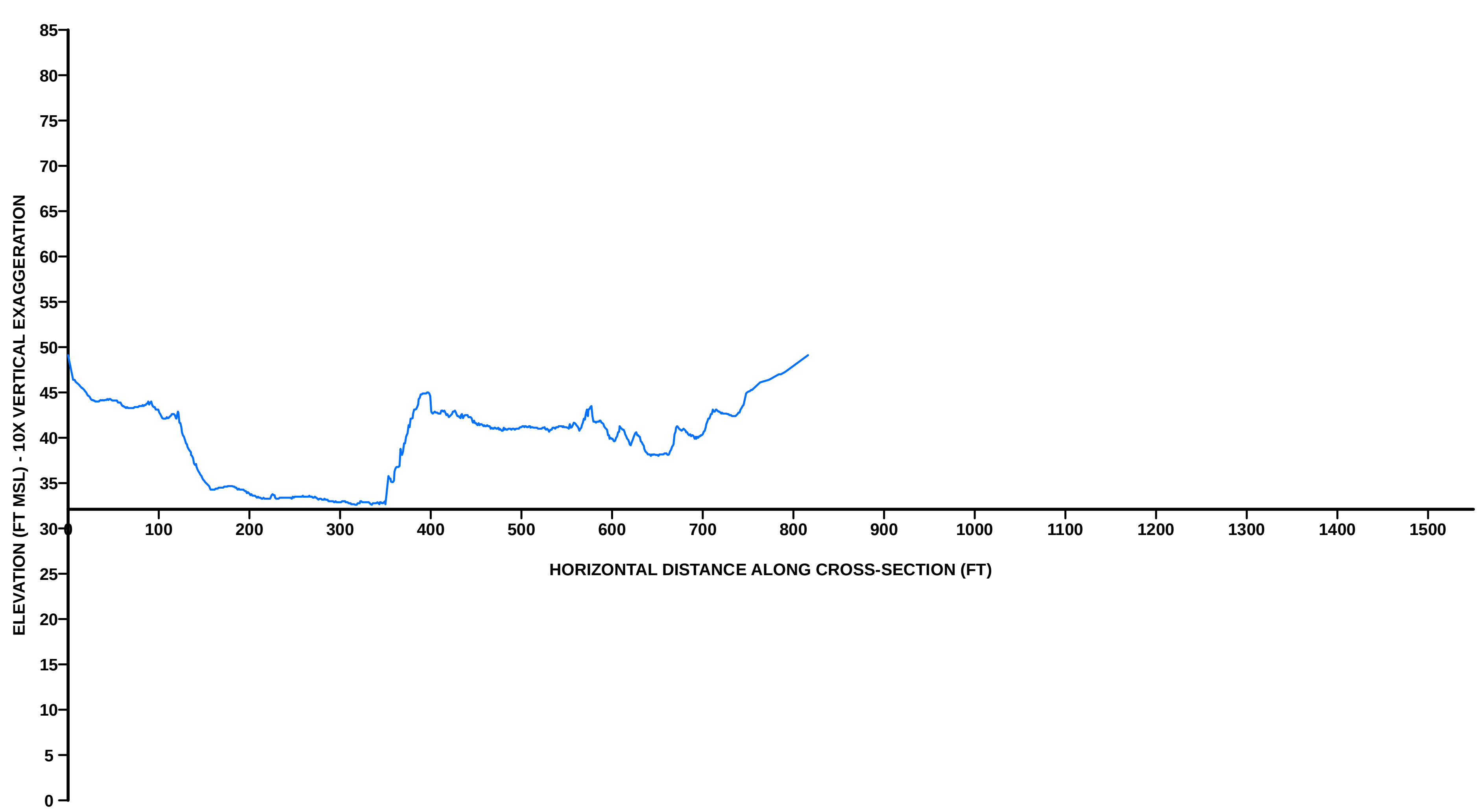


EHS Support *consider it done*	GLENS FALLS / LOWER HUDSON RIVER	VELOCITY CROSS SECTION 3	FIGURE 3





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GLENS FALLS / LOWER HUDSON RIVER

VELOCITY CROSS SECTION 4

FIGURE 4

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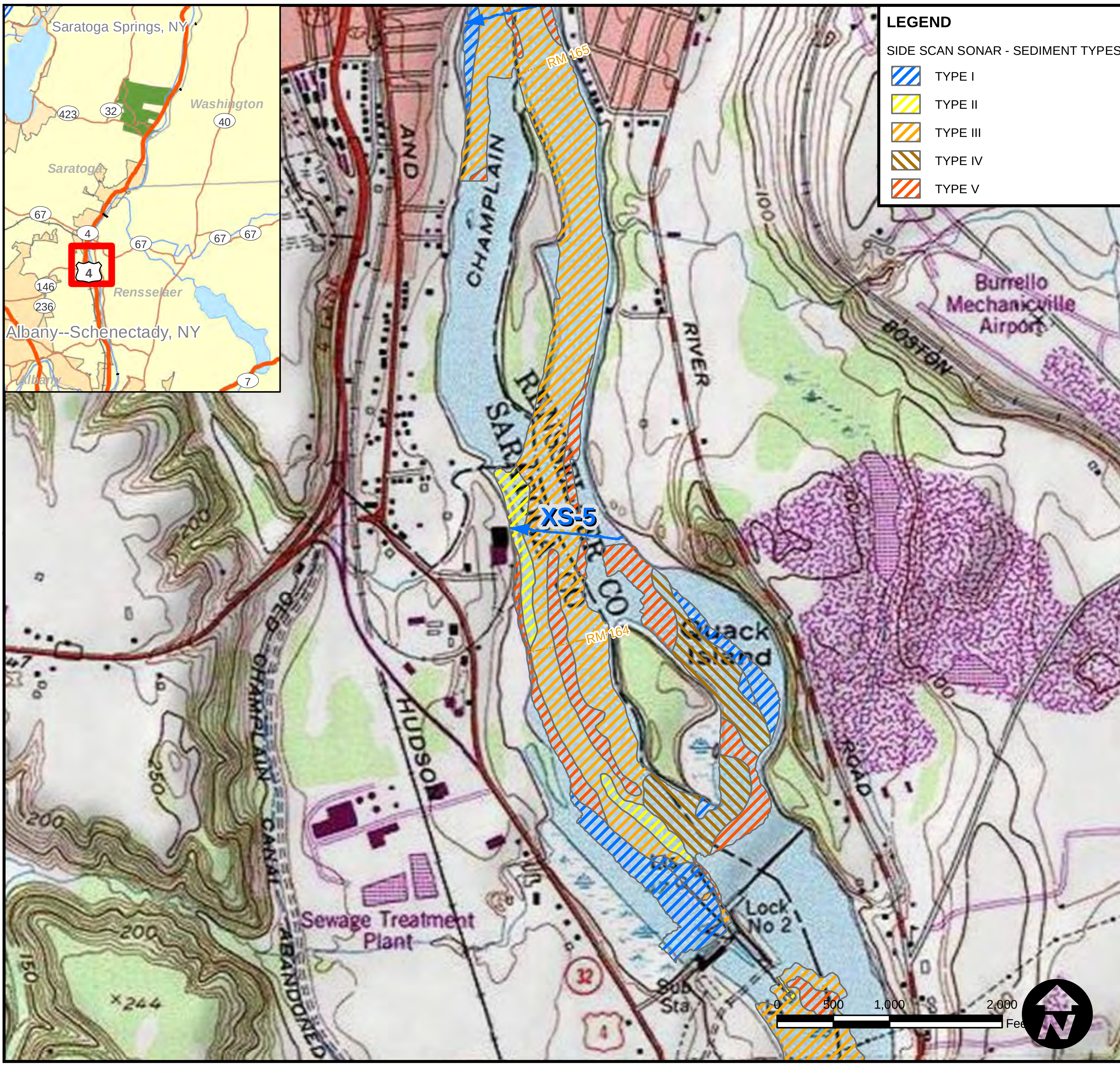

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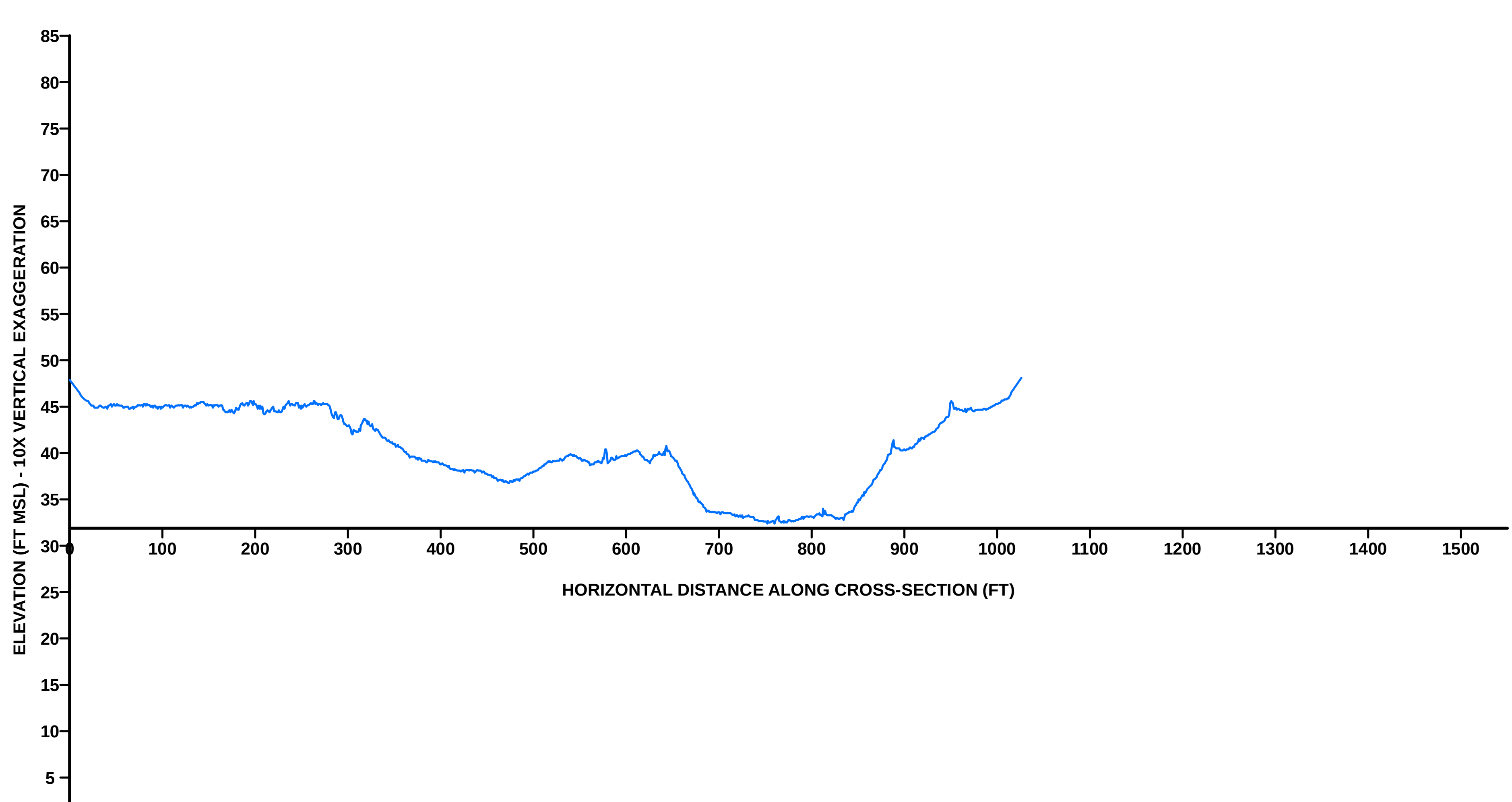

EHS Support *consider it done*	GLENS FALLS / LOWER HUDSON RIVER	VELOCITY CROSS SECTION 5	FIGURE 5

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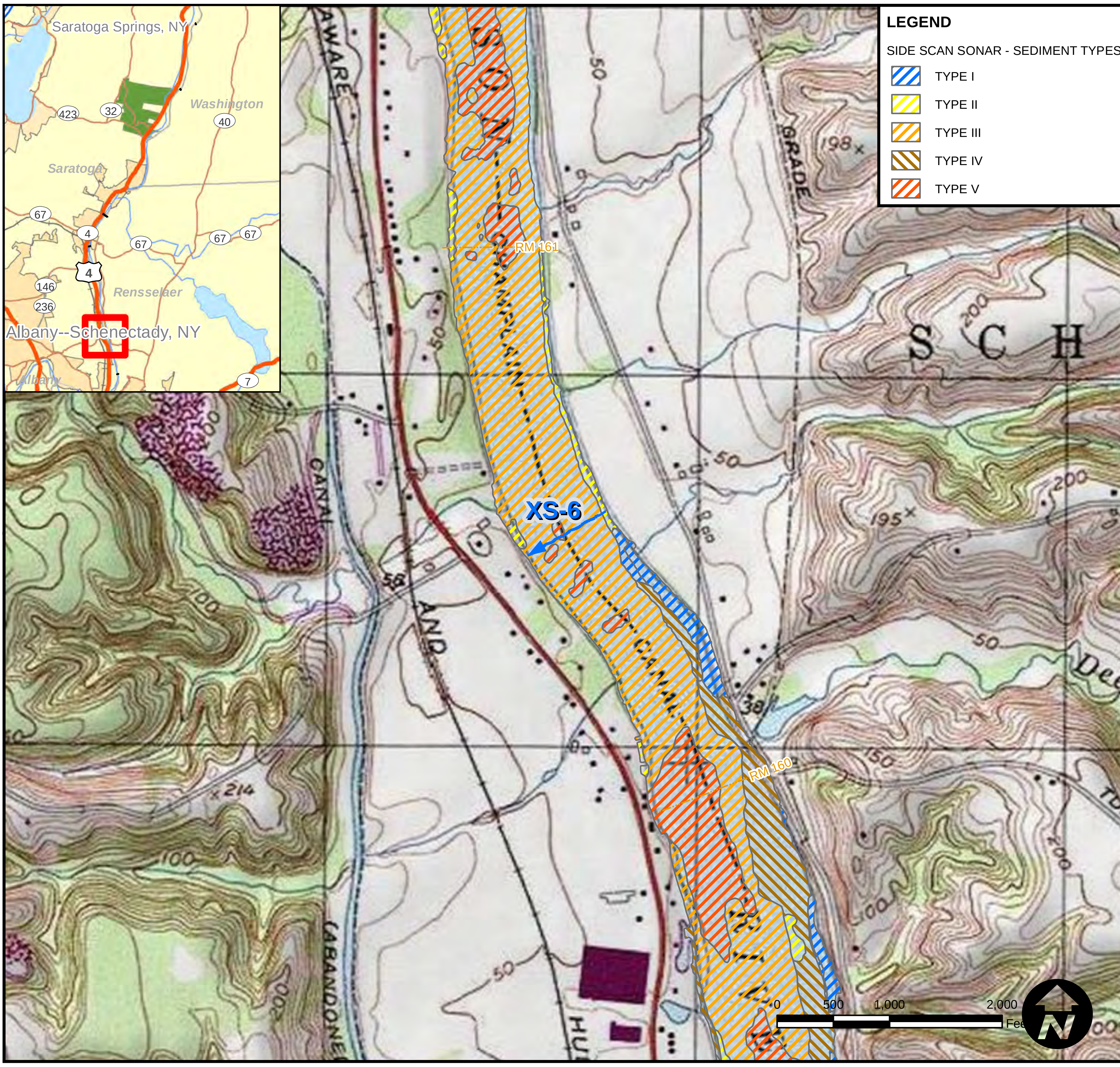

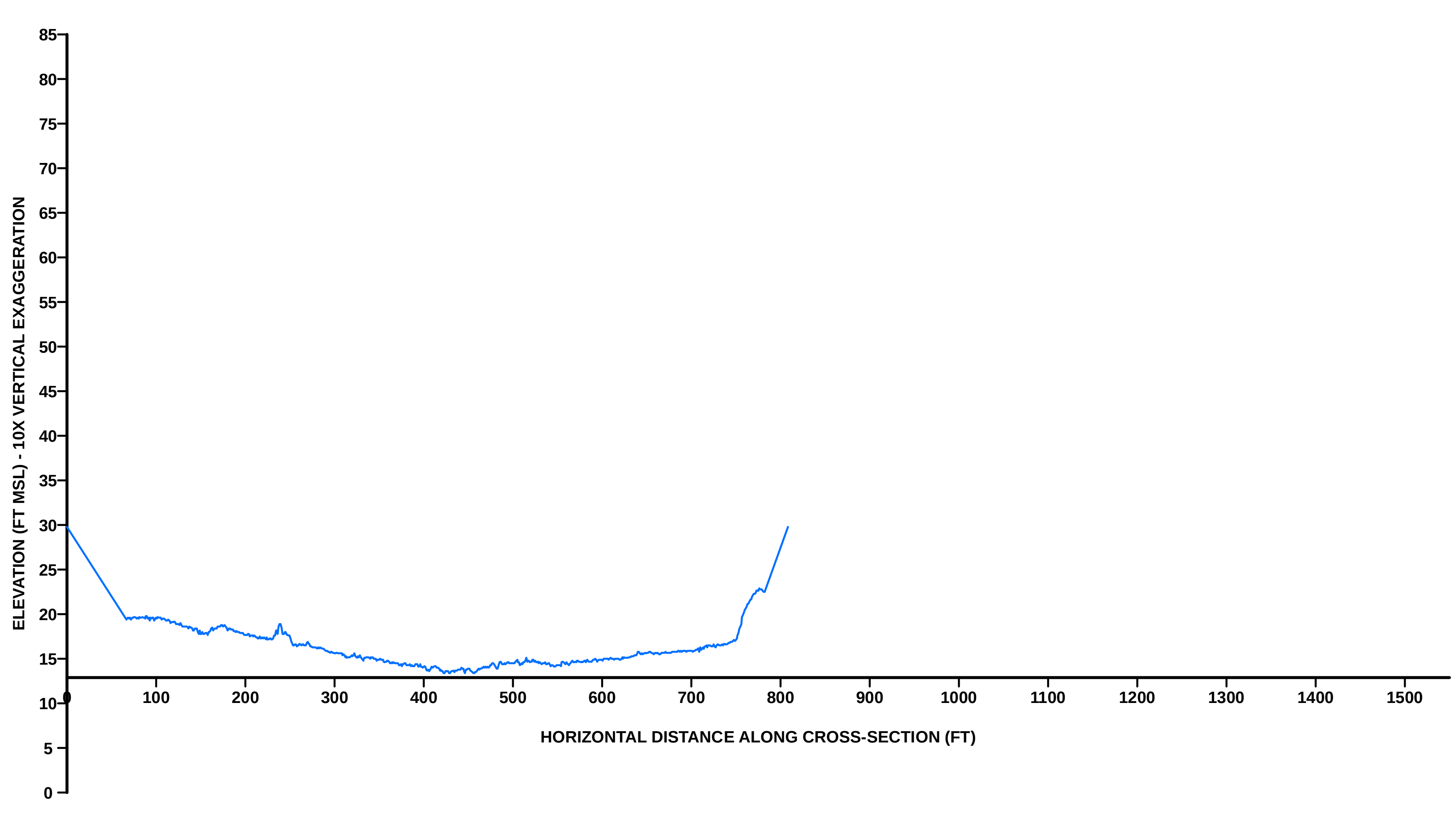

EHS Support *consider it done*	GLENS FALLS / LOWER HUDSON RIVER	VELOCITY CROSS SECTION 6	FIGURE 6

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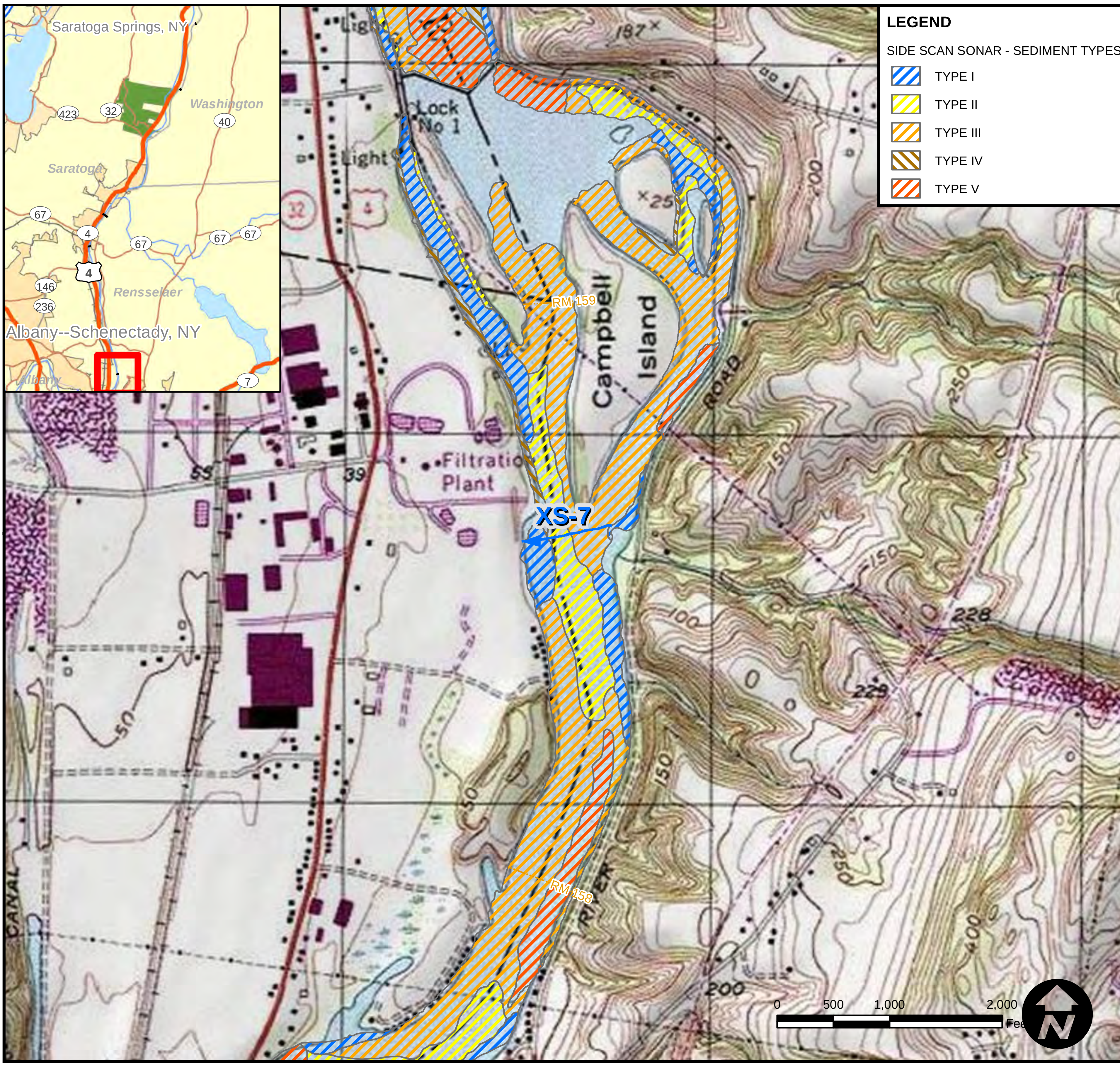

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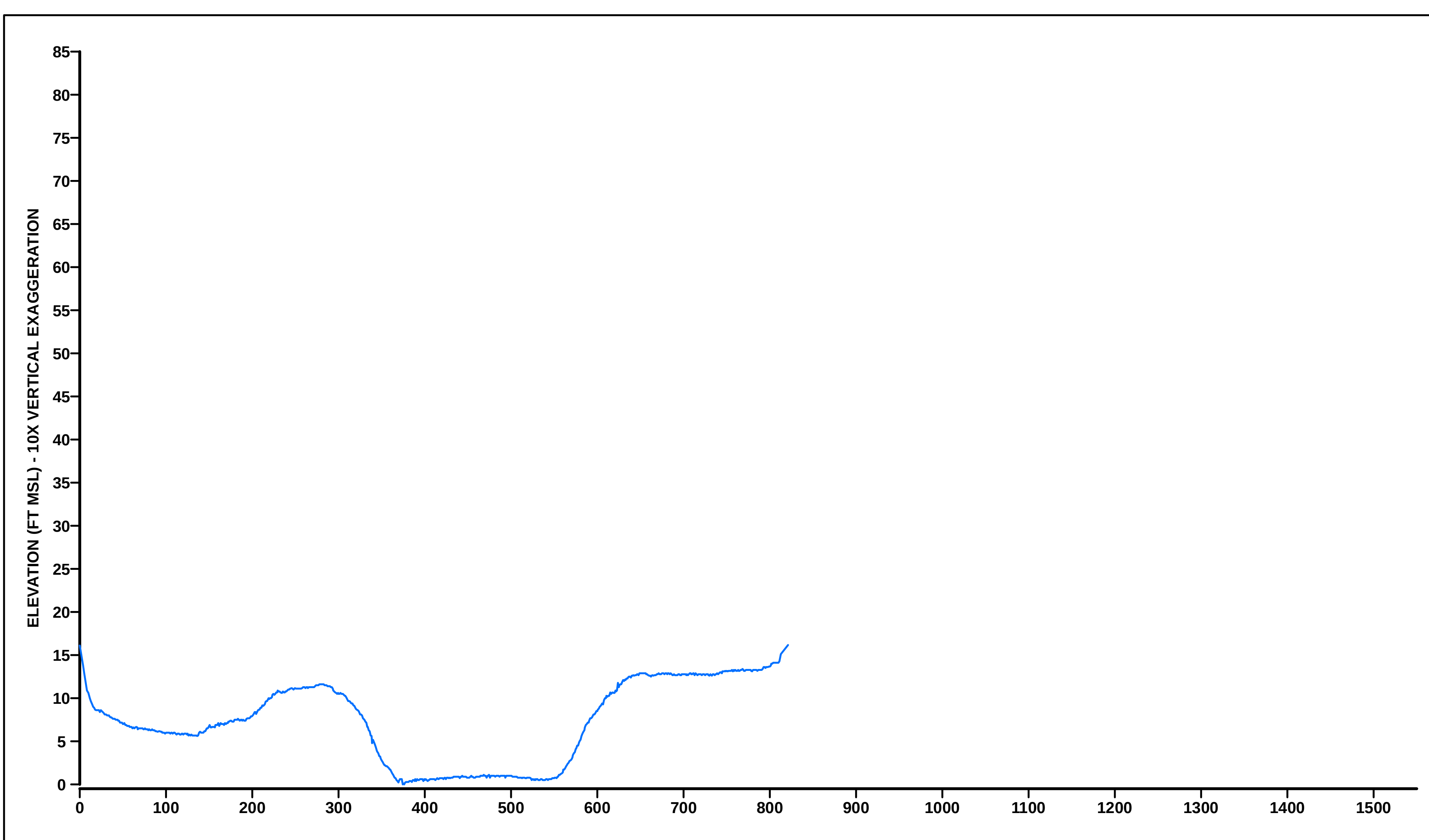

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GLENS FALLS / LOWER HUDSON RIVER

VELOCITY CROSS SECTION 7

FIGURE 7