FINAL STUDY REPORT
SEDIMENT INTRODUCTION AND TRANSPORT STUDY
RSP 3.15

CONOWINGO HYDROELECTRIC PROJECT

FERC PROJECT NUMBER 405

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August 2012

EXECUTIVE SUMMARY

Exelon Generation Company, LLC (Exelon) has initiated with the Federal Energy Regulatory Commission (FERC) the process of relicensing the 573-megawatt Conowingo Hydroelectric Project (Conowingo Project). The current license for the Conowingo Project was issued on August 14, 1980 and expires on September 1, 2014. FERC issued the final study plan determination for the Conowingo Project on February 4, 2010, approving the revised study plan with certain modifications. The final study plan determination required Exelon to conduct a Sediment Introduction and Transport Study.

The Conowingo Dam currently traps sediment and associated nutrients generated by erosion and upstream land uses. Previous studies have therefore suggested that the Conowingo Hydroelectric Project has the potential to adversely impact the water quality of Chesapeake Bay by the release of sediment behind the dam as a result of a scour event associated with a major storm, or from the loss of sediment trapping capability when Conowingo Pond reaches its sediment storage capacity. Because sediment deposition and transport is a basin-wide, multi-dimensional issue, the goal of this Sediment Introduction and Transport study was to provide data for the future development of an overall sediment management strategy for the lower Susquehanna River and Chesapeake Bay by others.

This study involved three tasks: a review and compilation of existing information (Task 1); a quantitative assessment of sediment-related impacts of the Project on downstream habitat (Task 2); and an evaluation of options to manage sediment at the Project (Task 3). In conducting the tasks associated with this study, Exelon tested the following assumptions underlying previous studies relating to the Project’s potential effects: 1) 400,000 cubic feet per second (cfs) is the trigger flood event for scour; 2) the two upstream reservoirs—Lake Clarke and Lake Aldred—are at steady-state equilibrium with respect to sediment trapping; and 3) Tropical Storm Agnes (1972) was associated with a major scour event in Conowingo Pond.

Existing literature and data examined in Task 1 involved both regional and local published scientific investigations and Project-specific field studies. Specifically, Exelon reviewed: the sedimentary context of the Project area; previous studies of the Project area; relicensing field studies, which included a characterization of bank stability, shoreline erosion, and nearshore sedimentation; and additional relevant information, such as local bed level control by bedrock and tributary input. A key finding of Task 1 was that prior to the construction of Conowingo Dam, the river in the Project area was likely very similar to the condition of the river today downstream of the dam. A natural barrier existed at the site of the dam, and flow was strong enough to inhibit sediment deposition until near the mouth of the river.

In Task 2, Exelon performed three quantitative assessments to examine localized sediment-related impacts of the Project on downstream habitat. The first analysis calculated sediment entrainment potential ratios for different Project release scenarios by comparing bottom shear stresses to the critical shear stresses required to initialize and sustain mobility of substrates supporting persistent habitats for immobile life stages of biota. The second analysis tested hypotheses of earlier studies of potential scour in Conowingo Pond during major storm events. This was accomplished by using the HEC-6 model previously developed by the U.S. Geological Survey (USGS) for the lower Susquehanna River reservoir system. The third analysis used a regression equation developed by the USGS relating discharges at Conowingo Dam to quantities of bottom sediment scour in Conowingo Pond to compare with the HEC-6 results.

The HEC-6 results:

1. Do not seem to support the conclusion that the catastrophic impact to the Chesapeake Bay from Tropical Storm Agnes was due to scour from Conowingo Pond;

2. Suggest Lake Clarke is not in equilibrium and is, in fact, trapping sediment; and

3. Contradict the net scour regression model which is predicated on a 400,000 cfs scour threshold.

Building on the results of Tasks 1 and 2, for Task 3, Exelon evaluated watershed-based sediment and nutrient management practices currently in place, including the Environmental Protection Agency's Chesapeake Bay Total Maximum Daily Load (TMDL) Program, which indicate that Best Management Practices (BMPs) from all sediment/nutrient source sectors are effective in reducing sediment and nutrient loads to Conowingo Pond. Exelon also examined traditional methods of preserving reservoir storage capacity and developed potential components of a proposed Sediment Management Plan for the Project. BMPs for erosion and sediment control on Project lands that may be evaluated and incorporated into a proposed Sediment Management Plan are:

- Streambank protection
- Stream bank stabilization
- Establish riparian buffers

Finally, as part of Task 3, Exelon conducted a cumulative impacts analysis of Project relicensing on the lower Susquehanna River Basin and Chesapeake Bay. With or without a Sediment Management Plan, the cumulative impact of the Project will be to continue to reduce sediment and nutrient loads to the Chesapeake Bay until sediment storage capacity in Conowingo Pond is reached.

In addition to challenging the hypotheses upon which assumptions regarding Project impacts are based, this report identifies and highlights discrepancies and limitations of existing data and reveals the need for a single comprehensive and integrated analysis of the lower Susquehanna River watershed. The U.S. Army Corps of Engineers is currently in the process of conducting such a study which includes all three reservoirs, riverine processes in the Susquehanna River, and the tidal river mouth and upper Chesapeake Bay. This analysis will be able to better isolate Conowingo Pond scour from other sources of sediment passing the dam. Data provided herein has been utilized by the Corps in its analysis, as well as contributing to both ongoing and future efforts to develop an overall sediment management strategy for the lower Susquehanna River and Chesapeake Bay.

An initial study report (ISR) was filed on May 6, 2011. A meeting was held on September 22, 2011 with resource agencies and interested members of the public. Formal comments on the ISR including requested study plan modifications were filed with FERC on March 21, 2012 by several resource agencies and interested members of the public. Exelon filed responses to the ISR comments with FERC on April 20, 2012. On May 21, 2012, FERC issued a study plan modification determination order. The order specified what, if any, modifications to the ISR should be made. For this study, FERC's May 21, 2012 order required no modifications to the original study plan. However, FERC did recommend that Exelon as part of its final license application, include a sediment management plan with provisions for establishing benchmarks and any potential actions that may be necessary for continued operation of the project. Exelon considers "continued operation of the project" to include both generation facilities and project recreation facilities.

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1.0 Introduction

Exelon Generation Company, LLC (Exelon) has initiated with the Federal Energy Regulatory Commission (FERC) the process of relicensing the 573-megawatt (MW) Conowingo Hydroelectric Project (Project). Exelon is applying for a new license using the FERC's Integrated Licensing Process (ILP). The current license for the Conowingo Project was issued on August 14, 1980 and expires on September 1, 2014.

Exelon filed its Pre-Application Document (PAD) and Notice of Intent (NOI) with FERC on March 12, 2009. On June 11 and 12, 2009, a site visit and two scoping meetings were held at the Project for resource agencies and interested members of the public. Following these meetings, formal study requests were filed with FERC by several resource agencies. Many of these study requests were included in Exelon's Proposed Study Plan (PSP), which was filed on August 24, 2009. On September 22 and 23, 2009, Exelon held a meeting with resource agencies and interested members of the public to discuss the PSP.

Formal comments on the PSP were filed with FERC on November 22, 2009 by Commission staff and several resource agencies. Exelon filed a Revised Study Plan (RSP) for the Project on December 22, 2009. FERC issued the final study plan determination for the Project on February 4, 2010, approving the RSP with certain modifications.

The final study plan determination requires Exelon to conduct a Sediment Introduction and Transport Study which is the subject of this report. The objective of this study is to provide data that will be useful in the future development of an overall sediment management strategy for the river and Chesapeake Bay. This is achieved by: 1) reviewing the processes influencing sediment transport past the Conowingo Dam to the upper Chesapeake Bay and the impacts of these processes; 2) assessing localized sediment-related impacts of project operations on downstream habitat to the downstream end of Spencer Island; and 3) discussing regional Best Management Practices (BMPs) that encompass the lower Susquehanna River drainage and sediment management options for Project lands.

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2.0 Background

The Susquehanna River contributes about 50 percent of the freshwater discharged to the Chesapeake Bay (Bay) and, in a normal-flow year, about 25 percent of the sediment load and the greatest quantity of nutrients from non-tidal areas (nearly 66 percent of the nitrogen and 40 percent of the phosphorus transported to the Bay from the major river basins which contribute almost 90 percent of the freshwater) (Langland et al 1995; Langland 2009). Since their construction, the lower Susquehanna River hydroelectric dams (Safe Harbor, Holtwood, and Conowingo) have been trapping sediment and sediment-associated nutrients in their respective reservoirs (Lake Clarke, Lake Aldred, and Conowingo Pond). The lowermost dam, Conowingo Dam, represents the last barrier to sediment transport to the Bay.

The inference drawn from previous studies conducted in the Project area is that a potential effect of the ongoing operation of the Project is the impact to the Bay of a scour event associated with a major storm. This is based on these hypotheses:

1) 400,000 cfs is the trigger flood event for scour;
2) Safe Harbor and Holtwood impoundments are in equilibrium, and
3) Tropical Storm Agnes was associated with a major reservoir scour event in Conowingo Pond

These hypotheses are addressed in this report.

An additional hypothesis addressed is that there may be an impact to substrate character below the dam and the delivery of sediment downstream of Spencer Island.

To examine these hypotheses, it is necessary to consider the numerous overlapping and multi-dimensional sediment issues relevant to this Project. The literature survey provided in this report is intended to provide this background. Figure 2.0-1 provides an overview of the interrelationships of sediment transport issues addressed in this report (Task 1). Second, a HEC-6 analysis was conducted to test the aforementioned hypotheses and a sediment mobility analysis was conducted to examine potential downstream substrate effects (Task 2). Lastly, existing regional sediment management programs and in-reservoir sediment management options are discussed, and a list of actions Exelon can take on Project lands that offer the most beneficial impact with respect to sediment is presented (Task 3).

3.0 Review and Compilation of Existing Information (Task 1)

Figure 3.0-1 depicts the Project area for this report. The sources of existing literature and data in support of this report can be categorized as published scientific investigations of relevant disciplines, with and without a regional (lower Susquehanna River and upper Chesapeake Bay) or local (Project area specific) context, and unpublished Project-specific field studies. With this in mind, the review of existing literature and data is broken out into the following sub-sections:

- Sedimentary Context of Project Area (Section 3.1)
- Previous Studies of Project Area (Section 3.2)
- Relicensing Field Studies (Appendix A)
- Other Studies Relevant to Project Study (Section 3.3 and Appendix B)

A number of field studies have been conducted to gather baseline data in support of the relicensing process. These studies include a shoreline inventory and habitat/wetlands surveys in 2006 – 2008 that yielded information on sediment erosion and deposition in the Project area. Studies conducted in 2010, concurrent with this report, provide additional data used as input to Task 2 analyses. A summary of these studies are provided in Appendix A.

3.1 Sedimentary Context of Project Area

Any discussion of sediment transport through a riverine system must consider river type – bedrock versus alluvial. The constraints on sediment movement in each are different. Existing literature and relicensing field studies indicate that the Project area can be divided into three types along a bedrock-alluvial continuum.

1) Holtwood Dam to downstream end of Hennery Island: little to no alluvial cover
2) Hennery Island to Conowingo Dam: continuous downstream thickening wedge of alluvial cover
3) Below Conowingo Dam: discontinuous surface of exposed bedrock or bedrock with a much thinner alluvial cover than in Conowingo Pond

This segmentation is an effect of the presence of the Conowingo Dam. Historical information and geological data suggest that prior to construction of Conowingo Dam the river had great enough energy and stream power throughout the Project area to sustain a mobile bedload with little sediment deposition until the river mouth was reached. The modern sedimentary setting, however, is one of interrupted sediment transport with significant sediment deposition in the lower Susquehanna River reservoirs. The sedimentary context of the Project area is discussed below to understand the response of this riverine system to the presence and operation of the Project.

3.1.1 Sedimentary Geology of the Lower Susquehanna River

Throughout the lower Susquehanna River in the Conowingo Project area the presence of bedrock is a major determinant of channel adjustment and sediment transport. In the Project area, the river transitions through different positions along a bedrock-alluvial channel continuum. This must be considered as an overprint on the sedimentary processes observed in alluvial systems. Sediment transport through the system must be understood within this context.

Alluvial channel morphology results from the entrainment, transport, and deposition of the unconsolidated sediments of the valley fill and floodplain deposits they traverse (Richards 1985). Alluvial river form "self-adjusts" in accordance with force-resistance relationships of flowing water and unconsolidated boundary sediments. In contrast, bedrock channel form and process are primarily governed by the physical character of the bedrock (lithology and structure) rather than the hydraulic and sediment-transport characteristics of the river (Ashley et al 1988). Channels with both bedrock exposures and accumulations of alluvium are intermediate between the extremes of alluvial and bedrock channels.

A useful sediment descriptor of the continuum between bedrock and alluvial channels is that of a "threshold" channel (NRCS 2007). The bed and bank of threshold channels are not easily mobilized by stream flow while alluvial channels are continuously or frequently reshaped by stream flow through erosion and deposition. Threshold channels are found where there are bedrock outcrops or coarse boundary materials.

The mobility and transport of an alluvial cover in a bedrock channel is complex (Turowski et al 2008a). A bedrock channel classification relevant to the Conowingo Project uses cover properties as its basis. Therein, a bedrock channel cannot substantially widen, lower, or shift its bed without eroding bedrock. End member types in this classification are: 1) channels confined entirely in bedrock with steep bedrock walls and exposed bedrock within the channel; 2) channels with steep bedrock walls, but thick alluvial cover in the bed; and 3) channels with an exposed bedrock bed, but set in an alluviated plain. The Conowingo Project, upstream and downstream of the Conowingo Dam, contains distinct conditions of bedrock exposure and alluvial cover that encompasses gradations of these types. These distinct conditions influence and greatly complicate the movement of sediment through the system.

In the gorge between Holtwood Dam and the downstream end of Hennery Island (the gorge), the river has little to no alluvial cover and can be classified at the bedrock channel extreme. From the base of Hennery

Island to the Conowingo Dam, the river is a bedrock channel with a continuous downstream thickening wedge of alluvial cover with a discontinuous distribution of consolidated and unconsolidated shorelines (see Appendix A). Below Conowingo Dam, the bed is a discontinuous surface of exposed bedrock or bedrock with a much thinner alluvial cover than in Conowingo Pond. There is a discontinuous distribution of consolidated and unconsolidated shorelines. Much of the unconsolidated shorelines within the bedrock channel are the consequence of rail embankment fill and former canal towpath berms.

Historical documents illustrating channel plan and profile prior to construction of the Conowingo Dam and recent investigations of the “strath terrace” landform prominent in the Conowingo Project area provide insight to the sediment regime of the Conowingo Project area prior to dam construction - historically and during the recent geologic past of the Quaternary period (2.5 million years ago to the present).

The 1900 United States Geological Survey topographic map of the Susquehanna River in the project reach identifies “Amos Falls” at the present location of Conowingo Dam (Figure 3.1.1-1). Longitudinal channel profiles in Pratt (1909) **(**Figure 3.1.1-2**)**, Matthews (1917) **(**Figure 3.1.1-3), and Knopf and Jonas (1929) **(**Figure 3.1.1-4**)** indicate a 20-foot drop associated with Amos Falls. The 1799 Hauducoeur map of the area shows two sets of falls between Octoraro Creek and Conowingo Creek (Hector’s Falls and Amos’s Falls)[1] (Figure 3.1.1-5). Other rapids and falls are noticeable on early maps and mentioned in contemporary descriptions of navigation through the river. Most notable of these are Bald Friar Falls and Smiths Falls, above and below the Conowingo Dam, respectively. Brown (2010) offers this description of accounts of the river between Peach Bottom and Smith Falls:

> The nine mile stretch from Peach Bottom to below Smith Falls was another test of the pilot’s skill. The gradient on this stretch of the river is 4.49 feet per mile (Shank 1986), 35 percent less than the upper gorge, but still much faster than on the upper river. Before entering Maryland the mile wide river narrowed to 32 navigable feet at Fanny’s Gap (Magee 1920). Beyond Fanny’s Gap was Bald Friar Falls in Maryland, in which lay the infamous Hollow Rock, which claimed many lives in later years. At Amos Falls was the notorious Job’s Hole which, if a body were dropped into it, it was never seen again (Brubaker 2002). Smith’s Falls

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[1] The Amos Falls of the USGS map is the Hector’s Falls of the Hauducoeur map.

> was more a barrier against going up river than a riffle, for it consisted of numerous rocks protruding from the water.

The pre-construction Labelle survey (1920) extends about two miles upstream of Conowingo Creek to about a half-mile downstream of Octoraro Creek. This survey identifies the locations of Hector Falls just upstream of where the dam would be placed and the beginning of rapids near Glen Cove opposite Conowingo Creek[2] (Figure 3.1.1-6 and 3.1.1-7).

Prior to construction of Conowingo Dam, the river in the modern impoundment and below the dam was a difficult-to-navigate bedrock channel. This is further substantiated by the studies of strath terraces in the project area and exposed bedrock surfaces in the gorge reach summarized below (Pazzaglia and Gardner 1993; Pazzaglia et al 1998, 2006, 2010; Reusser et al 2004, 2006).

Straths are erosional surfaces formed on the channel floor by bedload abrasion. Lateral erosion cuts wide straths during periods of prolonged base level[3] stability. During episodic pulses of accelerated vertical incision the strath surfaces are elevated and abandoned above river margins to produce a terrace landform. Straths are mantled with coarse alluvium representing the bedload transported through the river when the surfaces were cut; their thicknesses represent scour and entrainment depths of the prevailing flow. Along the project reach of the Susquehanna River, Quaternary strath terraces have been identified and mapped in all three bedrock-type reaches distinguished.

At the confluences of Muddy Creek, Fishing Creek, Broad Creek, Octoraro Creek, Deer Creek strath terraces are preserved 30 to 50 meters above the present channel. The alluvium consists of clasts ranging 2 to 8 cm with an occasional 1-meter boulder. Other terraces, 6 and 12 meters above the present channel, occur along the Susquehanna and Tidewater Canal and Conrail tracks at Peach Bottom, Muddy Creek, Octoraro Creek, and downstream of the Conowingo Dam to the river mouth. In the gorge area, a gravel mantled terrace 20 meters above the modern channel is present along the west bank from Holtwood Dam to Muddy Creek. Other strath surfaces are exposed along the sides of the gorge and on island tops without an alluvial mantle other than some boulders.

The correlation of strath ages and riverine deposits at the mouth of the modern Susquehanna River suggest strath formation was coincident with river sedimentation at the mouth of the ancestral Susquehanna River. This suggests that the Quaternary history of the lower Susquehanna River was one

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[2] The rapids at Glen Cove are the Amos Falls of the Hauducoeur map.

[3] Base level is the lowest level towards which a stream can erode, e.g., sea level for coastal streams.

of a river with great enough energy and stream power to sustain a mobile bedload with little sediment deposition until the river mouth was reached. Though this characterization reflects processes over recent geologic time, and is not a snapshot in time that can be directly extrapolated to a historic time scale, the historic maps and contemporary communications noted above suggest this may also have been the condition of the river prior to dam construction.

3.1.2 Modern Sedimentary Setting

Fine-grained suspended sediment and particle-bound and dissolved nutrients (nitrogen and phosphorus) originate within the Chesapeake Bay watershed from upland erosion by different land uses (e.g., agriculture, mining, construction) and from stream corridor erosion (channel bed and banks) (Gellis et al. 2003, 2005). Sediment also originates from the ocean and from within the Bay itself (shoreline erosion, coastal marsh erosion, biogenic material) (Langland et al. 2003). Dissolved nitrogen and phosphorus are transported to surface waters by point source discharges, runoff and soil water, and groundwater (Phillips and Lindsey 2003).

In a year of normal or average stream flow, the Susquehanna River contributes nearly 50 percent of the freshwater discharge to Chesapeake Bay and about 25 percent of the sediment load from non-tidal areas (Langland et al 1995; Langland 2009). The Susquehanna River is the major source of sediment to the northern bay (Langland et al. 2003). Agriculture is the dominant source of nitrogen and phosphorus to the Susquehanna River Basin (Sprague et al. 2000).

Before reaching Chesapeake Bay, sediment originating from upland erosion is stored within the watershed on upland surfaces (e.g., bases of hillslopes, swales and depressions), in reservoirs and impoundments behind dams, and on floodplains (Herman et al. 2003). During storm events, sediments delivered to impoundments, and sediment already stored within impoundments, are made available for transport, deposition, resuspension (scour) and redeposition. Conowingo Pond is the largest of the three lower Susquehanna River reservoirs with a surface area of 9,000 acres. By comparison, the surface areas of Lake Clarke and Lake Aldred are 6,080 acres and 2,560 acres, respectively[4]. The design water-storage capacities of the three reservoirs are 150,000 acre-feet (Lake Clarke)[5], 60,000 acre-feet (Lake Aldred)[5], and 310,000 acre-feet (Conowingo Pond). After construction, the reservoirs began fill with sediment.

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[4] Lake Clarke and Lake Aldred surface areas are converted from square miles provided in Hainly et al (1995).

[5] From Hainly et al (1995)

Previous reports suggest the two upper reservoirs, Lake Clarke and Lake Aldred, have reached a state of equilibrium (steady-state) with respect to sediment deposition. That is, these reservoirs no longer store increasing volumes of sediment and have reached their sediment-storage capacity. While sediment continues to be deposited and eroded from those reservoirs and transported downstream to the next reservoir, there is a net throughput of sediment. In contrast, there is a net deposition of sediment in Conowingo Pond. That is, Conowingo continues to "trap" sediment. Updated storage-capacity curves indicate as of 2008, 86 percent of the sediment-storage capacity of the lower 11.5 miles of Conowingo Pond had been lost by sediment deposition (Langland 2009). Hirsch (2012) suggests that Conowingo Pond is presently approaching a long-term equilibrium where the average rate of deposition and average rate of scour are equal. This condition is discussed more in Section 6.3.

Lake Clarke, created in 1931, was surveyed in 1931, 1939, 1940 1950, 1951, 1959 and 1964 (Reed and Hoffman 1997; Langland and Hainly 1997). Based on these surveys, the water storage capacity of the reservoir decreased from about 145,000 acre-feet[6] in 1931 to about 81,000 acre-feet in 1950. Much of the deposition during this time was sand and coal which was dredged each year from 1954 to 1972 as part of a coal-recovery operation. A survey conducted in 1964 indicated that the dredged material was being replaced by the deposition of incoming sediment. Subsequent surveys have been conducted 1990, 1993, 1996, and 2008. Since 1950, only small changes in water capacity have been measured, suggesting the reservoir reached a state of equilibrium (steady-state) with respect to sediment deposition since 1950. However, Langland (2009) reports that a net deposition of 1,700,000 tons of sediment occurred in Lake Clarke between 1996 and 2008.

Lake Aldred, created in 1910, was surveyed in 1939, 1950, 1961, 1990, 1993, 1996, and 2008. Reed and Hoffman (1997) report that the decrease in quantity of sediment stored in the lake from 1939 to 1961, identified in the 1961 survey, is attributable to decreasing sediment loads reaching the lake after the construction of Safe Harbor Dam in 1931. Reed and Hoffman (1997) concluded that since Lake Aldred is about half the size of Lake Clarke, and Lake Clarke reached equilibrium with sediment transport in about 20 years, Lake Aldred probably reached a state of equilibrium in 10 years, (i.e., around 1920). However, Langland (2009) reports a net deposition of 1,000,000 tons of sediment occurred in Lake Aldred between 1996 and 2008.

The Academy of Natural Sciences of Philadelphia (1994) more aptly describes the steady-state equilibrium condition of this reservoir system as a punctuated equilibrium. That is, periods of gradual

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[6] The value 145,000 acre-feet does not agree with the design capacity value of 150,000 acre-feet reported in Hainly et al (1995).

accumulation are punctuated by episodic flood-driven scour events with stochastic timing and magnitudes unable to be predicted with certainty. Hirsch (2012) similarly describes the filling of these reservoirs as a stochastic punctuated process; not simply filling to a specific time after which the full reservoir remains in a steady-state. What can be predicted with confidence, however, is that the long-term average level of stored sediment in the reservoirs will be below their non-flood steady state levels because of sporadic scouring by major floods.

The Academy report also points out that the actual quantity of sediments derived from the three reservoirs during major floods, rather than from other reaches of the lower Susquehanna River or from its floodplain, needs to be more accurately estimated than has previously been done so that the impact of the reservoirs can be isolated from the impacts of other sources of sediment during these events.

3.2 Previous Studies of Project Area

Numerous empirical and simulation sediment studies have been conducted by USGS and others in the Project area. These include quantitative studies on sediment accumulation rates, storm event scour, reservoir storage volume, sediment-storage capacity, sediment chemistry, sediment and nutrient loads, and sediment transport modeling. These are summarized below. Key parameters are tabulated in Table 3.2-1.

3.2.1 Sediment Accumulation

USGS has compared historic bathymetric surveys (1929, 1959, 1990, 1993, and 1996) and its most recent 2008 survey to identify areas of net sediment accumulation, net sediment loss, and scour (Langland 2009; Langland and Hainly 1997; Reed and Hoffman 1997) in Conowingo Pond. Langland and Hainly (1997) depict discrete areas of scour and deposition (between 1993 and 1996) as a plan view map. In contrast, Reed and Hoffman (1997) illustrate cross-sectional vertical changes 1959-1993. Each study quantifies net sediment gains and losses overall in three sections of the reservoir – upper, middle, and lower reservoir sections.

Bathymetric data, in combination with sub-bottom profiling (for sediment thicknesses), bottom-sediment sampling (for grain-size distributions), and sediment transport modeling (see Section 3.2.6) have been integrated in these USGS studies to evaluate sedimentary processes active in the reservoir. The following is a summarization of these USGS investigations.

The 3.2-mile section of the reservoir immediately below Holtwood Dam downstream to Hennery Island experiences high water velocities due to releases from Holtwood Dam, discharges from the Muddy Run

Pump Storage facility, and a naturally narrow channel. As a consequence, appreciable sediment deposition does not occur here. Similar to a wedge of sediment, thicknesses increase downstream ranging 0-10 feet in the upper section below Hennery Island, 10-20 feet in the middle section, and greater than 20 feet in the lower section below Broad Creek to the Conowingo Dam. Most of the sand in the bottom sediment of the reservoir is found in the upper section (45 percent sand and 7 percent clay) with only 5 percent sand (35 percent clay) in the sediment immediately above the dam. Coal content ranges 2-30 percent throughout the reservoir.

USGS has converted bottom elevation changes in bathymetry to masses of sediment, assuming an average density of dry sediment of 67.8 pounds per cubic foot. This has allowed areas of sediment accumulation (and scour) to be quantified and trends in sediment accumulation identified. The spatial distribution of accumulation has been related to hydraulic parameters such as flow velocity and discharge. Sediment deposition has also been compared with sediment load estimates entering and leaving the reservoir.

An updated 2009 report calculates: 1) approximately 12 million tons of sediment was deposited in Conowingo Reservoir between 1996 and 2008 with all of the deposition occurring in the lower reaches of the reservoir; 2) there was a net sediment loss of 1.8 million tons in the middle reservoir; and 3) a net deposition in the lower reservoir of 13.8 million tons. The reservoir above the Peach Bottom Power Plant displayed little volumetric change and several of the USGS studies suggest that this portion of the reservoir has reached equilibrium with sediment deposition and storage capacity.

3.2.2 Sediment Scour

As noted above, scouring during major flood events interrupts periods of reservoir filling (Academy of Natural Sciences of Philadelphia 1994; Hirsch 2012). The dynamics of sediment and nutrient storage in the reservoir system can more accurately be described as periods of gradual accumulation (net deposition) punctuated by episodic scour events (major storms) that remove stored sediment and increase storage capacity. A flood pulse of sediment and nutrient loading to the Bay is followed by a decrease in loading as deposition replaces scoured sediment. The impact of this process on sediment and nutrient loading to Chesapeake Bay is to alter the timing of sediment and nutrient delivery to the Bay (more during major floods and less during non-flood periods).

The most in-depth analyses of sedimentary processes in the lower Susquehanna River reservoir system during major storm events can be found in Langland and Hainly (1997) and Hirsch (2012). Analytical approaches to quantifications described in Langland and Hainly (1997) rely on the works of Gross et al (1978) and Lang (1982) which established a "scour threshold" at about 400,000 cfs, that is, the stream flow above which sediment is scoured from the lower Susquehanna River reservoirs and carried downstream.

Gross et al (1978) originally suggested this value as the scour threshold in the reservoirs noting that the quantity of suspended sediment passing the USGS Harrisburg station is less than the suspended sediment load measured at the USGS station at Conowingo Dam at peak daily discharges exceeding 400,000 cfs. Lang (1982) compared suspended sediment concentrations at the Harrisburg and Conowingo stations during three high flow events – March 1979, March 1980, and February 1981 **(**Figure 3.2.2-1**)**. The author concluded that the source of sediment to account for the greater suspended sediment load at Conowingo Dam than at Harrisburg during the March 1979 storm (peak discharge >400,000 cfs) is the resuspension, or scour, of sediment behind the lower Susquehanna River dams. Neither of these reports, however, provides data on the river channel or the suspended sediment load between Harrisburg and Conowingo. This is a data gap that affects the logic of 400,000 cfs as a scour threshold for the reservoirs.

Langland and Hainly (1997) identified areas of sediment scour and sediment deposition in the lower Susquehanna River reservoirs by comparing bottom elevation contours of bathymetric surveys conducted in 1993 and 1996. Scour was assumed to be the consequence of resuspension by flows greater than 400,000 cfs. Deposition would occur when flows less than 400,000 cfs redeposited scoured sediment or newly introduced sediment. The change in sediment mass during the interval between the two surveys (at established reservoir cross sections) was estimated by applying a conversion factor representing average density of dry sediment to changes in water volume. The change in water volume was estimated between cross sections over an averaged depth.

The only storm event with a measured discharge greater than 400,000 cfs between the two surveys occurred in January 1996. Thus, Langland and Hainly (1997) attributed the computed mass of scoured sediment primarily to that particular storm. Although a storm with a peak instantaneous discharge of 365,000 cfs (March 26, 1994) was noted in the report, this storm is not considered by the authors to contribute to the observed changes in bottom elevation over the three-year period between surveys. This method calculated 4,700,000 tons of sediment were scoured from the reservoir system and transported downstream.

In their report, Langland and Hainly (1997) estimated the overall error of their methodology by comparing their results (based on bathymetry) with those of an input/output model. Assuming all scour is from one particular storm, mass balance requires that the total suspended sediment load moving through the system during that storm (i.e., river input entering the system plus contributions of reservoir sediment) approximate the suspended sediment load leaving the system (i.e., output). The contribution of reservoir sediment (referred to as the Reservoir Factor in the current literature review) can be viewed as positive (added to wash load in the water column by resuspension) or negative (removed from the wash load by settling and deposition). The Reservoir Factor equals the total mass of sediment deposited in the reservoirs between surveys plus the net mass of deposition plus the net mass of scour. This equation was solved by Langland and Hainly (1997) as follows:

- Suspended sediment concentrations measured at the USGS Marietta station during the January 1996 storm event estimates a river input of 3,200,000 tons
- Reservoir Factor is a net scour of 4,700,000 tons of sediment
- Total estimated mass of sediment deposited in the system between surveys is 6,900,000 tons
- Suspended sediment concentrations measured at the USGS Conowingo station during the January 1996 storm event estimates an output of 7,000,000 tons

Based on this calculation, the authors estimated that a total of 14,800,000 tons of sediment moved through the system but only 7,000,000 tons exited it. This leaves 7,800,000 tons of sediment, more than 50 percent, unaccounted for in the first calculations. Langland and Hainly (1997) went on to identify possible sources of error for the discrepancies between the two approaches:

- Difficulty in obtaining samples at the dam during dangerous storm conditions;
- Accuracy of depth sounding equipment utilized in the surveys;
- Averaging depth to calculate cross-sectional areas;
- Interpreting missing data from backup paper charts; and
- Not including inputs from smaller tributaries.[7]

Another potential source of error may be the reliance on a 400,000 cfs scour threshold value used to explain changes in bathymetry. In fact, Schuleen and Higgins (1953) (cited in Reed and Hoffman 1997) report preferential scour in Lake Clarke with net scour of silt and clay when river flow exceeded 250,000 cfs and net scour of sand likely when river flow exceeded 840,000 cfs.

The bases of the hypothesis that 400,000 cfs is the scour threshold are the works of Gross et al (1978) and Lang (1982). Both those investigations viewed sediment transport through the reservoir system as a

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[7] Conestoga River and Pequea Creek are included.

simple mass balance between suspended sediment loads at Harrisburg and Conowingo. Neither study considered other sediment load data between Harrisburg and Conowingo, including sources other than the reservoirs themselves. These are the limitations of their studies. As originally suggested by the Academy of Natural Sciences of Philadelphia (1994) (see Section 3.1.2), there continues to be a need to clearly discriminate between scour in the reservoirs and other sediment sources during major floods.

Hirsch (2012) suggests that as Conowingo Pond has filled, the decrease in cross-sectional area through which a given discharge must flow increases flow velocity such that there is less deposition from settling suspended sediment, and greater bottom scour due to increasing bottom shear stresses. The consequence is greater scour at discharges that exceed the scour threshold. Hirsch (2012) also suggests, based on suspended sediment concentrations and discharge data measured at the Conowingo Dam USGS station, that somewhere between January 1996 and September 2004 a change in scour threshold to between 175,000 and 300,000 cfs occurred.

3.2.3 Rates of Sediment Accumulation[8]

USGS also analyzed its dataset to determine average annual sediment deposition rates in Conowingo Reservoir since construction of the dam (1928), including the time covered by the term of the existing license (1980 to 2014).

1929 to 1958	3.1 million tons per year
1959 to 1993	2.5 million tons per year
1985 to 1989	1.8 million tons per year (SRBC estimate) [9]
1996 to 2008	1.5 million tons per year

Climate (number, duration, timing and magnitude of storm events) and implementation of sediment-erosion and runoff-control BMPs in the watershed are important factors influencing rates of accumulation. Annual rates also depend on the length of time over which the data are extrapolated.

Decreases in sediment deposition rates in the reservoir from 1929 to 1993 have been attributed by USGS to watershed BMPs and may also reflect reduced reservoir trapping efficiencies. The period 1985-1989 experienced two years with well below normal rainfall and no scour events. Similarly, for the period

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[8] The USGS reports convert volume changes in water capacity (based on bathymetric changes) to mass of sediment. These numbers, therefore, represent an accumulation rate. The term deposition rate used in the source documents are retained here.

[9] From SRBC (1991) estimate based on input/output balance between Harrisburg and Conowingo.

1996-2008, there were minimal scour events and well below normal rainfall for three of four consecutive years (1999-2002).

Using the average deposition rate for 1959 to 2008 of 2.0 million tons per year, a reservoir trapping efficiency of 55 percent, and no large scour events, USGS predicts that the 30 million tons of sediment needed to bring the reservoir to steady-state (sediment storage capacity) is 15 to 20 years (2023 to 2028), extending into the new license period. USGS computes that a reduction of sediment yield rates of 20 percent will extend this 5 to 10 years.

Radionuclides (cesium-124, cesium-127, and lead-210) adsorbed onto sediment particles have been used as tracers of sediment transport and deposition and as tools to compute sediment accretion rates and reservoir trapping efficiencies (Donoghue et al 1989; McLean et al 1991; McLean and Summers 1990). These studies have been conducted by the Maryland Department of Natural Resources (MDNR), Oak Ridge National Laboratory, USGS, and others. During a time period without major storm scour events some of the conclusions of these studies are that more than 60 percent of river sediment entering the reservoir system is trapped there, 3 percent is deposited on the Susquehanna Flats (the 10 kilometers of the upper Bay below the river mouth), and 37 percent is transported beyond Susquehanna Flats. Net accretion rates range from about 2 cm per year half a kilometer downstream of the Peach Bottom Atomic Power Station to about 7 cm per year at the mouth of Broad Creek.

Future weather patterns, particularly scour events and BMP impacts to sediment loads, make estimates of future sediment accumulation rates very difficult to predict with any certainty.

3.2.4 Reservoir Storage Volume and Sediment-Storage Capacity

Based on comparisons of bathymetric surveys, the USGS has calculated changes in water-storage capacity of Conowingo Pond and converted volume changes to sediment mass in order to assess sediment deposition. In 2008, USGS conducted a bathymetric survey of Conowingo Pond (Langland 2009) to update storage volume relationships based on a 1996 bathymetric survey (Reed and Hoffman 1997). Water volume changes and quantities of sediment deposition (or scour) at 21 cross-sections were computed. Quantification of the remaining sediment-storage capacity volume was also updated by comparing cross-sectional area changes along the length of the reservoir with conveyance-based equilibrium cross-sectional areas. Three-dimensional longitudinal profiles were also simulated. The total storage capacity of Conowingo Pond is 204 million tons; current storage is 174 million tons; thus there is about 30 million tons of sediment storage capacity remaining.

3.2.5 Sediment Quality

The Susquehanna River Basin Commission (SRBC) issued a report in 2006 characterizing the sediment behind the three lower Susquehanna River dams (Hill et al 2006). This was a cooperative effort of the Maryland Geological Survey (MGS), the University of Maryland, and the United States Geological Survey. An objective of this study was to provide information on sediment quality.

Coal is a major constituent of the sediment and correlates with sand and silt content. Within Conowingo Pond, the average coal content in cores increases upstream to Holtwood Dam. High coal content (high carbon content) promotes anoxic conditions which can affect the presence and movement of metals and nutrients. Metals were found to be within the range of the main stem of northern Chesapeake Bay. Elevated metal concentrations are correlated with fine grained sediment and localized sources, and are found in higher concentrations at greater depths within cores.

Relatively low sulfur concentrations were found. PAHs, PCBs, and pesticides are present behind all three dams, with higher concentrations found in the upper Conowingo Pond. Hot spots of radioactivity were not found.

3.2.6 Sediment Transport Modeling

The USGS has performed quantitative sediment transport modeling studies in the form of a HEC-6 sediment transport simulation (Hainly et al 1995) and a regression model of peak and daily mean stream flow data that predicts bottom scour (Langland and Hainly 1997). These USGS reports are summarized below.

3.2.6.1 HEC-6 Sediment Transport Simulation (Hainly et al 1995)

The Corps HEC-6 numerical model can simulate hydraulic characteristics of a stream and the deposition and scour of different sediment grain-sizes. USGS selected this particular model because of its ability to simulate long-term trends of deposition and scour; scour routines that handle the full range of grain sizes observed in reservoir inflows; and to compute sediment transport by grain-size fractions, handling both hydraulic sorting and bed armoring. Input inflow data included particle-size fractions (bedload and suspended sediment) of mean daily loads of up to nine discharge values selected to define the full range of the sediment-transport curve. Empirical input data included bottom grain-size distributions of cross-sections (sand, silt and clay) and sub-bottom seismic profiling data for sediment thickness. Simulation variables included fall-velocities; specific gravities; shear-stress thresholds for both deposition and erosion; compaction; and grain-shape. Hydrologic data included tributary inflow and outflows; discharge durations; and temperature.

The model was hydraulically calibrated by the USGS for 1987 (calendar year) flows and closely replicated the high water profile of the 1972 Tropical Storm Agnes. Sediment transport was calibrated to estimates of monthly and annual inflows and outflows of sediment loads for calendar years 1987-89. Inflow and outflow loads and the reservoir trap efficiencies for the calibration period were computed. The model initially appeared to under-predict reservoir traps efficiencies for 1987 when compared to other models (Cohn et al 1989) and empirical concentration and flow data. The model was subsequently revised by having more coarse sediment enter the system. The output data of the revised model for the three reservoir system as a whole, for the calibration year of 1987 and verification years of 1988 and 1989, are provided in Table 3.2.6.1-1**.** The data show no sand passing the system, passage of clay and silt with some trapping, and a consistent overall trapping efficiency of 65 to 70 percent.

The sediment transport simulation of the model for May and June 1972 (which includes the Tropical Storm Agnes flood) indicated some scour of clay and silt during this two-month period with 86 percent of the sand being trapped (Table 3.2.6.1-2**).** Hainly et al (1995) believed the model did not simulate sediment transport during Agnes as well as the period 1987-1989 because it simulated about 2 million tons of sediment deposited in the system rather than the 23 million tons of scour estimated with a simple mass balance of suspended sediment loads between Harrisburg and Conowingo.

3.2.6.2 Regression Model of Bottom-sediment Scour (Langland and Hainly 1997)

A regression model was developed by Langland and Hainly (1997) relating discharges at Conowingo Dam to quantities of bottom sediment scour in Conowingo Pond. The regression curve was fit to scour loads based on differences between entire loads of suspended sediment entering the three reservoir system (input) and exiting the system at Conowingo Dam (output) for six storm events between 1972 and 1996 when peak flows at Conowingo Dam exceeded 400,000 cfs (Figure 3.2.6.2-1). These six storms are identified by Langland and Hainly (1997) as occurring in 1972 (Agnes), 1975 (Eloise), 1996 (January), and three unidentified storms between 1979 and 1996.

This model is based on the hypotheses that 400,000 cfs is the scour threshold and that the Safe Harbor and Holtwood impoundments are in steady-state equilibrium. This is why the difference in reservoir system input and output is attributed to scour in Conowingo Pond. This regression curve was used by Langland and Hainly (1997) to predict loads of total nitrogen and phosphorus from bottom scoured sediments from Conowingo Pond (not the system as a whole). Langland (2009), in contrast, used this curve to estimate the sediment load between 1996 and 2008 from the entire reservoir system from three flood events with daily mean flows greater than 390,000 cfs.

3.2.7 Flow and Sediment Regimes below Conowingo Dam

The effects of river regulation on downstream sediment dynamics is currently understood primarily in terms of calculated sediment-trapping efficiencies and suspended sediment loadings to Chesapeake Bay.

Reported sediment trapping efficiency computations vary widely. USGS estimated the sediment trapping efficiency of Conowingo Dam in 1997 to be 70 percent and uses a value of 55 percent in 2009 calculations of future conditions. Based on radionuclides, Olsen et al (1989) estimated 50 percent; Doneghue et al (1989) estimated 11 percent; and McLean et al (1991) estimated 8 to 23 percent during a 10-year period (1966 to 1976) that experienced two major storms. By removing the effect of scour by these storms, their estimate for sediment retention increases to 33 to 63 percent. Based on reservoir geometry and inflow rates, Williams and Reed (1972) estimated 17 percent.

Suspended sediment and nutrients are monitored at USGS Gage Station 01578310 immediately downstream of the Conowingo Dam as part of the River Input Monitoring (RIM) program. RIM includes sites at the downstream non-tidal reaches of nine major tributaries to Chesapeake Bay. Additional multi-agency monitoring sites throughout the bay watershed are regularly monitored as part of the Chesapeake Bay Non-tidal Monitoring Program. Long-term (1984-2010) trends in flow-weighted concentrations, flow-adjusted concentrations, and annual loads have been evaluated by USGS and SRBC. Flow-weighted concentrations are used to assess actual concentrations and their variability; flow-adjusted concentrations estimate trends independent of stream flow and season. Flow-adjusted trends would represent changes in the watershed, such as those associated with human activities and water quality management, unrelated to flow. Statistically significant long-term downward trends in flow-adjusted concentration of total nitrogen, total phosphorus, and suspended sediment are identified at Conowingo Dam and throughout the Susquehanna River watershed (SRBC 2011; Langland et al 2012) (Figure 3.2.7-1). Langland et al (2012) also evaluated data in the short-term. All the RIM sites received increased annual loads of nutrients and sediment in 2010 compared to 2009 due to increased runoff and stream flow. The combined loads of the RIM sites to the bay increased 33 percent for total nitrogen, 120 percent for total phosphorus, and 330 percent for total sediment. Langland et al (2012) attribute the large increase in phosphorus and sediment loads to two large storm events that occurred in the Potomac River basin in 2010.

The river below the dam is a bedrock-floored channel with a patchy distribution of an alluvial substrate, largely lacking in sediment finer that medium sand. This diminished supply of sediment downstream is a consequence of many inter-related factors, not simply a matter of coarse sediment being trapped behind Conowingo Dam. These factors include flow strength and timing of regulated water releases and storm discharges; sediment load passing the dam from upstream; tributary sediment supply downstream of the dam; and sediment-transport capacities of water releases and storm flows. Existing scientific literature of sedimentary processes below large dams is included in the literature review in Appendix B.

3.3 Other Studies Relevant to Project Study

3.3.1 Substrate Mobility and Biota

Substrate mobility is an element of sediment transport that impacts stream ecology. Schwendel et al (2010) summarizes the published literature pertaining to the impacts of flowing water on benthic communities. Under conditions of low flow velocity and low shear stress sediment will not be entrained, thus, the impact on benthic organisms is limited to the shear force (drag and lift) exerted by flowing water which could lead to a patchy distribution of benthic organisms and the downstream displacement of macrophytes, periphyton, and invertebrates. Bedload transport will begin as flow velocities and shear stresses increase. With Phase-I bedload transport finer sediment is winnowed and rolled over a mostly stable coarser bed. This can impact biota by abrasion. With Phase-II bedload transport, a critical flow velocity is reached that initiates the movement of larger particles which may disrupt armored surfaces and resulting in the patchy distribution of scour and deposition. With more extreme flood events, the whole bed may be mobilized potentially affecting habitat structure by plant and invertebrate displacement and invertebrate mortality by rolling material. Thus, assessments of shear stress and entrainment are means to examine the relationship between benthic biota and bed stability.

Bovee et al (2004) describe how, with the varying discharges accompanying hydropeaking dams, habitat patches can move from one place to another. The instability of patch formation, deformation and migration affect organisms with limited mobility more than highly mobile organisms. Mobile organisms can move to a preferred habitat at another location. Shear stresses capable of moving substrate can also displace infauna. Persistence of habitat, defined as habitat that remains in the same location over variable discharges, is a measure of the spatial stability of a particular habitat patch.

The analysis of localized downstream response of sediment to Project operations in Section 4.1 looks at the effect of shear stress on the persistent habitats where granular substrates exist.

3.3.2 Tropical Storm Agnes: Sediment Delivery from Susquehanna River to Chesapeake Bay

The wealth of data that was collected during and immediately following Agnes provides our best insight to date of the effects of major storms on Chesapeake Bay and the role of sediment discharged to it by the Susquehanna River. A composite of the findings of these studies follows. These include Chesapeake Bay Research Council (1973); Zabawa and Schubel (1974); Gross et al (1978); Schubel and Zabawa (1977); Schubel (1974, 1977); Hirschberg and Schubel (1979); and Schubel and Pritchard (1986).

Suspended sediment concentrations at Conowingo Dam during May 1972 and the first 20 days of June 1972, 10-25 milligrams per liter (mg/l), were higher than normal for that time of year. During the passage of Agnes, concentrations over 10,000 mg/l were reached (June 23) (Figure 3.3.2-1). On June 25, one day after the river crested, concentrations fell to 1,456 mg/l. Surface and mid-depth concentrations of sediment along the axis of the upper Bay following Agnes on June 26 shows a sharp downstream decline from about 700 mg/l off Turkey Point to 400 mg/l at Tolchester to 175 mg/l at the Bay Bridge off Annapolis. While still anomalously high, suspended sediment concentrations in the upper Bay had been reduced considerably by June 29 due to sediment settling and deposition. By the end of July the suspended sediment concentration of the upper Bay was near "normal". While significant erosion occurred farther upstream in the drainage basin, the impact of Agnes on Chesapeake Bay was one of deposition, not erosion. There was little evidence of shoreline or bay bottom erosion.

To identify the sedimentary record left by Agnes and delineate depositional patterns, cores 2 to 4 meters in length were retrieved from upper Chesapeake Bay in August 1972. Cores identified an Agnes sediment layer consisting of laminated silts and clays with minor fine sand. There was a sharp contact with the underlying structureless and bioturbated layer. The sand was primarily quartz and detrital coal. Grain size and clay mineralogy analyses indicated no significant differences between the upper Agnes layer and the lower layer aside from the laminations. The sediment load discharged to the upper Bay was similar in texture as that normally discharged, consisting primarily of silt and clay with fine sand. This is supported by core data showing there is little difference in Agnes sediment and pre-Agnes deposits.

Repeat coring of sampling stations indicated that by June 1973 burrowing infauna had destroyed the laminations with the exception of the station with the thickest Agnes unit. At Susquehanna Flats, about 10 acres of new islands (mud and fine sand) and several hundred acres of new intertidal areas were formed. Being of low relief, they were rapidly eroded.

Examination of these cores indicated that most of the sediments discharged to the upper Bay were deposited in the upper 45 kilometers (above Tolchester) with an average thickness of about 20 cm. More specifically, the thickness of the Agnes layer was greatest between Howell Point and Elk River (20 to 30 cm), under 20 cm from Pooles Island to Howell Point, and 10 to 20 cm between Elk River and Turkey Point (Figure 3.3.2-2). A recognizable layer attributable to Agnes, only a few millimeters thick, was identified in grab samples collected just above the Bay Bridge at Annapolis.

As a point of comparison, Pb_{210} analysis indicated that the Great Flood of 1936 (March 1936) produced a deposit about 36 cm thick in the upper 45 kilometers of the Bay. Although the peak flow of the 1936 storm was less than the peak Agnes flow, the total volume of water discharged was greater and the sediment layer deposited in the Bay by the Great Flood was thicker (Hirschberg and Schubel 1979).

4.0 Downstream Impacts (Task 2)

4.1 Localized Downstream Response of Sediment to Project Operations

4.1.1 Study Objective

The substrate below Conowingo Dam is mainly bedrock with some areas of loose sediment size (Figure 4.1.1-1**)**. While not devoid of finer grained sediment, the fact that the non-bedrock substrates are primarily coarse gravel suggests that the prevalent flow is too swift to allow for the deposition of fine material and/or there is a limited supply of fine-grained sediment. Project operations can influence both of these conditions by water releases and sediment impoundment. And, by affecting the distribution of substrate, can affect the distribution of habitats. Thus, the objective of this study, as stated in the RSP, is to identify Project-related impacts to downstream sediment that could affect habitat.

4.1.2 Methodology Rationale

Substrate mobility affects benthic habitat. The organisms most susceptible to being impacted by bed instability are those with limited mobility. As discussed in Section 3.3.1, analyses of bottom shear stress and particle motion are used to examine the relationship between benthos and bed stability.

The IFIM study for this project (RSP 3.16) identifies the location of persistent habitats for immobile life stages of target species. Persistent habitats remain at the same location over variable discharges; they are a measure of spatial stability (Bovee et al 2004). However, the IFIM model constraints include a static substrate. Thus, this analysis focuses on the potential for sediment to mobilize at the identified persistent habitats under varying flow conditions. A finding of extensive sediment mobility poses a potentially adverse impact to immobile life stages, if present.

Wilcock et al (2009) distinguishes between two classes of sediment transport principles, incipient motion and transport rate. Sediment transport rates are inappropriate for issues regarding frequency of bed disturbance. Rather, the incipient motion principle should be applied. Therefore, an incipient motion analysis is conducted for this study.

The presence of vegetation can interfere with sediment mobilization by changing ambient hydraulics and by trapping or binding sediment. Thus, the distribution of vegetation at persistent habitats was also evaluated.

4.1.3 Methods

The analytical methods used in this report have been adapted from other studies evaluating the movement of coarse grained alluvial cover of bedrock channels and/or river segments affected by flow regulation below dams (Elliot and Gyetvai 1999; Elliot and Hammack 2000; Elliot 2002; Haschenburger and Wilcock 2003; Pohl 2004; Barton et al 2005; Turowski et al 2008b).

A sediment grain resting on a stream bed during fluid flow is subjected to a number of opposing forces (Boggs 2001; Fischenich 2001). Gravity and frictional forces (and cohesion for fine, clay-sized particles) act to resist motion while drag and lift forces are exerted by the flowing water to promote movement. A threshold state occurs when forces acting to move the particle are balanced with forces resisting movement. The critical conditions of flow to initiate grain movement can be estimated by the average boundary shear stress (τ_0) (force per unit area in flow direction) exerted by the fluid on the stream bed. The critical shear stress (τ_c) is that needed to initiate sediment movement.

The Shields equation is commonly used to estimate the τ_c to entrain a median grain size of bottom sediment, or, the critical discharge associated with τ_c (i.e., the minimum stream flow to entrain d_{50}[10] sediment). Gessler (1971) (cited in USACE 1995) reviewed Shields' data and developed a probabilistic approach to incipient movement of sediment mixtures. When τ_c equals τ_0 there is a 50 percent chance for a given particle to move. Thus, there can be entrainment of some grains even when τ_0 is less than τ_c. All grains of a given size class will not be entrained until τ_0 is greater than $2\tau_c$.[11]

When τ_0 is compared to τ_c at various locations (such as along a stream cross-section) for different discharges, one can assess sediment-entrainment potential of each discharge with respect to a particular surface on the cross-section (Elliot and Hammack 1999; Elliot 2002). Entrainment potential (EP) can be expressed as the τ_0/τ_c ratio. A ratio of 1 represents incipient movement of a few particles or in a small area. A ratio of 2 represents widespread mobility.

In this study, boundary shear stresses associated with simulated Conowingo Dam releases are compared to critical shear stresses associated with substrates of persistent habitats. τ_0 was computed by River 2D

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[10] d_{50} is the median particle size

[11] The "entrainment potential" calculations in this report are comparable to the "relative shear stress" calculations in RSP 3.16 (Instream Flow Habitat Assessment below Conowingo Dam) and differ in terminology in order to be consistent with each study's respective literature. The equations and methods used in both reports are identical, and the grain size classes are the only difference. The grain size classification in this study (Appendix C) is consistent with the sediment transport literature, while the mussel study utilizes HSI grain size classes to be consistent with other analyses conducted in that report.

modeling software (see RSP 3.16). Substrate and vegetation data were collected in RSP 3.17. τ_c values used for non-cohesive grain size classes are taken from Julien (2010) (Table 4.1.3-1). The d_{50} value of the streambed used to select an appropriate τ_c was assumed to be the predominant grain size of the substrate[12]. For grain sizes that have a range of τ_c values, the lowest value was chosen as this would represent the worst-case for sediment mobility by maximizing the τ_0/τ_c ratio. This analysis does not evaluate erosion or deposition, only whether an unconsolidated non-cohesive sediment grain of a particular size fraction will be mobilized.

Persistent habitats derived in RSP 3.16 for immobile life stages were used in this study. These are:

- Striped bass fry
- Striped bass spawning
- Shortnosed sturgeon fry
- Shortnosed sturgeon spawning
- Smallmouth bass fry
- Smallmouth bass spawning
- American shad fry
- American shad spawning
- Stonefly
- Mayfly
- Caddisfly

Persistent habitats were derived for four simulated release flow-pairs:

- Minimum 3,500 cfs ; maximum 86,000 cfs
- Minimum 5,000 cfs ; maximum 86,000 cfs
- Minimum 7,500 cfs ; maximum 86,000 cfs
- Minimum 10,000 cfs ; maximum 86,000 cfs

This represents the full range of Project flows from minimums to full generation. The minimum values are required minimum releases established by the settlement agreement of 1989. The maximum value of 86,000 cfs is the full generation flow.

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[12] Sediment classified in accordance with the Udden-Wentworth scale (see Appendix C).

A finding of incipient particle movement or widespread mobility indicates that particle critical shear has been exceeded, but it does not imply erosion and removal of the habitat. This analysis assesses whether sediment be mobilized, not whether erosion or deposition occurs. These are theoretical calculations and repeated visits to habitat locations show that substrates remain. Clearly the critical shear stresses are not exceeded for long enough periods of time to remove the substrate or prevent sediment reaching these locations from being deposited.

Entrainment potential is being used in this study as a means to assess the likelihood that sediment mobility due to Project operations causes adverse disturbances to immobile biota potentially inhabiting suitable substrates. For this study, persistent habitats were chosen as the basis of the analyses because, by definition, these habitats exist over the full range of Project operations and are therefore appropriate for an analysis of bed disturbances by Project operations.

The following steps were completed for this study:

1. Identify non-bedrock (mobile) substrate areas
2. Overlay persistent habitat areas on non-bedrock substrates under varying Project release regimes
3. Assign τ_c values to each substrate grain size within habitat
4. Overlay shear stress layer on non-bedrock substrate substrates
5. Compute entrainment potential for each substrate under varying Project release flow regimes
6. Overlay vegetation layer on habitats

4.1.4 Results

Twelve non-bedrock substrate areas are identified (Figure 4.1.4-1; Table 4.1.4-1). Detailed views of each are provided in Appendix D with associated vegetation. All but two (Areas 3 and 11) had persistent habitats present. Table 4.1.4-2 identifies the acreage of substrate type in each area and Table 4.1.4-3 indicates which substrates in each area coincided with a persistent habitat under four release flow-pairs. The areas with the most permutations of persistent habitat, life stages, and flow scenarios are Areas 1, 9, 10, and 12. Area 1 is at the mouth of Octoraro Creek and Areas 9, 10, and 12 are below Deer Creek and Smith Falls. The analysis that follows focuses on these four areas.

Table 4.1.4-4 summarizes the results of computed entrainment potentials for each substrate area. For each substrate area under each of the evaluated release flows evaluated (3,500 cfs, 5,000 cfs, 7,500 cfs, 10,000 cfs, 86,000 cfs) the acreage of computed EP values (<1, 1-2, >2) is shown. This table is visually depicted in Figures 4.1.4.1-1 through 4.1.4.1-4.

4.1.4.1 Area 1

At Area 1, at the mouth of Octoraro Creek, the boulder and cobble substrates remain immobile (EP < 1) under each flow release condition (Figure 4.1.4.1-1). The area of maximum mobilization (EP > 2) occurs in a small patch of granule substrate in the shallow pool and remains the same for 3,500, 7,500 and 10,000 cfs releases. Partial mobilization in the shallow pool granule substrate (EP 1-2) increases from one patch at 3,500 cfs to two similar patches at 7,500 and 10,000 cfs. At 86,000 cfs the flow pattern changes such that the shallow pool granule EP is reduced to < 1 and with partial and widespread entrainment shifting to the shallow riffle with granule substrate.

The persistent habitats in the boulder and cobble substrates under all flow scenarios are unaffected by sediment mobility. Persistent habitats with granule substrates exhibit varying degrees of entrainment in different locations under each flow release scenario. Vegetation during the growing season would not affect sediment mobility in the sensitive granule substrate areas in Area 1.

The boulder and cobble substrates of Area 1 comprise persistent habitat for striped bass fry, striped bass spawning, shortnosed sturgeon fry, shortnosed sturgeon spawning, caddisfly, American shad spawning, and American shad fry (Table 4.1.4-3**).** These substrates are stable under all flow release scenarios. The granule substrate areas comprise persistent habitats for striped bass fry, striped bass spawning, shortnosed sturgeon fry, caddisfly, and American shad fry. While the granule substrate areas are mobile for all scenarios, at 86,000 cfs the acreage of widespread mobility is reduced by 93% with a shift in location of incipient motion. At most, the area of widespread mobility of the granule substrate (0.0286 acres) represents a very small portion (less than 1%) of the total acreage of mobile substrate (4.75 acres) and its modeled instability has little impact on the available habitat at this site.

4.1.4.2 Area 9

Area 9 surrounds Robert Island below Smith Falls. At Area 9, all substrates have EP < 1 at 3,500 cfs, but partial entrainment begins at the downstream tip of the medium sand substrate at 5,000 cfs (Figure 4.1.4.1-2). At 7,500 cfs this area progresses to widespread mobility with other patches of the sand becoming partially mobile. At 10,000 cfs a large swath of the medium sand had EP 1-2 or >2 while some of the pebble substrate has begun to move (EP 1-2). At 86,000 cfs there is mobility throughout most of the medium sand and pebble substrates, either 1-2 or >2, while the boulder and cobble remain immobile for each scenario. However, as an overprint, during the growing season SAV will have a strong influence on substrate mobility. The sand and pebble substrates have heavy and moderate water milfoil cover, respectively. The SAV will trap and bind sediment grains and act as a force in opposition to grain movement in accordance with the bottom shear stresses.

The boulder and cobble substrates of Area 9 comprise persistent habitat for striped bass fry, striped bass spawning, shortnose sturgeon fry, caddisfly, and American shad fry (Table 4.1.4-3**).** These substrates are stable under all flow release scenarios. Medium sand is persistent habitat for shortnose sturgeon fry, small mouth bass spawning, caddisfly, and American shad fry. The pebble substrate is persistent habitat for shortnose sturgeon fry, shortnose sturgeon spawning, American shad spawning, and American shad fry. The effect of habitat instability for immobile biota at these locations may be mitigated during the growing season due to the impact of the SAV.

The growing season for the SAV species is July through September (RSP 3.17: Downstream EAV/SAV Study). Periodicity tables produced in the IFIM study (RSP 3.16) indicate the seasonal occurrences of target species. The SAV growing season coincides with the occurrence of American shad fry and caddisfies. At other times during the year, if other conditions are suitable and target organisms are present, sand and pebble substrate mobility may adversely impact the target species when flows increase in strength from 7,500 to 86,000 cfs. During the growing season, American shad fry and caddisfly habitat would be more stable due to the flow dissipation by vegetation.

4.1.4.3 Area 10

At Area 10, along the river margin at Port Deposit, all three substrates (medium sand, granule, and boulder) remain immobile at 3,500 and 5,000 cfs (Figure 4.1.4.1-3). The areas of incipient sand mobility expand between 7,500 cfs and 10,000 cfs. At full generation (86,000 cfs) most of the sand and the riverward half of the granule substrate are in widespread motion. The boulders remain immobile throughout. The heavy water milfoil community in the granule substrate will not have a direct effect on grain motion in that it is located where the model shows EP < 1 for all flows. The moderate water milfoil on the sand substrate, however, may retard mobility during the growing season.

At this location, boulder substrate is a persistent habitat only for caddisfly **(**Table 4.1.4-3**).** This substrate is stable under all flow release scenarios. However, granule substrate is persistent habitat for smallmouth bass fry, smallmouth bass spawning, and American shad fry. Granule mobility begins at 10,000 cfs and the substrate is unstable at 86,000 cfs. Medium sand substrate is persistent habitat for shortnose sturgeon fry, smallmouth bass spawning, and American shad fry. The sand substrate gradually progresses from incipient motion at 7,500 cfs to widespread motion at 86,000 cfs. SAV may have a stabilizing effect on the sand during the growing season.

There is potential for adverse impacts of habitat instability for target species in sand and granule habitats at release flows above 7,500 cfs. Entraining flows will be dissipated by SAV during the growing season. This will benefit caddisflies and American shad fry.

4.1.4.4 Area 12

Area 12, near Spencer Island, all three substrates (pebble, cobble, and boulder) remain immobile at 3,500, 5,000, 7,500 and 10,000 cfs (Figure 4.1.4.1-4). At 86,000 cfs the entire extent of the pebble substrate mid-channel between Spencer Island and the west margin of the river is mobilized (EP >2). During the growing season the pebble substrate is minimally covered with water milfoil which is expected to have a minimal impact on the modeled entrainment potential. The boulders and cobbles remain stable throughout all flows.

The boulder substrate here is a persistent habitat for smallmouth bass and caddisfly, and cobbles are persistent habitat for mayfly, caddisfly, and American shad fry (Table 4.1.4-3). Both these substrates are stable under all flow release scenarios. The pebble substrate is persistent habitat for striped bass fry and striped bass spawning. The pebble substrate undergoes widespread mobility during flows greater than 10,000 cfs but less than 86,000 cfs. Substrate mobility may adversely impact target species between 10,000 and 86,000 cfs, if present.

4.1.5 Conclusions

Mobile substrates are limited downstream of the dam. Where present, boulder and cobble are most prevalent. Four areas provide the most persistent habitat for the most species. One area is at the mouth of Octoraro Creek and the other three are located below Deer Creek and Smith Falls. It is postulated that tributary sediment supply and change in river hydraulic gradient are key reasons for these habitats to have developed at these locations.

Trapping of coarse sediment behind Conowingo Dam limits the supply downstream. Additionally, flow conditions in the river are naturally turbulent, inhibiting deposition until the change in gradient below Smith Falls. Between Rowland and Roberts Islands, the river bottom would be essentially bedrock without the Project, much as it is today, except where there is a discrete sediment supply.

The sediment from major tributaries, Octoraro Creek and Deer Creek, is the source for sediment deposited in areas of locally dissipated flow. This occurs at Areas 1, 9, 10, and 12. The paucity of non-bedrock substrate downstream of the dam boosts the value of the few habitats that exist. The shear stress analysis indicates that there is potential for substrate instability impacts for target species, if present, in sand and gravel substrates below Smith Falls, for modeled Project operation releases ranging 7,500 to 86,000 cfs. These areas are the sand and pebble substrates at Area 9, the sand and granule substrates in Area 10, and the pebble substrate in Area 12.

4.2 Storm Events

4.2.1 Study Objectives and Rationale

A potential impact of the ongoing operation of the Project is the impact to the Bay from a scour event in Conowingo Pond associated with a major storm. Three hypotheses underlie previous analyses examining this potential impact:

1. 400,000 cfs is the trigger flood event for scour;
2. Safe Harbor and Holtwood are at equilibrium, and
3. A major scour event from Agnes was associated with Conowingo Pond.

The HEC-6 model previously developed for the lower Susquehanna River by USGS was selected as an existing analytical tool to test these hypotheses.

If scour of lower Susquehanna River reservoir sediments contributes large quantities of sediment to load already transported to the pond from the watershed, one would expect to see the distribution of the suspended sediment grain sizes to be skewed to coarser sizes compared to non-storm flows. The greater bottom shear stress of storms can resuspend larger grain size fractions and will keep a greater proportion of them in suspension. As a corollary, one would also expect catastrophic storm deposits to be recognized in the sediment record as a coarser grained deposit than non-storm deposits. Thus, another objective of this task is to test the hypothesis that the contribution of scoured bottom sediment from the reservoirs to the total suspended sediment load passing Conowingo Dam during catastrophic storms is reflected in grain size.

In summary, the methodology rationale described above leads to the following questions which are the specific objectives for this study.

1. Are HEC-6 simulations of scour and deposition during storms exceeding 400,000 cfs consistent with scour quantities predicted by the regression model based on a scour threshold of 400,000 cfs?

2. Are HEC-6 simulations of sediment movement between reservoirs in bulk and by grain size class consistent with storm scour quantities determined from mass balance input/output models comparing Harrisburg/Marietta suspended loads with Conowingo Dam suspended loads?
3. Are large quantities of reservoir bottom scour recognized as a source of suspended sediment at Conowingo Dam by its grain size distribution?

4.2.2 Methods

4.2.2.1 HEC-6 Model

HEC-6 is a 1-dimensional numerical model developed by the US Army Corps to simulate and predict changes in river profiles from scour (resuspension) and deposition. Using a series of stream geometry cross sections as input, HEC-6 applies the standard step backwater method to develop a water surface profile of a given river reach, where energy slope, velocity, depth are computed at each cross section. Using these computed hydraulic parameters, sediment transport rates are then calculated at each section for a series of grain size fractions. These sediment transport rates, along with the magnitude and duration of stream flow, allow for a volumetric accounting of sediment transport in one direction (upstream to downstream) and the deposition and scour of specific grain sizes. HEC-6 is typically used to model a series of steady-state flows over long periods; however it is capable of being applied to single flood events.[13]

The lack of appropriate input data for the current study precluded a revision of the 1990 USGS HEC-6 model for the lower Susquehanna River reservoir system in this study. Since sediment deposition has led to changes in water depth since the 1987-1989 calibration period of the model, a sensitivity analysis was conducted to see if changes in depth in this system affect simulated velocities and shear stresses produced by the model. Table 4.2.2.1-1 shows simulation values for velocity and shear stress at each of the HEC-6 transects between Holtwood Dam and Conowingo Dam for the 1972 Agnes event with the model bathymetry and with 5-foot raised bottom. Velocities and shear stresses virtually do not change. The water column depth is great enough over the bed such that changes in bed elevation do not alter velocity and shear stress. Therefore, the 1990 model is suitable for this analysis.

Original HEC-6 input decks were procured from the USGS (Michael Langland, pers. comm., USGS, September 16, 2010) and the HEC-6 model of the lower Susquehanna River was reconstituted in an

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[13] HEC-6 User's Manual (Introduction)

electronic format. The model encompassed the river reach from the Marietta USGS gage downstream to Conowingo Dam, approximately 34 miles, and included stream flow and sediment inputs from Pequea Creek and Conestoga River, the largest tributaries and sediment sources to the Susquehanna River between Marietta and Conowingo Dam.

Key inputs to the USGS HEC-6 model included a series of 42 stream geometry cross sections, as well as the mobile and immobile stream bed sediment thickness at each cross section (Figure 4.2.2.1-1). The input for the main river reach and two tributaries to Lake Aldred (i.e., Pequea Creek and Conestoga River) included sediment load (tons/day), by grain size classification, and flow (cfs) relationships. In addition, particle size distributions for sand, silt, and clay are included for the in-channel sediment located at each model cross section. User specified inputs included stream flow and duration, inflow temperature, sediment properties and transport parameters (i.e., specific gravity and shear stress thresholds) and a rating curve at the downstream end of the river reach.

USGS hydraulically calibrated the model for 1987 (calendar year) flows and was able to closely replicate the high water profile of the 1972 Hurricane Agnes flood. The sediment transport simulation was calibrated by USGS to estimates of monthly and annual inflows and outflows of sediment loads for calendar years 1987-89. The estimated inflow and outflow loads, as well as the reservoir trap efficiencies for the calibration period were computed based on a methodology developed by Cohn et al (1989).

Initial HEC-6 simulations by USGS for the calibration year of 1987 indicated that no sand and only small amounts of coarse silt passed the three reservoirs (Clarke, Aldred, Holtwood, and Conowingo) in the river reach, which was deemed reasonable given that the peak flow for the period was 236,000 cfs. The simulations also indicated that the finer silt and nearly all clay material passed the three reservoirs. However, the model predicted low reservoir trap efficiencies compared to those predicted by the Cohn methodology and field measurements. To address this discrepancy, the USGS elected to shift the particle size distribution data described in the sediment load versus discharge relationships within the model, so that less clay and more silt and sand would enter the system. These adjustments were made until the computed trap efficiency for the reservoir system was within one standard error of those predicted by the Cohn methodology. After these adjustments were made the model predicted sediment transport reasonably well for low and intermediate flows. As noted earlier in Section 3.2.6.1 the simulations for Tropical Storm Agnes were considered to have underestimated scour from the reservoirs.

In the current study, the model is applied to previous storm events with discharges greater than 400,000 cfs - June 22-28, 1972, September 26-30, 1975, January 20-23, 1996 and September, 19-21, 2004. The simulated storm events span the period 1972 to 2004.

4.2.2.2 Scour Regression Model

The Langland and Hainly (1997) regression model (see Section 3.2.6.2) used to estimate scour quantities to compare with the HEC-6 results. Peak stream flow has a narrower spread of the 95-percent confidence limit than daily mean stream flow ($R^2 = 0.91$) (Figure 3.2.6.2-1). Thus, peak stream flow is considered the better predictor of bottom scour in this report. The regression equation defining this relationship was used to estimate tons of bottom scour within Conowingo Pond as a consequence of the same four storm events in 1972, 1975, 1996 and 2004 that were analyzed with the HEC-6 model for comparison purposes.

4.2.2.3 Grain Size Distribution

The USGS suspended sediment database provides daily discharge and size distributions of suspended material at Conowingo Dam from 1979 into 1996. During this span, three storm events (February 1984, April 1993 and January 1996) with discharges greater than 400,000 cfs occurred. Twenty-one data points were recorded during these events compared to 255 data points recorded when the daily mean flow at the station was less than 400,000 cfs. This set of data was analyzed to evaluate the impact of flow events greater than 400,000 cfs on sand transport in Conowingo Pond. Specifically, analysis attempted to determine whether sand content transported during storm events, as a percentage of total suspended sediment, was greater than the sand content transported during normal flow. In order to accomplish this, data were evaluated using the Mann-Whitney U Test.

4.2.3 Results

The output data of the HEC-6 simulations are summarized in Tables 4.2.3-1 and 4.2.3-2. The data include trapping efficiencies of each reservoir for sand, silt and clay; tons of sediment passing through each reservoir (total, sand, silt, and clay); and net deposition and scour in each reservoir (total, sand, silt, and clay). The scour quantities (total) derived from the regression equations are presented in Table 4.2.3-3. This table also includes peak flow and flow frequency. Table 4.2.3-4 provides the suspended sediment grain size distribution during the 1996 storm.

1) HEC-6 simulations indicate that each reservoir traps little to no silt or clay during each storm event, essentially passing it through the system (Table 4.2.3-1). Some silt/clay scour is suggested in Lake Clarke and Lake Aldred. While Lake Clarke and Conowingo Pond trap virtually all sand received from upstream during the simulated storm flows, Lake Aldred passes much of it through

to Conowingo Pond where it is deposited. Overall, Lake Aldred behaves differently than Lake Clarke and Conowingo Pond, acting more as a conduit of sediment transport that the other two reservoirs.

2) The breakdown of quantities of sediment associated with the HEC-6 simulated trapping efficiencies shown in Table 4.2.3-1 is provided in Table 4.2.3-2. In Conowingo Pond, nearly all the sand entering the reservoir from Aldred during each storm is deposited; silt passes during the highest flows (Agnes) but up to 10 percent is trapped in the lesser storms; and all clay passes. Net scour does not occur in Conowingo Pond. Table 4.2.3-3 presents regression curve estimates of the quantity of sediment attributable to scour in Conowingo Pond during each storm evaluated. The absence of scour in Conowingo Pond in the HEC-6 model contradicts the regression model. And, although scour is computed by the HEC-6 simulation in Lake Clarke and Lake Aldred, it is far less than quantities indicated by the studies discussed earlier.

3) Both the HEC-6 model (see #1 above) and Langland and Hainly (1997) suggest Lake Aldred behaves more as a conduit of sediment transport than the other two reservoirs. While scour and depositional areas are identified in Lake Aldred, minimal net changes in sediment mass and storage-capacity were identified (Langland and Hainly 1997). Rather than exporting more sediment than it imports (from sediment supplied by bottom scour), sediment entering and/or scoured from within Lake Aldred may just be redeposited elsewhere in the reservoir or passed through it.

   Channel shape may be a contributing factor. Lake Clarke and Conowingo Pond are larger and wider than Lake Aldred (Table 4.2.3-5). The smaller and narrowing morphology of Lake Aldred may favor transport over deposition. Reed and Hoffman (1997) illustrate how conveyance, a measure of carrying capacity of a channel, is affected by shape. Theoretically, more water is conveyed through a deeper and narrower channel of the same cross-sectional area as a shallower and wider channel because less water is in frictional contact with the channel boundaries. Lake Aldred is not only narrower, overall, than the other two reservoirs but is characterized with steep sided “deeps” in the narrowest reaches (Reed and Hoffman 1997; Langland 2009).

   There are 16 tributaries entering Lake Aldred, including Pequea Creek, Conostoga River, and Otter Creek (PPL and Kleinschmidt 2007). Sediment influx from Otter Creek and 13 smaller tributaries are not included in the HEC-6 run or the Langland and Hainly (1997) analysis. The inclusion of these tributaries might have brought the apparent behavior of Lake Aldred in line with the other reservoirs.

Similarly, the exclusion of tributaries to Conowingo Pond (e.g., Muddy Creek, Fishing Creek, Peters Creek, Michaels Run, Broad Creek and Conowingo Creek) as additional sources to the suspended sediment load reaching the Pond from upstream produces a data gap in both the HEC-6 and Langland and Hainly (1997) analyses produces an over estimation of the contribution of bottom scour to Conowingo Project sediment output during storms events. Other suspended sediment sources unaccounted for include overland sheet flow conveyed to channel margins.

4) Turbulence created by the operation of bottom-release turbine gates and flood release gates at Conowingo Dam inhibits deposition of sediment near the dam (Hainly et al 1995; Reed and Hoffman 1997; Langland 2009). Hainly et al (1995) estimates this effect extends upstream from the dam for about 1.25 miles (River Mile 11). This turbulence occurs during non-storm normal operations (turbines) and during storm events (flood gates) regardless of flow relative to 400,000 cfs.

   Nearly 85 percent (2,010,000 tons) of the net scour in Conowingo Pond reported in Langland and Hainly (1997) occurred in the lower Pond. Of this, more than half (1,119,000 tons) occurred within the zone of influence of turbulence generated by the dam. Thus, a large percentage of scour estimated by Langland and Hainly (1997) in Conowingo Pond is not a consequence of the storm generated resuspension.

5) HEC-6 depicts a system that, during major storm events, carries little sand in suspension and delivers little sand downstream. This is supported by the suspended sediment distribution at Conowingo Dam measured during the January 1996 storm, and by the sedimentary record of major storm events in upper Chesapeake Bay.

   Williams and Reed (1972) evaluated the grain size distribution of suspended sediment transported by streams in the Susquehanna River basin during times of peak discharges. Consistent particle size distributions are displayed across physiographic provinces, averaging 10 percent sand, 50 percent silt and 40 percent clay.

   The daily mean flow hydrograph at Conowingo for the January 1996 storm event is provided in Figure 4.2.3-1. Table 4.2.3-4 shows the corresponding size distribution of suspended sediment flowing over the dam. Less than 10 percent of the suspended sediment load was sand. This is not unlike the non-storm size distribution. The statistical analysis conducted of size distributions of suspended material at Conowingo Dam indicates no significant difference (a = 0.05) in sand transport during flow events greater than 400,000 cfs and flow events less than 400,000 cfs (p = 0.223). Median sand transported during high flow events for this interval, as a percent of suspended sediment, was 2.9 percent. During periods of flow less than 400,000 cfs, mean percent sand transported was 5.7 percent.

These data support the findings of the Army Corps reported in Cerco (2012). Flow and the corresponding percent silt and clay for the time period spanning the 1980s through 2011 show that sediment flowing over the spillway consistently contains only a few percent of sand, despite flow rates sufficient to erode the bottom , i.e., greater than 388,000 cfs. Sediment core data (see Section 3.3.2) show deposits in upper Chesapeake Bay from Agnes, a catastrophic storm, consist of laminated silts and clays with minor fine sand and little difference in grain size and clay mineralogy between Agnes and pre-Agnes sediment deposits. This would seem to support the HEC-6 analysis.

4.2.4 Conclusions

The storm event sediment transport analysis conducted for this study tested three hypotheses. The conclusions reached with respect to these hypotheses are:

1. The HEC-6 analysis does not seem to support the conclusion of the literature that the catastrophic impact to Chesapeake Bay from Agnes was due to scour from Conowingo Pond.
2. The model suggests Lake Clarke is not in equilibrium and is, in fact, trapping a lot of sediment. It does, however, support the hypothesis that Lake Aldred is in equilibrium.
3. The HEC-6 analysis contradicts the scour regression model which is predicated on a 400,000 cfs scour threshold and computations equating sediment input to the three reservoir system at Safe Harbor and output at Conowingo to a simple comparison of suspended sediment loads at Harrisburg/Marietta and suspended sediment loads at Conowingo.

The literature review and HEC-6 analysis highlight the need for a single comprehensive and integrated analysis of the lower Susquehanna River watershed, including all three reservoirs, riverine processes in the Susquehanna River, and the tidal river mouth and upper Bay, in order to address the discrepancies and limitations of previous studies. Such an analysis will serve to better isolate reservoir scour from other sources of sediment passing Conowingo Dam.

The Army Corps is currently conducting such a study. Their study should be able to fill data gaps and resolve questions surrounding the aforementioned hypotheses.

4.3 US Army Corps Lower Susquehanna River Watershed Assessment

On September 23, 2011 the Maryland Department of the Environment (MDE) entered into a cost-sharing agreement with the Baltimore District of the Corps to serve as the non-federal sponsor of the Lower Susquehanna River Watershed Assessment, MD and PA (LSRWA). Specific tasks for this study are assigned to the Corps, US Environmental Protection Agency (EPA), USGS, MDE, SRBC, The Nature Conservancy, MDNR, and MGS.

Study goals and objectives put forth for this study are[14]:

1. Evaluate strategies to manage sediment and associated nutrient delivery to the Chesapeake Bay.
    - Strategies will incorporate input from Maryland, New York, and Pennsylvania Total Maximum Daily Load Watershed Implementation Plans.
    - Strategies will incorporate evaluations of sediment storage capacity at the four hydroelectric dams on the lower Susquehanna River.
    - Strategies will evaluate types of sediment delivered and associated effects on the Chesapeake Bay.
2. Evaluate strategies to manage sediment and associated nutrients available for transport during high flow storm events to reduce impacts to the Chesapeake Bay.
3. Determine the effects to the Chesapeake Bay from the loss of sediment and nutrient storage from behind the hydroelectric dams on the lower Susquehanna River.

The LSRWA is integrating four numeric models for this study (USACE 2011). These are:

- Chesapeake Bay Program Watershed Model (WSM)
- 1D HEC-RAS model
- 2D Adaptive Hydrodynamic (ADH) model
- Chesapeake Bay Environmental Modeling Package (CBEMP)

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[14] http://mddnr.chesapeakebay.net/LSRWA/docs.cfm (accessed Aug 21, 2012).

The integration of these models for this study is depicted in Figure 4.3-1 and the step-wise approach of applying the models is graphically summarized in Figure 4.3-2. This integrated transport modeling approach will enable the evaluation of the effects of various scenarios.

Appendix E contains a summary presentation of LSRWA findings as of July 2012. The current schedule anticipates working existing conditions models by Fall 2012. Exelon has participated in the LSRWA technical meetings and contributed several datasets at the approximate cost of $160,000 to date.

4.3.1 EPA Watershed Model

The EPA Chesapeake Bay Program Watershed Model (WSM) uses a modified HSPF (Hydrological Simulation Program-FORTRAN) to simulate flow and sediment/nutrient load delivery to the Chesapeake Bay from the watershed (Martucci et al 2006; USEPA 2010a). Sediment transport is modeled as separate land and river processes. The latest refinement of the model, Phase 5.3, combines processes of land surface erosion, storage, and delivery to river segments based on land use and distance from a river reach to estimate an Edge-of-Stream Load. Riverine sediment deposition and scour processes are then modeled to compute a load delivered to a river segment outlet. Sand, silt, and clay are simulated separately. This model will be applied to the lower Susquehanna River watershed to provide loads to the reservoirs from key locations within the watershed (USACE 2011).

4.3.2 HEC-RAS Model

HEC-RAS, developed by the Corps, consists of four 1D (one dimensional) components for the analysis of steady flow water surface profile computations; unsteady flow simulation; movable boundary sediment transport computations; and water quality analysis in rivers. It will be applied to route sediment loads (assessed by grain size fraction) received from the watershed (derived from the WSM model) through the upper two reservoirs (Lake Clarke and Lake Aldred) accounting for both sediment deposition and erosion. The output HEC-RAS sediment rating curve will serve as the input sediment rating curve for the ADH model (USACE 2011)

4.3.3 ERDC-2D ADH Model

ADH (Adaptive Hydraulics) is a 2D (two dimensional) model developed by the Corps Engineering Research and Development Center (ERDC). The ADH model can simulate riverine transport for cohesionless sand and cohesive silt and clay, bed erosion and deposition, and morphologic change. It can interface with HEC-RAS hydraulic data and model tidal areas. In combination with HEC-RAS data, ADH can route the sediment load (assessed by grain size fraction) through the Conowingo Pond, Conowingo Dam, and Susquehanna Flats. Two separate ADH models are being developed – one for

Conowingo Pond and one for Susquehanna Flats which extends up the river to the Conowingo Dam. The ADH output will serve as input for the Chesapeake Bay Environmental Models (USACE 2011).

4.3.4 Chesapeake Bay Environmental Model Package

CBEMP (Chesapeake Bay Environmental Model Package) is a system of watershed, hydrodynamic and eutrophication models with dynamic sediment transport capabilities. The three models at the core of the package are the watershed HSPF model, CH3D-WES and CE-QUAL-ICM (Cerco et al 2004). HSPF computes the distribution of flows and loads from the watershed; these flows are input for the CH3D-WES hydrodynamic model which computes three-dimensional intratidal transport; and the computed loads and transport are the input to CE-QUAL-ICM, a eutrophication model. Refinements of the computational grid and model recalibrations have been ongoing since the initial coupling of these models, including those to provide assessment capabilities of living resources (i.e., benthos, zooplankton, and SAV) and to improve the accuracy of water clarity indicators, DO, and chlorophyll.

CBEMP is currently being used to support Bay TMDL development and it will be used in the LSRWA to assess potential impacts to bay water quality and living resources (light attenuation, SAV, chlorophyll, nutrients and dissolved oxygen) of sediment and nutrient loads from the Susquehanna River projected by ADH simulations under different modeling scenarios (USACE 2011)

Eight preliminary modeling scenarios are being considered (USACE 2011).

- Baseline existing conditions of water quality and sediment accumulation
- Water quality and sediment loads after implementation of Bay TMDL
- Impact of reaching steady-state behind Conowingo Dam on TMDL achievement and water quality
- Effect of scour behind Conowingo Dam at steady-state during winter/spring runoff using January 1996 event
- Effect of scour behind Conowingo Dam at steady-state during tropical storm in June/July
- Effect sediment bypassing Conowingo Dam by varying intake and/or outfall locations; seasonal placement; rate of placement; sediment characteristics
- Effect of dredging fines in any of the reservoirs
- Effect of Conowingo Dam operation

5.0 Sediment Management (Task 3)

5.1 EPA Chesapeake Bay TMDL Framework

The EPA Chesapeake Bay TMDL Program currently in place is a comprehensive regulatory framework that addresses sediment and nutrient loadings in the lower Susquehanna River basin (USEPA 2010b).

The EPA established a watershed Total Maximum Daily Load (TMDL) for Chesapeake Bay for sediment, nitrogen, and phosphorus on December 29, 2010. TMDLs for sediment and nutrients were developed so that the Bay and its tidal tributaries achieve water quality standards for dissolved oxygen, water clarity, and chlorophyll *a* by the year 2025. The Bay TMDL will be implemented in phases with an interim target allocation of 60 percent total load reductions by 2017 and 100 percent by 2025. A state's progress toward meeting TMDL goals will be assessed by EPA every two years**.**

The TMDL allocates loads by major river basin and state in the Chesapeake Bay watershed; included are the Susquehanna River Basin and its watershed states of Maryland, Pennsylvania, and New York. To meet TMDL goals, states must implement measures to reduce sediment and nutrient loads from major sources. To this end, states developed Final Phase I Watershed Implementation Plans (WIPs) describing strategies, actions, and schedules to meet TMDL allocations. EPA's review of final WIPs resulted in modifications that are reflected in the final TMDL and revised WIPs. Final Phase II WIPs with the first set of two-year milestones (2012-2103) were submitted to EPA on March 30, 2012 from all jurisdictions with the exception of New York. Phase III WIPs are currently scheduled to be submitted to EPA in 2017.

5.2 Load Reductions

EPA findings that are used to support the TMDL allocations are provided in Section 4 of the TMDL document (Sources of Nitrogen, Phosphorus, and Sediment to the Chesapeake Bay). Existing load estimates are based on the 2009 scenario run through the Phase 5.3 Chesapeake Bay Watershed Model. The 2009 scenario uses 2009 estimates for land uses, point and nonpoint source loads, numbers of animals, and atmospheric deposition, and tracked and reported BMPs in each Bay watershed. Table 5.2-1 provides the model estimates of sediment and nutrient loadings to Chesapeake Bay by major source sector and jurisdiction. The major sectors contributing sediment/nutrient loads from these states are shown as follows:

- Nitrogen – agriculture, forest lands, storm water runoff, point sources, septic systems, and atmospheric deposition.
- Phosphorus - agriculture, forest lands, storm water runoff, point sources, and atmospheric deposition.

- Sediment - agriculture, forest lands, storm water runoff, point sources.

Regulated point sources included in the EPA simulation are: municipal wastewater discharges, industrial discharges, combined sewer and sanitary sewer overflows, NPDES permitted storm water discharges (MS4s, industrial, construction) and NPDES permitted CAFOs (concentrated animal feeding operations). Nonpoint sources included in the simulation are: agricultural applications (manure, biosolids, chemical fertilizers), atmospheric deposition, forest lands, septic systems, nonregulated storm water runoff, oceanic inputs, stream bank and tidal shoreline erosion, tidal resuspension and wildlife. The model accounts for natural background.

Reductions in sediment accumulation rates in Conowingo Pond have been attributed to the implementation of lower Susquehanna River basin-wide BMPs (Langland 2009). Simpson and Weammert (2009) of the Mid-Atlantic Water Program at the University of Maryland conducted a comprehensive analysis of the way BMPs are implemented in the Chesapeake Bay watershed. They assign effectiveness values to defined BMPs that have been utilized or are proposed to be utilized in state WIPs based on average operational conditions. This is a more realistic approach than previous studies that based BMP effectiveness on controlled research conditions. Their effectiveness values vary with level of management, design, hydrogeomorphic location, and land use (Table 5.2-2).

The US Department of Agriculture evaluated the usage of BMP implementation on farmlands throughout the Bay watershed (NRCS 2011). Their study uses models to quantify the reductions in sediment and nutrient loading to basin streams by the implementation of agricultural conservation practices such as cover crops, conservation tillage, and forest buffers in the 10 percent of watershed comprised of cultivated cropland in use 2003-2006. NRSC (2011) calculates reductions in sediment and nutrient loads to Chesapeake Bay from the Susquehanna River due to conservation practices used in 2003-2006, compared to loading without use of these practices (Tables 5.2-3). Loads delivered to edge of field are equivalent to farm field exports and loads delivered to watershed outlets are equivalent to loads delivered to streams. These tables indicate these BMPs have reduced sediment/nutrient loads to and from the Susquehanna River as follows:

- Sediment loss from fields reduced 52 percent; delivery to Bay from all sources reduced 6 percent
- Total nitrogen loss from fields reduced 36 percent; delivery to bay from all sources reduced 19 percent

- Total phosphorus loss from fields reduced 39 percent; delivery to bay from all sources reduced 16 percent

In summary, implementation of watershed BMPs from all sediment/nutrient source sectors are effective in reducing sediment/nutrient loads to Conowingo Pond.

5.3 Watershed Implementation Plan BMPs

The final WIPs prepared by Susquehanna River watershed states (Maryland, Pennsylvania, and New York) are the most up-to-date compilation of current and future watershed-based management practices and programs to reduce sediment and nutrient loading to the lower Susquehanna River, including Conowingo Pond. None of the WIPs include strategies to escalate sediment/nutrient reduction efforts if the sediment trapping efficiency of Conowingo Pond is found to decline.

Individual state efforts described in the WIPs (directly or by reference) are listed below by state.

Maryland

- Barnyard Runoff: Animal waste management systems, livestock and poultry; barnyard runoff controls including roof control, diversions, and heavy-use poultry area concrete pads; manure storage; and forested and grass buffers
- Livestock Waste: Precision feeding of livestock and poultry; Phytase feed additives for poultry; ammonia emission controls; comprehensive nutrient management plans; enhanced nutrient management; dairy and poultry manure incorporation technology; manure transport; alternative uses of manure; mortality composters; Maryland animal feeding operation permits; 100-foot contained animal feeding operations and Maryland animal feeding operation setbacks; and 35-foot contained animal feeding operations and Maryland animal feeding operation vegetative buffers
- Field Erosion and Excess Nutrients: Cereal and commodity cover crops; conservation plans including contour farming, strip cropping, conservation tillage, residue management, crop rotations, grassed waterways, sediment basins, and grade stabilization structures including terraces, diversions, and drop structures; conservation tillage including minimal disturbance, continuous and annual no-till, and advanced no-till; nutrient management agriculture; yield reserve; managed precision agriculture; agronomic improvements in plant design to maximize nutrient uptake; cropland irrigation

management; forested and grass buffers; 10-foot minimum riparian setbacks for fertilizer Addition; and P-sorbing materials

- Pasture Erosion: Rotational grazing; precision rotational grazing; forested and grass buffers; stream fencing; off-stream watering systems; and stream protection without fencing
- Land Retirement and Restoration: Highly erodible land retirement; tree, shrub, and grass planting; wetland restoration; stream restoration; and shoreline erosion controls
- Urban Runoff: Municipal separate storm sewer system pollutant discharge elimination system; municipal separate storm sewer system stormwater management plan; stormwater pollution prevention plan; refined urban nutrient management; regenerative stormwater conveyance; and urban tree canopy
- Sewage: Revoking and reissuing permits; plant retrofits for enhanced nutrient removal; and nutrient trading program
- Supporting Agencies: Maryland Department of the Environment; Maryland Department of the Environment Water Management Administration; Maryland Department of Agriculture; Maryland Associate of Soil Conservation Districts; USDA/NRCS; and University of Maryland Extension Office

New York

- Barnyard Runoff: Animal waste management systems, rotational loafing lots; barnyard runoff controls including roof control and diversions; manure storage; and forested and grass buffers
- Livestock Wastes: Precision feeding of livestock and poultry; comprehensive nutrient management plans; enhances nutrient management; mortality composters; and contained animal feeding operations permits for more than 200 animals
- Field Erosion and Excess Nutrients: Cereal and commodity cover crops; conservation plans including contour farming, strip cropping, conservation tillage, residue management, crop rotations, grassed waterways, sediment basins, and grad stabilization structures including terraces, diversions, and drop structures; conservation tillage including minimal disturbance, continuous and annual no-till, and advanced no-till; nutrient management agriculture; yield reserve; manage precision agriculture; and forested and grass buffers

- Pasture Erosion: Rotational grazing; precision rotational grazing; forested and grass buffers; stream fencing; off-stream watering systems; and stream protection without fencing
- Land Retirement and Restoration: Highly erodible land retirement; tree, shrub, and grass planting; wetland restoration; stream restoration; and road ditch stabilization
- Forest Harvesting: New York State Department of Environmental Conservation BMP Field guide including guidelines and technical references for harvesting, skidding, landing, and constructing haul roads
- Mining: Marcellus Shale mining and high volume hydraulic fracturing regulated by state multi-sector pollutant discharge elimination system; general permit for stormwater discharges; erosion and sediment control and post-construction stormwater management for well pads, access roads, pipelines, etc.; spill prevention and control countermeasures including secondary containment for process liquids; and wastewater disposal plans
- Urban Runoff: Municipal separate storm sewer system pollutant discharge elimination system; municipal separate storm sewer system stormwater management plan; stormwater pollution prevention plan; residential phosphorous fertilizer prohibited without a soil test demonstrating a need for all lawn or non-agricultural turf growth (pending Legislative approval); and fertilizer on lawn or non-agricultural turf prohibited between December first and April first on impervious surfaces, and within twenty feet of surface water except where there is a continuous vegetative buffer of at least ten feet (pending Legislative approval)
- Roadways: Hydro-seeding, grade breaks and check dams, underdrains, French mattresses, crown reshaping, profile and cross slope modification, high-water bypass, and different surface aggregates; in-stream design structures including cross vanes and culverts; and wetland and other buffers to restore and capture road ditch runoff, reduce energy and capture sediments, and denitrify atmospheric and automobile exhaust sources of nitrogen
- Supporting Agencies: New York State Department of Environmental Conservation, New York State Department of Environmental Conservation Division of Water; New York State Department of Health; New York Soil and Water Conservation Districts; USDA/NRCS; and Upper Susquehanna Coalition

Pennsylvania

- Barnyard Runoff: Animal waste management systems, barnyard runoff controls including roof control and diversions; manure storage; and forested and grass buffers
- Livestock Waste: Precision feeding of livestock and poultry; comprehensive nutrient management plans; enhanced nutrient management technology including solid separation and flocculation; manure treatment, methane digesters; manure-to-energy programs; Pennsylvania Nutrient Trading Program
- Field Erosion and Excess Nutrients: Cereal and commodity cover crops; conservation plans including contour farming, strip cropping, conservation tillage, residue management, crop rotations, grassed waterways, sediment basins, and grade stabilization structures including terraces, diversions, and drop structures; conservation tillage including minimal disturbance, continuous and annual no-till, and advance no-till; nutrient management agriculture; yield reserve; managed precision agriculture; and forested and grass buffers
- Pasture Erosion: Rotational grazing; precision rotational grazing; forested and grass buffers; stream fencing; off-stream watering systems; and stream protection without fencing
- Land Retirement and Restoration: Highly erodible land retirement; tree, shrub, and grass planting; wetland restoration; and stream restoration
- Mining: Coal mining permit requires national pollutant discharge elimination system permit; and erosion and sediment control general permit for oil and gas activities that disturb five acres or more at one time including exploration, production, processing, treatment operations, and transmission facilities
- Urban Runoff: Municipal Separate Storm Sewer System Pollutant Discharge elimination System; municipal separate storm sewer system stormwater management plan; and stormwater pollution prevention plan
- Sewage: Revoking and reissuing permits; plant retrofits for enhanced nutrient removal; and nutrient trading program
- Roadways: Environmentally sensitive dirt and gravel road maintenance; dirt and gravel road erosion and sedimentation controls; street cleaning; and street restoration
- Supporting Agencies: Pennsylvania Department of Environmental Protection; Pennsylvania Department of Agriculture; Pennsylvania Infrastructure Investment

Authority; State Conservation Commission and County Conservation Districts; USDA/NRCS; and Susquehanna River Basin Commission

Specific sediment/nutrient BMPs identified by County Conservation Districts in the four counties surrounding the Conowingo Project include Agricultural BMPs and Erosion and Sediment Control BMPs. Agricultural BMPs include:

- Alternative Crops
- Animal Waste Management
- Conservation Tillage
- Contour Farming
- Cover Crops
- Critical Area Planting
- Crop Residue Management
- Crop Rotation
- Dead Bird Composting Facility
- Diversion
- Grade Control Structure
- Grassed Waterway
- Grazing land Management System
- Filtering Practices
- Infiltration Practices
- Manure Storage
- Manure Transport
- No-Till
- Nutrient Management Planning
- Pasture Renovation and Planting
- Phytase Feed Additive
- Permanent Vegetative Cover
- Retirement of Highly erodible Land
- Sediment control Pond
- Soil and Manure Analysis
- Soil Conservation and Water Quality Plans
- Stream and Streambank Protection and Fencing
- Stream Restoration
- Stripcropping
- Terraces
- Tree Planting
- Vegetative Filter Strip
- Watering Facility
- Waste Management system
- Wetland Restoration

The Erosion and Sediment Control BMPs include:

- Check Dam
- Earth Dike
- Erosion Matting
- Grass Buffer

- Inflow Protection
- Inlet protection
- Outlet protection
- Pipe slope Drain
- Roadway Systems
- Sediment Basin
- Sediment Trap
- Seeding/Mulch
- Silt Fence
- Stabilized Construction Entrance
- Strawbale Dike
- Super Silt Fence
- Swale
- Total Stormwater Management

5.4 Chesapeake Bay Program BMPs for Sediment and Nutrients (CBP 2006)

Chesapeake Bay Program (2006), in its report titled *Best Management Practices for Sediment Control and Water Clarity Enhancement*, specifically addresses sediment-related BMPs applicable to the Bay watershed. These include riparian buffers, stream restoration, urban stormwater management; structural shoreline erosion controls; and restoring SAV. A summary of these BMPs is provided in Table 5.4-1.

5.5 Preserving Reservoir Storage Capacity

Methods to curtail the accumulation of sediment in reservoirs are typically viewed from three perspectives: 1) control volume of sediment entering reservoir, 2) create flow conditions within reservoir to prevent accumulation, or 3) remove sediment that has already been deposited. (Annandale 1987; Sloff 1991; Palmieri et al 2003). Traditional methods are summarized in Table 5.5-1.

A particular method is not necessarily appropriate or feasible for individual dams and reservoirs. For example, flushing requires complete drawdown or partial drawdown of the reservoir to generate high flow velocities capable of remobilizing deposited sediment; is most effective during flood events; causes sediment to be released at much higher concentrations than typical for the system; and partial drawdown usually only relocates sediment upstream to downstream (Morris and Fan 1998; Palmieri et al 2003).

Mechanical removal of reservoir sediment also may not be appropriate in all instances. FERC, in its Environmental Assessment (EA) for the Morgan Falls Hydroelectric Project (Project No, 2237-017) issued November 9, 2007, reviewed sediment accumulation in Bull Sluice Lake, a 7-mile long 684-acre impoundment on the Chattahoochee River, Georgia.[15] The EA found the reservoir to be at or approaching equilibrium with respect to sedimentation such that if dredging occurred, it would only increase

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[15] Environmental Assessment for Hydroelectric License. Morgan Falls Hydroelectric Project 2237-017. Georgia. Federal Energy Regulation Commission. Office of Energy Projects. Division of Hydropower Licensing. November 2007.

sedimentation until equilibrium was re-established. To prevent this from happening, dredging would have to be continuous rather than a one-time event. Requests by the Riverkeeper and American Rivers to dredge the reservoir to improve recreational boating and fishing and water resources were not found to be a reasonable alternative to current project operations because dredging would not provide any benefit to generation; would provide minimal benefits to boating recreationists; and costs far outweighed the benefits.[16]

5.6 In-Reservoir Options for Conowingo Pond

In-reservoir sediment management options at Conowingo Pond, including two not listed above, are assessed in two SRBC documents (SRBC 1995; SRBC 2002). Additionally, the Susquehanna Riverkeeper has actively engaged the USGS and Army Corps in discussions of potential in-reservoir management options. Table 5.6-1 summarizes these efforts and they are discussed further below.

The modification of dam operations to address sediment was dismissed outright by the Sediment Task Force Sediment Symposium convened in December 2000 because it conflicts with the Project's primary purpose of generating electricity (SRBC 2002).

5.6.1 Reservoir By-Passing

Sediment bypassing encourages the movement of sediments through dams during less critical flow periods (non-storm, or base load) so that there is storage capacity to receive sediment for deposition during higher flows. However, while this may reduce the loads passing the dam during these storm events, it does not effectively reduce the loads carried by larger storms that scour reservoir sediment. In addition, it would increase the base load of sediment reaching the Bay.

5.6.2 Flushing

Flushing high sediment flows through turbine units, acting as low-level outlets, was initially considered until it was recognized that large amounts of sediment are already passing over the spillway during high flow events. Flushing results in high flows transporting large amounts of sediment. Passing sediment over the spillway also does not gain lost capacity and does not reduce loads reaching the Bay.

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[16] Order Issuing New License. Georgia Power Company. Project No. 2237-017. May 22, 2008.

5.6.3 *In situ* Sediment Capping, Fixing, and Hardening

Capping is a method of controlling contamination in sediments by covering the contaminated material with clean dredged material to isolate the contaminant from the benthic environment. Sediments may also be chemically treated to “fix” the contaminant, i.e., render it inert in the ambient environment. Neither capping nor fixing is appropriate for preserving storage capacity since these techniques would not change the amount of sediment passing through the system to the Bay and does not add capacity. The idea of hardening the sediment to prevent scouring was considered. This would not, however, increase capacity. In addition, it was not clear how this could be done.

5.6.4 Siphoning

Siphoning (hydrosuction dredging) sediment from the reservoir side of the dam to the toe on the other side with a large flexible hose was reviewed as another possible option. This process can be accomplished during non-storm flows. However, downstream deposition will be higher than normal during times of average or lower flows and excessive oxygen demands may result.

5.6.5 Conventional Dredging

The effort and technical feasibility to dredge was quantified in the 1995 SRBC report. Depending on the length of discharge pipe used, a cutterhead dredge with an 8-inch pipe has a rated output range of 50 to 100 cubic yards per hour and a 20-inch pipe has an output of up to 300 to 1500 cubic yards per hour. Assuming the Conowingo Reservoir would require 8,000 feet of pipe to dredge at its widest reach, and 4,000 feet on average, a 20-inch diameter pipe would be able to dredge 350 to 500 cubic yards per hour. Assuming a yearly volume of sediment trapped of 2.3 million cubic yards, it would take 4,600 to 6,600 hours of dredging to keep up with average annual deposition; in other words, working 24-hours a day 190 to 275 days per year.

To dispose of this dredged material off-site, 80 100-ton railroad hopper cars would be filled each day at the 350 cubic yards per hour dredging rate, and 116 cars would be filled each day at the 500 cubic yards per hour rate.

SRBC also approximated the cost to dredge. Assuming an appropriately sized dredge and a disposal transport distance less than two miles, the unit cost to operate a 20-inch cutterhead is $12 (1995 dollars) per cubic yard. Assuming an annual average accumulation of 2.3 million cubic yards, it would cost $28 million (1995 dollars) per year just to keep pace with incoming sediment. Assuming a 71 percent cost escalation based on the Means Historical Cost Index, the 2010 costs are estimated to be $20.52 per cubic yard to dredge and $47.88 million per year to keep pace with sedimentation in the reservoir.

Options for the disposal of sediment removed from Conowingo Pond consist of placement at existing dredged material placement sites and beneficial use of the sediment. Complete sediment characterization is needed to identify the appropriate option. The discharge of dredged material to waters, including wetlands, require Federal and state permits. Non-toxic sediment may be permitted to be placed at open-water sites or upland contained sites. Toxic sediments would require a confined disposal facility. Other issues to be considered for the selection of a dredged material disposal site are volume of sediment and the distance between dredge site and disposal site.

5.7 Coarse Sediment Replenishment

Replenishment of sediments below dams is a means to re-supply a river system with an interrupted sediment supply. This procedure is used, in particular, to increase and improve salmonid habitat downstream of dams (Kondolf and Matthews 1991; Bunte 2004). The method of sediment placement can be active or passive, dependent on objective. Active (direct) replenishment involves the direct placement of sediment where it is needed to meet the objective while passive (indirect) replenishment involves introducing a bedload supply upstream of the intended areas of improvement relying on natural river flow to transport, distribute, and deposit the sediment in the desired fashion. Success may be short-term with the active approach if the replenished sediment is washed away. In contrast, the passive approach creates an artificial localized pulse of sediment to the system that depends on flows with the entrainment potential to transport the material away for the site of placement. Artificial pulses may move by translation downstream as a ‘sediment wave’ or be dispersed in place without moving downstream by translation (Sklar et al 2009). The success of sediment replenishment requires the selection of a technique and location appropriate for clearly developed objectives and the ability to predict sediment movement after placement.

6.0 Sediment Management Plan

6.1 Best Management Practices

Based on information collected in other studies, the proposed Sediment Management Plan for the Conowingo Project may evaluate and incorporate BMPs for erosion and sediment control on Project lands as part of a Shoreline Management Plan:

- Streambank protection
- Stream bank stabilization
- Establish riparian buffers

The shoreline erosion study of the reservoir conducted for the relicensing found the erosion to be predominantly due to natural processes - wind generated waves, river flow, surface runoff, and mass wasting (Appendix A). Boat wakes are likely another contributing factor at the summer recreation level of the Pond, and ice effects may be important during colder winters. Shoreline erosion was found to be ubiquitous, yet did not pose a threat to existing infrastructure or safety. Erosion does, however, supply sediment to the reservoir. And, depositional areas of shoaling have been identified in the reservoir, some of which inhibit recreational use.

6.2 Sediment Monitoring

The vast array and variance of data compiled in this report make it clear that the first step in establishing benchmarks (triggers) for potential impacts and actions, as required by FERC's Study Plan Determination (February 4, 2010), must be to establish physical benchmarks. This can be achieved by means of sediment monitoring with consistent protocols and methodologies. Physical benchmarking is an essential predecessor to establishing action benchmarks. Exelon started this process in the second field season of relicensing studies (2011) by conducting a bathymetric survey of Conowingo Pond in October 2011. On February 23, 2012 Exelon submitted the methods and results of the Year 2 bathymetric survey to FERC as an addendum to the RSP 3.15-Sediment Introduction and Transport Study.

This survey provided data with greater resolution than earlier USGS surveys and established a baseline for future surveys to monitor sediment accumulation, assess remaining storage capacity, and evaluate action benchmarks. Exelon is proposing to undertake a bathymetric survey every five years, at a minimum, to provide the physical benchmarking necessary to assess the need for, and support development of, actions for sediment management as appropriate.

As discussed in Section 3.1.2, Academy of Natural Sciences of Philadelphia (1994) and Hirsch (2012) describe the nature of steady-state equilibrium in the lower Susquehanna River reservoirs as a punctuated equilibrium. Figure 6.0-1 schematically illustrates this concept. It shows equilibrium as a condition wherein net deposition never permanently stops (although it occurs at reduced rates of increase) and stored sediment never permanently remains at the non-flood steady-state level. Storm events that remove stored sediment push the system below a non-flood steady state, and net deposition replaces scoured sediment.

Once the lower Susquehanna River reservoir system reaches a state of punctuated equilibrium, there is no long-term net sediment retention (i.e., negligible net deposition) and the dams no longer affect the long-term average of sediment delivery to Chesapeake Bay. However, their presence will continue to affect the timing of sediment delivery to the bay by increasing the variance around the long-term average.

In order to see where the current state of Conowingo Pond lies on the conceptual schematic of Figure 6.0-1, Exelon plotted Conowingo Pond sediment accumulation data provided in Langland (2009) and Exelon's Year 2 bathymetric survey (Figure 6.0-2 and Appendix F). The plot illustrates how the pond as a whole is on the rising limb of the curve, at a point where the rate of net deposition has begun to diminish and net scour is beginning to influence the reservoir's position above or below the long-term mean. The sediment management BMPs Exelon proposes in the Shoreline Management Plan address Project-related sediment contributions to Conowingo Pond and the Pond's approach towards true punctuated equilibrium about a long-term mean.

6.3 Management Plan

6.3.1 Background

FERC issued its Year Two *Determination on Requests for Modifications to the Conowingo Hydroelectric Project Study Plan* on May 21, 2012. In this determination, FERC requires that Exelon develop a sediment management plan (Plan) for inclusion in the Final License Application that is related to project operations. Specifically, the determination stated:

> *"We recommend that Exelon, as part of its final license application, include a sediment management plan with provisions for establishing benchmarks and any potential actions that may be necessary for continued operation of the project."* (Page B-6)
>
> *"…staff recommends that Exelon include provisions in its sediment management plan for conducting detailed engineering evaluation and cost estimates for potential sediment management and off-site disposal options once a management option is considered necessary."* (Page B-3)
>
> *"As sediment builds up near the intakes, sediment–laden water then could cause damage to turbines and hydropower facilities due to increased abrasion (Neopane, 2011). Therefore, a sediment management plan that includes provisions for establishing*

> *benchmarks would help plan for any actions that may need to be implemented to allow for continued operation of the project."* (Page B-5)

The FERC directives provide guidance for development of the Plan. The steps needed to develop and implement the Plan are enumerated in the text that follows. The steps are:

1. Identify potential action(s)
2. Evaluate and select action(s)
3. Identify benchmarks for action(s)

6.3.2 Identify Potential Action(s)

Exelon considers "continued operation of the project" to include both generation facilities and project recreation facilities. The following actions are identified as potentially necessary to manage sediment.

➢ **Powerhouse Intake Structure**

From the standpoint of operations, identifying the need for sediment and debris removal has similar approaches. That is, the need for removal occurs when the head loss across the trash racks drives capacity down. Units are taken out of service and intakes cleared when unit power level decreases to a pre-determined value.

Abrasion of turbine runners and other mechanical parts by sediment-laden waters could also cause damage. Sediment going through the turbine typically does not cause damage to the runner or wheel. Typically turbine inspections indicate slight wear on the turbine shaft packing and wicket gate end bushings.

Exelon's inspection program is identified as the vehicle for sediment management at the powerhouse intakes. The inspection program is presently geared towards debris removal and includes:

- Yearly capacity tests to identify if a unit is unable to meet its capacity.
- Trash rack differential instrumentation to monitor head loss.
- Turbine inspections every 4 years (3 units per year) for cavitation damage. If any is found, repairs are performed.
- Turbine shaft packing is repacked every 4 years.

Exelon will add sediment-specific protocols to its existing inspection program. The objective is to evaluate the need for sediment removal, along with debris, and determine if sediment accumulation and/or sediment pass through is adversely affecting project operations. Turbines will be inspected for evidence of abrasion (e.g., loss of metal) and sediment accumulation at the intakes will be monitored.

The sediment monitoring that began with the 2011 bathymetric survey will continue. Exelon will undertake a bathymetric survey every five years to provide the physical benchmarking needed to support the development of action benchmarks at the powerhouse intakes. Bathymetric surveys will have sufficient resolution to determine bathymetric changes at the hydroelectric plant intakes.

- **Recreation Facilities**

Shallow water depths due to sediment accumulation limit boat launch egress and ingress at Peters Creek (Peach Bottom Marina), Conowingo Creek, and Broad Creek. The minimum recreation pool elevation is 107.2 NGVD. During a field reconnaissance of navigability conducted in August 2012 when the pool elevation ranged 107.32 to 107.64 NGVD, the boat launch and areas immediately surrounding the ramp at Broad Creek were not useable for motorized boats due to the shallow water and dense vegetation. Water depths leading to the boat launch were generally two feet with areas being less than one foot near the launch. At Conowingo Creek, water depths in the main channel were 4.5 feet and two feet in the vicinity of the boat launch. At Peters Creek water depths were four to five feet in the main channel and zero at mud flats exposed at the time of the survey.

The actions Exelon has taken to date to identify ways to improve recreation boat access at these Project facilities are listed below.

- Recreation condition assessment and user preference surveys
- Tributary access study
- Bathymetric mapping
- Wetland and aquatic vegetation assessments
- Site-specific navigability assessments
- Dredging feasibility analysis for two sites (Peters Creek and Conowingo Creek)

The potential management action identified to improve recreational boat access at these facilities is sediment removal by dredging.

6.3.3 Evaluate and Select Action(s)

The need for, and feasibility of, implementing the potential actions identified will be evaluated as follows.

- **Powerhouse Intake Structure**

Station operators currently respond quickly to power loss from debris build-up. Clamming removes debris on the unit intake trash racks. Similarly, sediment removal procedures will need to allow for an expeditious response. Station personnel will need to be consulted to identify feasible protocols and methodologies that will allow for a prompt response. Once identified, sediment-specific issues such as disposal options, impacts of sediment quality, and regulatory constraints will be evaluated.

➢ Recreation Facilities

Additional site-specific evaluations are needed before identifying a facility to be dredged, the dredging methodology to be used, the areal extent and depth of dredging needed to support usage as well as protect aquatic resources, and sediment disposal options. Preliminary cost estimates for dredging Peters Creek and Conowingo Creek were conducted independent of wetland and aquatic vegetation surveys performed to delimit areas of dredging that do not impact these resources. These preliminary estimates need to be refined. Additional constraints to be considered are railroad bridge clearances at the mouths of Peters Creek and Conowingo Creek and sediment accretion on the pond side of the Peters Creek channel. Water depths have been observed to be one to two feet less on the pond side of the Peters Creek bridge than in the creek channel. The possible need to extend the dredging area to include the riverside of the bridge should be reviewed.

Exelon will take the following actions to perform these evaluations.

- Develop a sediment sampling plan
- Collect samples at each facility
- Laboratory analysis of samples
- Expand dredging/navigability analysis to include Broad Creek
- Refine feasibility analyses for all three facilities
- Cost estimate for each site
- Assess permitting and regulatory requirements

The site-specific reports will evaluate logistics and estimated costs of alternative methodologies (hydraulic or mechanical dredging); dredge area and volumes of sediment removed; and spoil disposal options. Disposal costs and options will be contingent on the findings of the laboratory analyses of sediment quality. Estimated costs will also include regulatory compliance and time frames, hydrographic surveys, construction documents, construction inspections and continued bathymetric monitoring. Exelon is currently initiating the development of the sediment sampling plan and will proceed with sample collection and analysis during the Fall of 2012. A report of findings of the site-specific evaluations will be completed by the end of 2012.

6.3.4 Identify Benchmarks for Action(s)

Action benchmarks are measurable thresholds that trigger the implementation of sediment management actions.

At the powerhouse, debris removal is currently triggered by the analysis of a combination of factors – net head, river flow, spill conditions, and unit output. Similarly, removal of accumulated sediment will commence when station personnel determine that a combination of conditions warrant a response. Continued monitoring of the bathymetry in front of the intakes, in concert with close examination of head loss at the racks, will be part of the protocol to identify the action benchmark for sediment removal. Regular inspections for abrasion will indicate if sediment in the water column is damaging turbines. Evidence of abrasion will be a benchmark for considering sediment removal.

At the three recreation facilities identified for potential sediment dredging, site-specific water draft depths will be an important consideration in determining need and action benchmarks. The States Organization for Boating Access (SOBA) recommends the toe of launching ramps and boating channels be a minimum of three feet below the lowest expected water level. Sediment accumulation and water depth will be monitored every five (5) years in association with bathymetric monitoring. These data will be the driver for depth benchmarks for action and area of removal.

7.0 Cumulative Impacts Analysis

Council of Environmental Quality (CEQ) regulations define ‘cumulative effects’ as “the impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (Federal or non-Federal) or person undertakes such other actions” (40CFR§1508.7).

For this analysis, the action is the relicensing and continued operation of the Conowingo Project. The cumulatively affected resource is the lower Susquehanna River Basin and the Chesapeake Bay. The geographic scope of this analysis is defined by the scope of EPA’s Bay TMDL, which covers a 64,000-square-mile area across seven jurisdictions. The temporal scope of this analysis includes a discussion of the past, present, and reasonably foreseeable future actions, and their effects on the resource 50 years into the future. Points of fact stated in this analysis have been discussed elsewhere in this document.

The impact of the Project has been to alter the sediment budget of the Lower Susquehanna River which had already been altered by Holtwood Dam (built 1910) when the Project was initially constructed in 1928. The Project has been, and currently is, interrupting downstream sediment transport by trapping sediment behind Conowingo Dam. This is due to the sediment storage capacity created by the Project. In effect, the Project added to sediment storage capacity created by the Holtwood and Safe Harbor projects. The cumulative impact of the Project to the system is to provide the last site of sediment storage along the Susquehanna River before sediment reaches Chesapeake Bay. This has benefited Chesapeake Bay by providing a means by which the quantity of fine-grained sediment and associated nutrients, sources of water quality impairment, reaching the Bay are reduced.

At the same time, Project trapping reduces the supply of coarse sediment reaching the Upper Bay. The Project’s impact on coarse sediment transport (sand and gravel) is exerted on a sediment supply already similarly affected by the Holtwood and Safe Harbor Dams. The paucity of sand and gravel substrates below the Project has been confirmed in ILP studies. However, coarse sediment likely was not deposited immediately downstream of the Conowingo Dam location prior to its construction. Past and ongoing interruption of its supply downstream, episodically replenished by the action of major storms, may have led to a reduction in coarse substrate habitat close to the river mouth.

The cumulative impact of the Project on the affected resource occurs within the context of watershed activities that directly control sediment reaching the Project. Regulations and voluntary incentives implemented to date by federal, state and local governments; non-governmental organizations; and stakeholders in the agricultural, storm water, and wastewater sectors of the watershed have reduced sediment/nutrient loads reaching the reservoirs, including the Project, but not enough to prevent Chesapeake Bay and its tidal tributaries from becoming impaired waterbodies unable to meet water quality criteria. Within this context, the Project has reduced sediment/nutrient loadings to the Bay from these watershed sources by trapping sediment.

Operational capacity will not be added and physical modification will not be made under the proposed action. The cumulative impacts of the action are evaluated within the context of the EPA Chesapeake Bay TMDL process and planned expansion program of the Holtwood Dam Project under possible future scenarios – with and without the Project reaching steady-state within the new license term.

The long-term average trapping efficiency of the Project is 55 percent, without accounting for large scour events or improvements in ongoing watershed BMP reductions. At this rate, USGS predicts the Project will reach its sediment storage capacity in the 2023 to 2028 time period. A reduction in sediment yield of 20 percent extends this another 5 to 10 years, and the passage of major storm producing large amount of scour will extend this more. It is important to note that the Bay TMDL assumes this 55 percent trapping efficiency through 2025.

With or without the proposed Sediment Management Plan the Project will continue trapping sediment as long as steady-state conditions are not reached. With successful implementation of the EPA Chesapeake Bay TMDL program, sediment loads to the Project will be reduced and the time to Project sediment-storage capacity will be prolonged. The cumulative impact of the Project will be to continue to reduce sediment and nutrient loads to Chesapeake Bay until sediment-storage capacity is reached.

If the Project reaches its sediment-storage capacity, the ability of the Project to trap sediment will be lost. The EPA has stated changes in Project sediment-trapping capacity are not expected to change the amount of sediment the Bay can assimilate (USEPA 2010b - Section 10). Interruption of a continuous supply of sand and gravel to the lower reaches of the river below the Project and Chesapeake Bay will continue regardless of the state of sediment trapping in the Project. The character of sediment transport during major flood events is unclear.

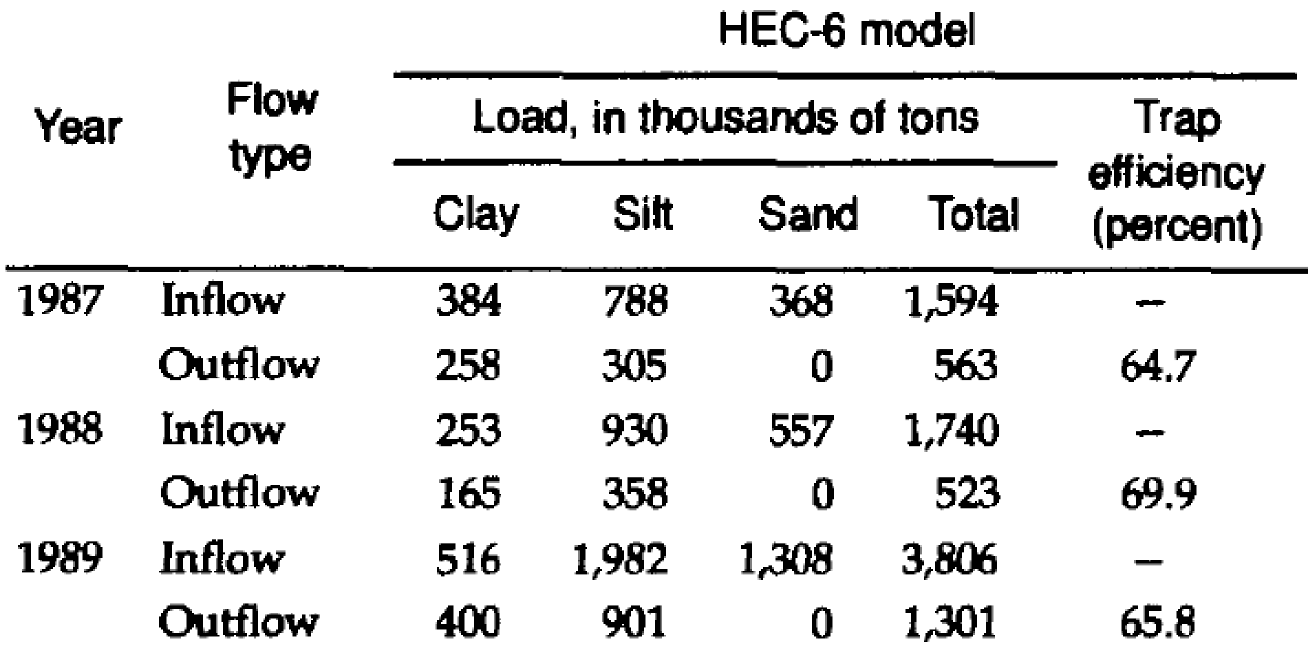
In summary, the impact of the Project on sediment, when added to other past, present, and reasonably foreseeable future actions, is beneficial or small. When the Project reaches steady state, these benefits will be reduced.

Table 3.2-1: Summary of Conowingo Pond Parameters

Dimensions	
Surface area	14 square miles
Length*	77,560 feet
Width (maximum)*	7,000 feet
Sediment Thickness*	
Upper	0-10 feet (average 3.1 feet)
Middle	10-20 feet (average 13.6 feet)
Lower	>20 feet (average 30 feet)
Sediment Content*	
Upper	45% Sand, 18% Silt, 7% Clay, 30% Coal
Middle	39% Sand, 36% Silt, 18% Clay, 7% Coal
Lower	5% Sand, 58% Silt, 35% Clay, 6% Coal
Total Sediment Deposition Since 1929**	
Upper	11,000,000 tons
Middle	59,500,000 tons
Lower	103,000,000 tons
Reservoir Capacity**	
Design Water Storage Capacity (1929)	280,000 acre-feet
Current Water Storage Capacity (2008)	162,000 acre-feet
Current Sediment Storage	174 million tons
Remaining Sediment Storage	30 million tons
Sediment Net Deposition/Loss 1996-2008**	
Loss (Middle Reservoir)	1.8 million tons of sediment
Deposition (Lower Reservoir)	13.8 million tons of sediment
Sediment Deposition/Accumulation Rates**	
1929 to 1958	3.1 million tons per year
1959 to 1993	2.5 million tons per year
1985 to 1989***	1.8 million tons per year
1996 to 2008	1.5 million tons per year
Average deposition, 1959-2008	2 million tons per year
Current trapping efficiency (based on average deposition)	55%

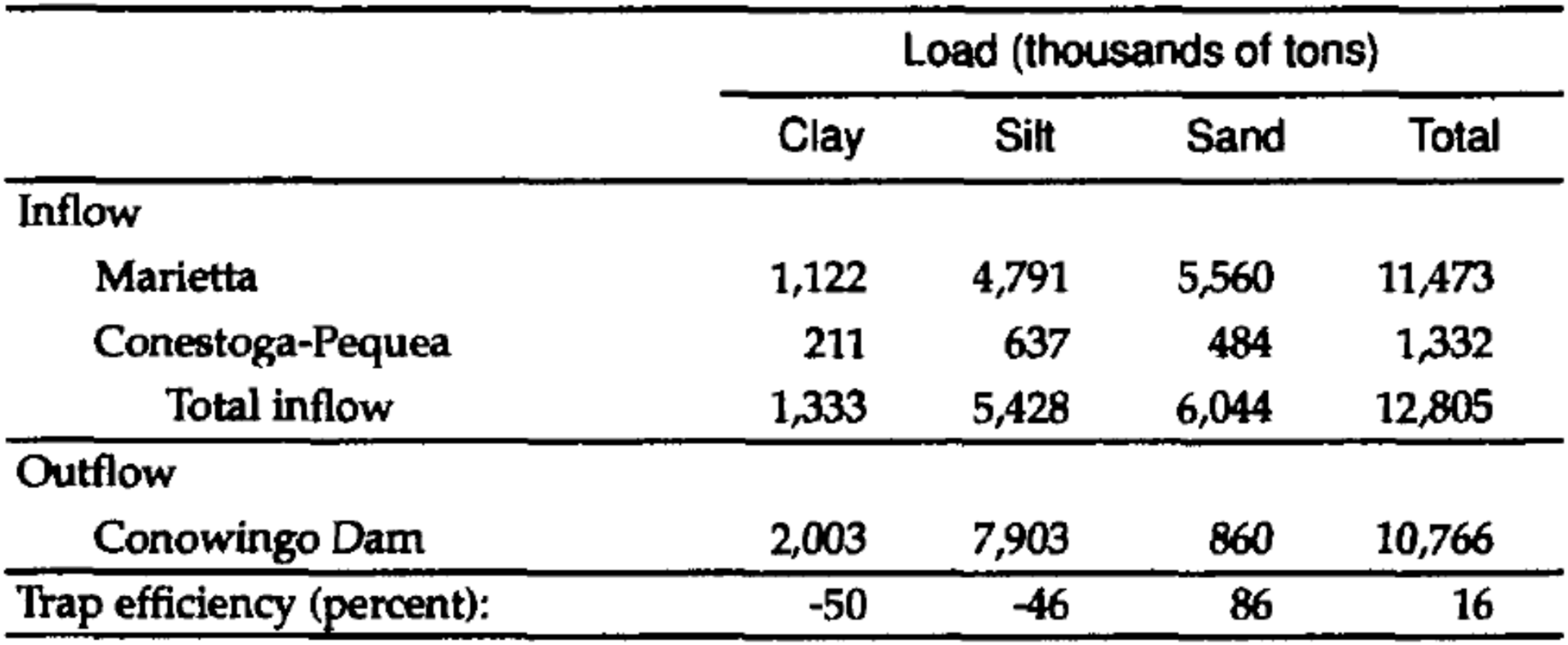
Notes:
* From Hainly et al 1995
** From Langland 2009
*** From SRBC 1991

Table 3.2.6.1-1
USGS HEC-6 Output (1987-1989)
(Hainly et al 1995)



Year	Flow type	HEC-6 model				
		Load, in thousands of tons				Trap efficiency (percent)
		Clay	Silt	Sand	Total	
1987	Inflow	384	788	368	1,594	--
	Outflow	258	305	0	563	64.7
1988	Inflow	253	930	557	1,740	--
	Outflow	165	358	0	523	69.9
1989	Inflow	516	1,982	1,308	3,806	--
	Outflow	400	901	0	1,301	65.8

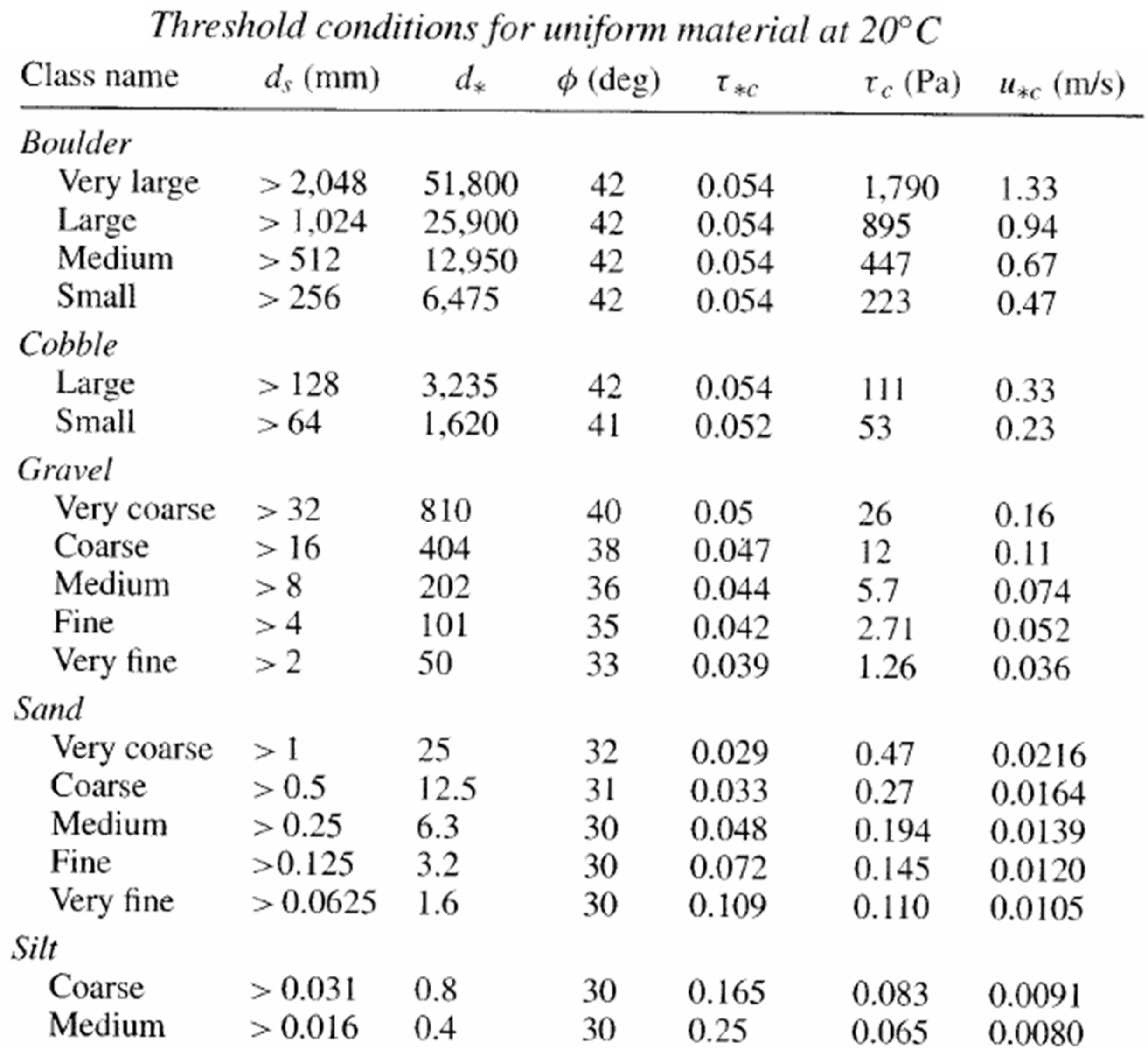
Table 3.2.6.1-2
USGS HEC-6 Output (May and June 1972)
(Hainly et al 1995)



	Load (thousands of tons)			
	Clay	Silt	Sand	Total
Inflow				
Marietta	1,122	4,791	5,560	11,473
Conestoga-Pequea	211	637	484	1,332
Total inflow	1,333	5,428	6,044	12,805
Outflow				
Conowingo Dam	2,003	7,903	860	10,766
Trap efficiency (percent):	-50	-46	86	16

Table 4.1.3-1: Critical Shear Values (τ_c)

[1 Pascal (Pa) = 1 Newton per square meter] from Julien (2010)



Threshold conditions for uniform material at 20°C

Class name	d_s (mm)	d_*	ϕ (deg)	τ_{*c}	τ_c (Pa)	u_{*c} (m/s)
Boulder						
Very large	> 2,048	51,800	42	0.054	1,790	1.33
Large	> 1,024	25,900	42	0.054	895	0.94
Medium	> 512	12,950	42	0.054	447	0.67
Small	> 256	6,475	42	0.054	223	0.47
Cobble						
Large	> 128	3,235	42	0.054	111	0.33
Small	> 64	1,620	41	0.052	53	0.23
Gravel						
Very coarse	> 32	810	40	0.05	26	0.16
Coarse	> 16	404	38	0.047	12	0.11
Medium	> 8	202	36	0.044	5.7	0.074
Fine	> 4	101	35	0.042	2.71	0.052
Very fine	> 2	50	33	0.039	1.26	0.036
Sand						
Very coarse	> 1	25	32	0.029	0.47	0.0216
Coarse	> 0.5	12.5	31	0.033	0.27	0.0164
Medium	> 0.25	6.3	30	0.048	0.194	0.0139
Fine	>0.125	3.2	30	0.072	0.145	0.0120
Very fine	> 0.0625	1.6	30	0.109	0.110	0.0105
Silt						
Coarse	> 0.031	0.8	30	0.165	0.083	0.0091
Medium	> 0.016	0.4	30	0.25	0.065	0.0080

Table 4.1.4 -1 Properties of Mobile Substrates Downstream of Conowingo Dam

Location		Description
1	Mouth of Octoraro Creek	Boulder, cobble, granule Shallow riffles and pools Sparse water milfoil on boulders
2	Along river margin (west)	Boulder Moderate water willow
3	Extends from river margin (east) Downstream of deep pool (Lee’s Ferry)	Boulder Heavy water pepper and smartweed along river margin
4	Along river margin (west)	Boulder Moderate water willow
5	Extends from river margin (east)	Shallow pool Boulder No vegetation
6	Along river margin (west)	Cobble Moderate water willow
7	Island side channel and margin (west)	Cobble and boulder Patches of moderate to heavy water willow on boulder
8	Mouth (and upstream) of Deer Creek (west)	Shallow run upstream Boulder Small patch of heavy water willow at mouth
9	Robert Island	Boulder, cobble, pebble, medium sand Sparse water milfoil on boulder; moderate water milfoil on pebble; heavy water milfoil on cobble and sand
10	Extends from river margin and small island (east)	Boulder, granule, medium sand Moderate-heavy water milfoil in all substrates
11	Along river margin (west)	Coarse sand Moderate hydrilla
12	Spencer Island margin and mid-channel	Boulder, cobble, pebble Heavy water milfoil and hydrilla on bedrock; Minimal water milfoil and hydrilla on pebble

Table 4.1.4-2

Acreage of Size Classes in Each Substrate Area

	Acreage					
Key Area	**Boulder**	**Cobble**	**Pebble**	**Granule**	**Coarse Sand**	**Medium Sand**
1	2.755146284	1.064930398		0.933551103		
2	1.820807644					
3	3.74539494					
4	1.512288672					
5	7.159753898					
6		0.364232318				
7	8.350300483	3.140611686				
8	7.577062344					
9	15.75832696	8.758523205	3.849973707			3.991093008
10	1.144731783			2.389628013		1.022703537
11					0.842376022	
12	1.042606012	0.639920039	2.655027049			

Table 4.1.4-3
Mobile Substrate Areas and Persistent Habitats

Non-Bedrock Substrate Areas	(in Thousands)	Striped Bass Fry	Striped Bass Spawning	Shortnosed Sturgeon Fry	Shortnosed Sturgeon Spawning	Small Mouth Bass Fry	Small Mouth Bass Spawning	Stonefly	Mayfly	Caddisfly	American Shad Spawning	American Shad Fry
1. Boulder (B), Cobble (C), Granule (G)	3.5 - 86	Y - B	Y - B	Y - C, G	N	N	N	N	N	Y - B, C, G	N	Y - B, C, G
	5 - 86	Y - B	Y - B	Y - C, G	N	N	N	N	N	Y - B, C, G	Y - B	Y - B, C, G
	7.5 - 86	Y - B	Y - B, C	Y - C, G	Y - C, B	N	N	N	N	Y - B, C, G	N	Y - B, C, G
	10 - 86	Y - B, C, G	Y - B, C, G	Y - C, G	Y - C, B	N	N	N	N	Y - B, C, G	Y - B	Y - B, C, G
2. Boulder	3.5 - 86	Y	Y	N	Y	N	N	N	N	Y	Y	Y
	5 - 86	Y	Y	N	Y	N	N	N	N	Y	Y	Y
	7.5 - 86	Y	Y	N	Y	N	N	N	N	Y	Y	Y
	10 - 86	Y	Y	N	Y	N	N	N	N	Y	Y	Y
3. Boulder	3.5 - 86	N	N	N	N	N	N	N	N	N	N	N
	5 - 86	N	N	N	N	N	N	N	N	N	N	N
	7.5 - 86	N	N	N	N	N	N	N	N	N	N	N
	10 - 86	N	N	N	N	N	N	N	N	N	N	N
4. Boulder	3.5 - 86	N	N	N	N	N	N	N	N	N	N	N
	5 - 86	N	N	N	N	N	N	N	N	N	N	N
	7.5 - 86	Y	Y	N	N	N	N	N	N	N	N	N
	10 - 86	Y	Y	N	N	N	N	N	N	N	N	N
5. Boulder	3.5 - 86	N	N	N	N	N	N	N	N	Y	N	N
	5 - 86	N	N	N	N	N	N	N	N	Y	N	N
	7.5 - 86	Y	Y	N	Y	N	N	N	N	Y	N	N
	10 - 86	Y	Y	N	Y	N	N	N	N	Y	Y	N
6. Cobble	3.5 - 86	N	N	N	N	N	N	N	N	N	N	N
	5 - 86	N	N	N	N	N	N	N	N	N	N	N
	7.5 - 86	N	N	N	N	N	N	N	N	N	N	N
	10 - 86	N	N	N	Y	N	N	N	N	N	N	N
7. Boulder (B), Cobble (C)	3.5 - 86	N	N	N	N	N	N	N	N	Y - B	N	N
	5 - 86	N	N	N	N	N	N	N	N	Y - B	N	N
	7.5 - 86	N	N	N	N	N	N	N	N	Y - B	N	N
	10 - 86	N	N	N	N	N	N	N	N	Y - B	N	N
8. Boulder	3.5 - 86	N	N	N	N	N	N	N	N	Y	N	N
	5 - 86	N	N	N	N	N	N	N	N	Y	N	N
	7.5 - 86	N	N	N	N	N	N	N	N	Y	N	N
	10 - 86	N	N	N	N	N	N	N	N	Y	N	N
9. Boulder (B), Cobble (C), Pebble (P), Medium Sand (MS)	3.5 - 86	N	N	N	N	N	Y - MS	N	N	N	N	Y - P, MS
	5 - 86	N	N	Y - MS, P	N	N	Y - MS	N	N	Y - B, C	N	Y - P, MS, C
	7.5 - 86	N	N	Y -MS, P	N	N	Y - MS	N	N	Y - B, C, MS	N	Y - P, MS, C
	10 - 86	Y - B	Y - B	Y - MS, P, C	Y - P	N	Y - MS	N	N	Y - B, C, MS	Y - P	Y - P, MS, C
10. Medium Sand (MS), Granule (G), Boulder (B)	3.5 - 86	N	N	N	N	Y -G	Y - G, MS	N	N	N	N	Y - MS
	5 - 86	N	N	N	N	Y - G	Y - G, MS	N	N	N	N	Y - MS, G
	7.5 - 86	N	N	Y - MS	N	Y - G	Y - G, MS	N	N	N	N	Y - MS, G
	10 - 86	N	N	Y - MS	N	Y - G	Y - G, MS	N	N	Y - B	N	Y - MS, G
11. Coarse Sand	3.5 - 86	N	N	N	N	N	N	N	N	N	N	N
	5 - 86	N	N	N	N	N	N	N	N	N	N	N
	7.5 - 86	N	N	N	N	N	N	N	N	N	N	N
	10 - 86	N	N	N	N	N	N	N	N	N	N	N
12. Cobble (C), Pebble (P), Boulder (B)	3.5 - 86	N	N	N	N	Y - B	N	N	Y - C	N	N	Y - C
	5 - 86	N	N	N	N	Y - B	N	N	Y - C	Y - C	N	Y - C
	7.5 - 86	N	N	N	N	Y - B	N	N	Y - C	Y - C	N	Y - C
	10 - 86	Y - P	Y - P	N	N	Y - B	N	N	Y - C	Y - C, B	N	Y - C

Y - Yes (Pressent)
N - No (Not Present)

Table 4.1.4-4
Entrainment Potential of Mobile Substates

	Acreage														
Model	**3500**			**5000**			**7500**			**10000**			**86000**		
Key Area	**<1**	**1 - 2**	**>2**	**<1**	**1 - 2**	**>2**	**<1**	**1 - 2**	**>2**	**<1**	**1 - 2**	**>2**	**<1**	**1 - 2**	**>2**
1	4.708696	0.016197	0.028613	4.682445	0.042448	0.028613	4.682445	0.042448	0.028613	4.682445	0.044458	0.026604	4.586371	0.165232	0.001903
2	1.802107	0	0.018625	1.802107	0	0.018625	1.802107	0.018625	0	1.802107	0.018625	0	1.820732	0	0
3	3.745244	0	0	3.745244	0	0	3.745244	0	0	3.745244	0	0	3.745244	0	0
4	1.512214	0	0	1.512214	0	0	1.512214	0	0	1.512214	0	0	1.512214	0	0
5	7.159414	0	0	7.159414	0	0	7.159414	0	0	7.159414	0	0	7.159414	0	0
6	0.364212	0	0	0.364212	0	0	0.364212	0	0	0.359695	0	0.004518	0.316110	0.048102	0
7	11.490293	0	0	11.490293	0	0	11.490293	0	0	11.463930	0.026363	0	11.490293	0	0
8	7.576572	0	0	7.576572	0	0	7.576572	0	0	7.576572	0	0	7.576572	0	0
9	32.355779	0	0	32.323484	0.032296	0	32.175605	0.147879	0.032296	31.279176	0.896429	0.180175	27.053177	0.372322	4.930280
10	4.556759	0	0	4.553354	0.003405	0	4.382409	0.153877	0.020473	4.140585	0.241824	0.174350	2.936696	0.315748	1.304314
11	0.842316	0	0	0.842316	0	0	0.777382	0.064935	0	0.754362	0.028208	0.059747	0.489374	0.066414	0.286528
12	4.337241	0	0	4.337241	0	0	4.337241	0	0	4.337241	0	0	1.790472	0	2.546769

Table 4.2.2.1-1

HEC-6 Depth Senistivity Analysis

1972 Flood Event (Current Model)									**1972 Flood Event (5-foot Increase in Bottom Elevation)**								
		957,387 cfs		**639,955 cfs**		**382,765 cfs**					**957,387 cfs**		**639,955 cfs**		**382,765 cfs**		
HEC-6 Transect	**River Mile**	**Average Velocity (fps)**	**Shear stress (lbs/sq. ft.)**	**Average Velocity (fps)**	**Shear stress (lbs/sq. ft.)**	**Average Velocity (fps)**	**Shear stress (lbs/sq. ft.)**	**Location Description**	**HEC-6 Transect**	**River Mile**	**Average Velocity (fps)**	**Shear stress (lbs/sq. ft.)**	**Average Velocity (fps)**	**Shear stress (lbs/sq. ft.)**	**Average Velocity (fps)**	**Shear stress (lbs/sq. ft.)**	**Location Description**
SECTION NO. 24.690	24.690	19.823	374.598	17.347	304.189	14.533	262.374	Holtwood Dam	SECTION NO. 24.690	24.690	19.828	374.594	17.352	304.188	14.539	261.715	Holtwood Dam
SECTION NO. 24.650	24.650	10.946	269.160	9.084	232.220	6.191	209.474		SECTION NO. 24.650	24.650	10.946	269.157	9.084	232.217	6.205	209.081	
SECTION NO. 24.270	24.270	25.105	0.986	18.971	0.790	11.323	0.954		SECTION NO. 24.270	24.270	25.104	0.983	18.970	0.785	11.323	0.843	
SECTION NO. 23.170	23.170	26.094	1.527	18.296	1.027	11.953	1.153		SECTION NO. 23.170	23.170	26.044	1.521	18.285	1.021	11.638	1.025	
SECTION NO. 22.500	22.500	18.740	1.324	13.862	0.583	9.322	0.224		SECTION NO. 22.500	22.500	18.707	1.250	13.851	0.544	9.069	0.198	
SECTION NO. 21.230	21.230	6.221	0.385	4.856	0.187	3.453	0.074		SECTION NO. 21.230	21.230	7.606	0.329	6.157	0.157	4.422	0.128	
SECTION NO. 20.010	20.010	4.763	0.020	3.661	0.011	2.564	0.005		SECTION NO. 20.010	20.010	5.696	0.026	4.514	0.015	3.288	0.065	
SECTION NO. 18.400	18.400	5.547	0.021	4.268	0.011	2.975	0.005		SECTION NO. 18.400	18.400	6.544	0.025	5.167	0.014	3.734	0.006	
SECTION NO. 17.260	17.260	3.960	0.023	3.015	0.012	2.078	0.006		SECTION NO. 17.260	17.260	4.658	0.027	3.634	0.016	2.583	0.008	
SECTION NO. 16.000	16.000	4.270	0.006	3.118	0.003	2.045	0.001		SECTION NO. 16.000	16.000	4.763	0.006	3.515	0.004	2.334	0.003	
SECTION NO. 14.800	14.800	3.927	0.016	2.867	0.007	1.881	0.003		SECTION NO. 14.800	14.800	4.379	0.017	3.232	0.008	2.147	0.003	
SECTION NO. 13.840	13.840	3.309	0.014	2.433	0.007	1.611	0.003		SECTION NO. 13.840	13.840	3.723	0.016	2.773	0.008	1.862	0.003	
SECTION NO. 12.520	12.520	4.869	0.007	3.573	0.005	2.358	0.002		SECTION NO. 12.520	12.520	5.473	0.011	4.064	0.007	2.719	0.004	
SECTION NO. 11.530	11.530	4.753	0.033	3.416	0.017	2.202	0.007		SECTION NO. 11.530	11.530	5.212	0.041	3.772	0.022	2.450	0.010	
SECTION NO. 10.320	10.320	3.092	0.034	2.201	0.017	1.404	0.007		SECTION NO. 10.320	10.320	3.350	0.048	2.398	0.024	1.538	0.010	
SECTION NO. 9.743	9.743	3.092	93.667	2.201	86.623	1.405	81.394		SECTION NO. 9.743	9.743	3.092	91.762	2.201	84.741	1.405	79.508	
SECTION NO. 9.742	9.742	13.223	103.430	12.987	70.642	12.907	36.666		SECTION NO. 9.742	9.742	13.223	103.430	12.987	70.642	12.907	36.666	
SECTION NO. 9.740	9.740	19.030	2.618	16.657	2.343	14.054	2.156	Conowingo Dam	SECTION NO. 9.740	9.740	19.030	2.618	16.657	2.343	14.054	2.156	Conowingo Dam

Table 4.2.3-1
HEC-6 Output: Trapping Efficiencies

Storm Event	1972	1975	1996	2004	Comments/ Units
					Calculates net accumulating (entering/leaving) in acre-feet) & converts to trapping efficiency (%)
Sand					
Clarke	95	100	99	100	Traps virtually all sand entering from upstream mainstem
Aldred	19	51	39	58	Sand in Aldred is from the tributaries; traps 20-60%
Conowingo	99	99	99	99	Traps virtually all sand entering from Aldred
Silt					
Clarke	-3	1	1	1	Passes virtually all silt entering from upstream mainstem
Aldred	-4	-1	-1	-1	Silt from Clarke and tribs virtually all passed
Conowingo	3	9	7	10	Silt from Agnes virtually passed; other storms trap approx. 10%
Clay					
Clarke	-3	0	0	0	Passes virtually all clay entering from upstream mainstem
Aldred	-3	-1	1	0	Clay from Clarke and tribs virtually all passed
Conowingo	0	0	0	0	Passes virtually all clay entering from Aldred

Table 4.2.3-2
HEC-6 Output
Quantities of Transport By Grain Size

Storm Event 1972			Storm Event 1975			Storm Event 1996			Storm Event 2004		
Total	In (tons)	Out (tons)	Total	In (tons)	Out (tons)	Total	In (tons)	Out (tons)	Total	In (tons)	Out (tons)
Clarke	8,431,840	4,712,650	Clarke	3,012,727	1,654,030	Clarke	3,109,143	1,685,342	Clarke	2,076,858	1,447,429
Aldred	7,431,552	7,483,294	Aldred	3,854,049	3,541,992	Aldred	3,312,999	3,144,829	Aldred	3,048,680	2,479,478
Conowingo	7,483,294	6,451,719	Conowingo	3,541,992	2,982,372	Conowingo	3,144,829	2,675,283	Conowingo	2,479,478	2,098,111
Sand			Sand			Sand			Sand		
Clarke	4,089,443	222,854	Clarke	135,269	6,673	Clarke	1,425,254	13,572	Clarke	926,981	3,211
Aldred	1,068,213	865,672	Aldred	672,682	329,046	Aldred	511,458	310,574	Aldred	486,478	204,155
Conowingo	865,672	8,782	Conowingo	329,046	1,928	Conowingo	310,574	2,019	Conowingo	204,155	1,606
Silt			Silt			Silt			Silt		
Clarke	3,530,843	3,650,285	Clarke	1,349,822	1,337,766	Clarke	1,369,316	1,357,238	Clarke	935,262	929,622
Aldred	5,007,853	5,220,180	Aldred	2,438,820	2,465,468	Aldred	2,171,291	2,199,323	Aldred	1,731,340	1,742,448
Conowingo	5,220,180	5,046,245	Conowingo	2,465,468	2,234,015	Conowingo	2,199,323	2,039,056	Conowingo	1,742,448	1,564,421
Clay			Clay			Clay			Clay		
Clarke	811,553	839,511	Clarke	309,637	309,591	Clarke	314,574	314,532	Clarke	214,614	214,596
Aldred	1,355,487	1,397,441	Aldred	742,546	747,478	Aldred	630,251	634,932	Aldred	530,862	532,874
Conowingo	1,397,441	1,396,692	Conowingo	747,478	746,429	Conowingo	634,932	634,208	Conowingo	532,874	532,084
Total	Net Deposition/Scour (cu. yds.)	tons	Total	Net Deposition/Scour (cu. yds.)	tons	Total	Net Deposition/Scour (cu. yds.)	tons	Total	Net Deposition/Scour (cu. yds.)	tons
Clarke	3,810,987	3,719,190	Clarke	1,421,533	1,358,697	Clarke	1,489,459	1,423,801	Clarke	971,542	629,429
Aldred	-168,741	-51,742	Aldred	311,523	312,057	Aldred	161,221	168,170	Aldred	275,051	569,202
Conowingo	1,134,171	1,031,575	Conowingo	660,995	559,620	Conowingo	543,291	469,546	Conowingo	457,199	381,367
Sand			Sand			Sand			Sand		
Clarke	4,034,000		Clarke	1,404,899		Clarke	1,472,803		Clarke	963,766	
Aldred	211,309		Aldred	358,513		Aldred	209,581		Aldred	294,547	
Conowingo	893,992		Conowingo	341,280		Conowingo	321,912		Conowingo	211,319	
Silt			Silt			Silt			Silt		
Clarke	-163,844		Clarke	16,538		Clarke	16,570		Clarke	7,738	
Aldred	-291,257		Aldred	-36,553		Aldred	-38,454		Aldred	-15,238	
Conowingo	238,595		Conowingo	317,493		Conowingo	219,845		Conowingo	244,208	
Clay			Clay			Clay			Clay		
Clarke	-59,170		Clarke	96		Clarke	88		Clarke	38	
Aldred	-88,793		Aldred	-10,437		Aldred	-9,906		Aldred	-4,258	
Conowingo	1,586		Conowingo	2,219		Conowingo	1,530		Conowingo	1,673	

Table 4.2.3-3

Scour Loads Derived from Regression Curve Model

Event	Date	Conowingo Peak Flow (cfs)	Flow Frequency	Sediment Load (Million Tons)
Scaled from Conowingo USGS Gage				
1972 (Agnes)	6/24/1972	1,130,000	~525 year	17.36
1975	9/27/1975	710,000	~53 year	5.84
1996	1/20/1996	909,000[1]	~178 year	11.30
2004 (Ivan)	9/19/2004	620,000	~29 year	3.37

1: The ice jam at Safe Harbor caused the large discrepancy between the Harrisburg and Conowingo gages.

Table 4.2.3-4

Suspended Sediment Grain Size Distribution (Jan 1996)
(USGS Conowingo Gage Station)

Date	Time	% silt/clay	% sand	Daily Mean Discharge (cfs)
17-Jan-1996	1545	90	10	15,200
20-Jan-1996	1415	95	5	439,000
21-Jan-1996	1315	93	7	622,000
21-Jan-1996	1615	92	8	622,000
21-Jan-1996	1900	92	8	622,000
22-Jan-1996	1045	97	3	428,000
22-Jan-1996	1500	99	1	428,000
22-Jan-1996	1930	97	3	428,000
23-Jan-1996	1415	99	1	272,000
23-Jan-1996	2030	99	1	272,000
24-Jan-1996	1745	99	1	198,000
25-Jan-1996	1345	97	3	204,000
29-Jan-1996	1400	97	3	284,000
31-Jan-1996	1400	99	1	159,000

Table 4.2.3-5
Lower Susquehanna River Reservoir Shapes
(from Hainly et al 1995)

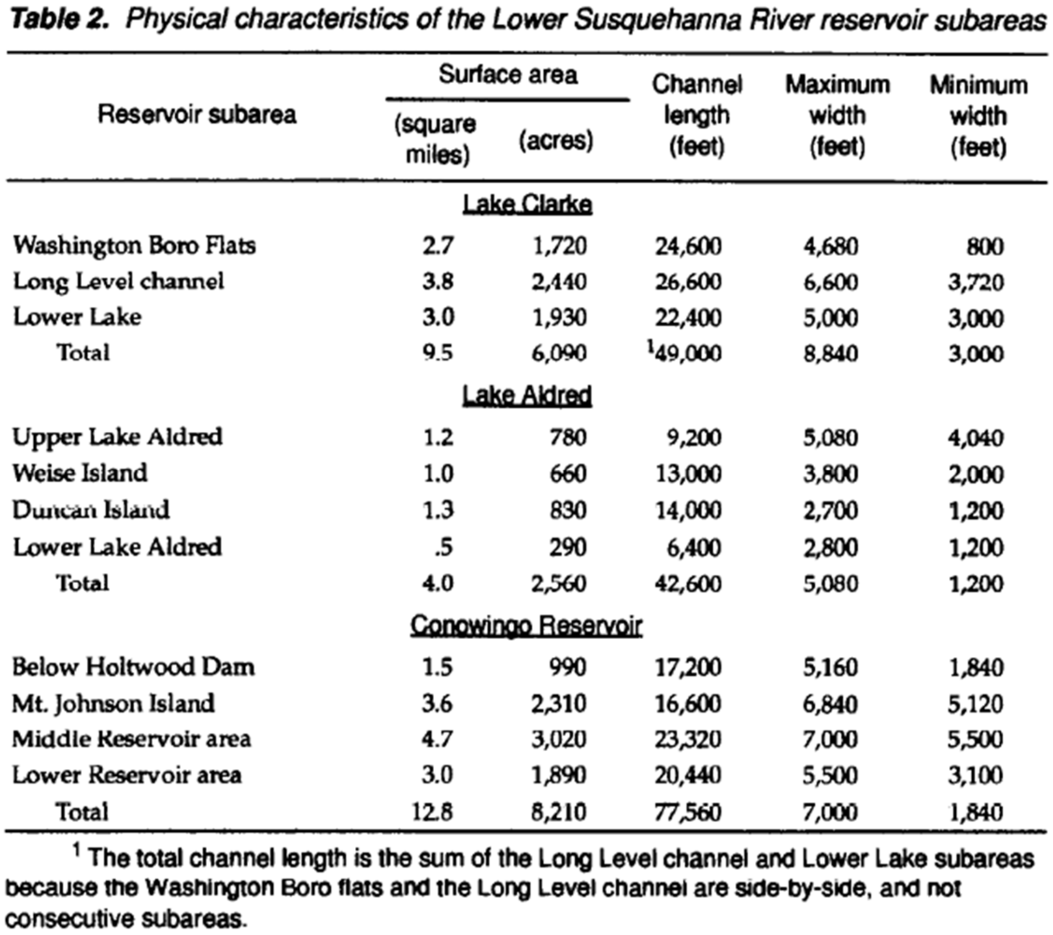


***Table 2.** Physical characteristics of the Lower Susquehanna River reservoir subareas*

Reservoir subarea	Surface area (square miles)	Surface area (acres)	Channel length (feet)	Maximum width (feet)	Minimum width (feet)
Lake Clarke					
Washington Boro Flats	2.7	1,720	24,600	4,680	800
Long Level channel	3.8	2,440	26,600	6,600	3,720
Lower Lake	3.0	1,930	22,400	5,000	3,000
Total	9.5	6,090	[1]49,000	8,840	3,000
Lake Aldred					
Upper Lake Aldred	1.2	780	9,200	5,080	4,040
Weise Island	1.0	660	13,000	3,800	2,000
Duncan Island	1.3	830	14,000	2,700	1,200
Lower Lake Aldred	.5	290	6,400	2,800	1,200
Total	4.0	2,560	42,600	5,080	1,200
Conowingo Reservoir					
Below Holtwood Dam	1.5	990	17,200	5,160	1,840
Mt. Johnson Island	3.6	2,310	16,600	6,840	5,120
Middle Reservoir area	4.7	3,020	23,320	7,000	5,500
Lower Reservoir area	3.0	1,890	20,440	5,500	3,100
Total	12.8	8,210	77,560	7,000	1,840

[1] The total channel length is the sum of the Long Level channel and Lower Lake subareas because the Washington Boro flats and the Long Level channel are side-by-side, and not consecutive subareas.

Table 5.2-1
Chesapeake Bay TMDL Estimates of Loads By Jurisdiction

Table 4-1. Percentage of total nitrogen delivered to the Bay from each jurisdiction by pollutant source sector

Jurisdiction	Agriculture	Forest	Stormwater runoff	Point source	Septic	Nontidal deposition
Delaware	3%	1%	1%	0%	2%	1%
District of Columbia	0%	0%	1%	5%	0%	0%
Maryland	16%	14%	28%	27%	36%	27%
New York	4%	7%	3%	3%	5%	5%
Pennsylvania	55%	46%	33%	25%	30%	42%
Virginia	20%	27%	33%	39%	24%	25%
West Virginia	3%	4%	2%	1%	2%	1%
Total	100%	100%	100%	100%	100%	100%

Source: Phase 5.3 Chesapeake Bay Watershed Model 2009 Scenario
Note: Nontidal deposition refers to atmospheric deposition direct to nontidal surface waters.

Table 4-2. Percentage of total phosphorus delivered to the Bay from each jurisdiction by pollutant source sector

Jurisdiction	Agriculture	Forest	Stormwater runoff	Point source	Septic	Nontidal deposition
Delaware	4%	1%	1%	0%	0%	0%
District of Columbia	0%	0%	1%	2%	0%	0%
Maryland	19%	14%	28%	21%	0%	27%
New York	5%	7%	3%	5%	0%	5%
Pennsylvania	24%	25%	16%	28%	0%	27%
Virginia	42%	45%	50%	42%	0%	38%
West Virginia	6%	7%	2%	3%	0%	2%
Total	100%	100%	100%	100%	100%	100%

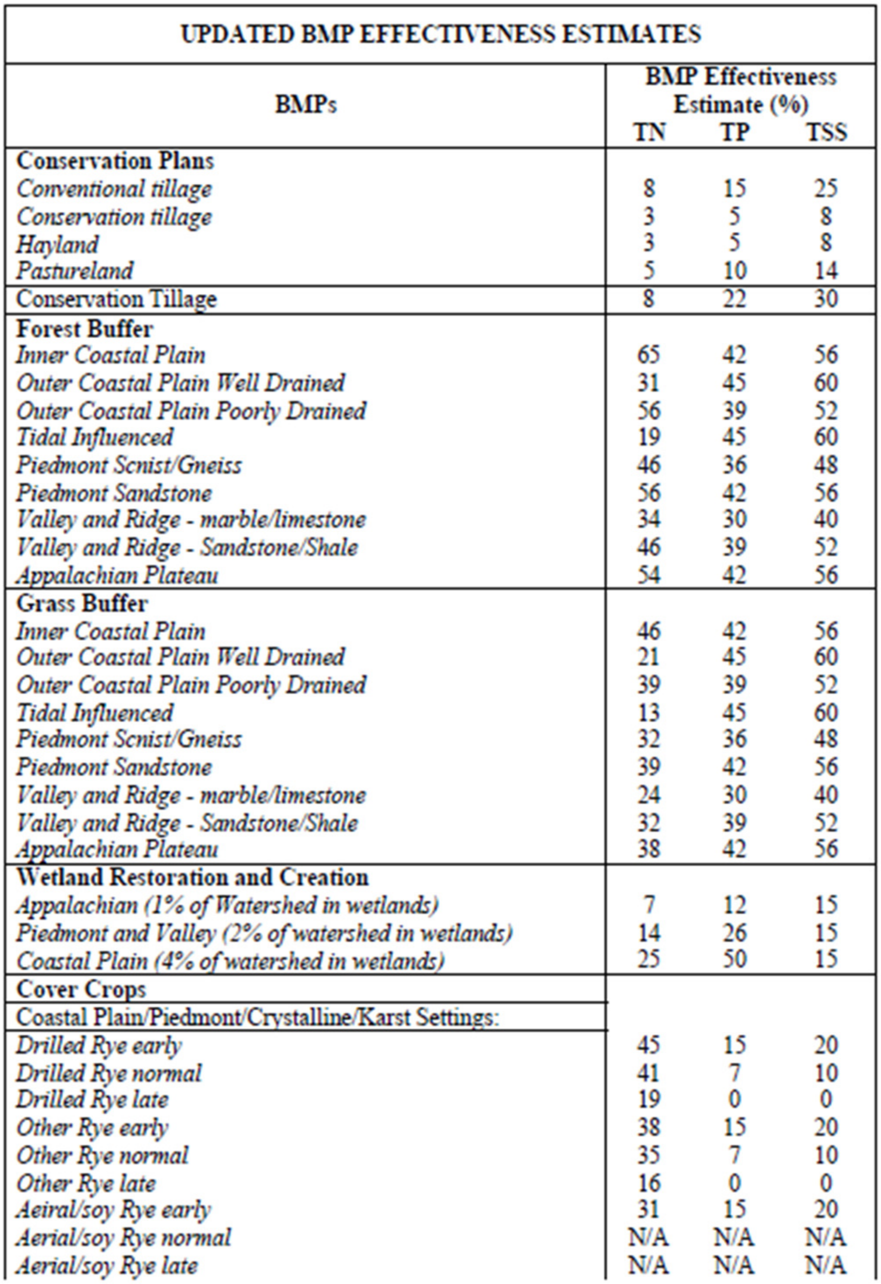
Source: Phase 5.3 Chesapeake Bay Watershed Model 2009 Scenario
Note: Nontidal deposition refers to atmospheric deposition direct to nontidal surface waters. Although the percentage contribution of phosphorus from nontidal deposition is provided here, the overall amount of phosphorus contributed from nontidal deposition is considered to be insignificant.

Table 4-3. Percentage of sediment delivered to the Bay from each jurisdiction by pollutant source sector

Jurisdiction	Agriculture	Forest	Stormwater runoff	Point source	Septic	Nontidal deposition
Delaware	1%	0%	1%	0%	--	--
District of Columbia	0%	0%	1%	27%	--	--
Maryland	15%	13%	32%	11%	--	--
New York	3%	8%	4%	3%	--	--
Pennsylvania	35%	34%	21%	23%	--	--
Virginia	41%	40%	39%	35%	--	--
West Virginia	5%	5%	3%	1%	--	--
Total	100%	100%	100%	100%	--	--

Source: Phase 5.3 Chesapeake Bay Watershed Model 2009 Scenario
Note: Only land-based sources of sediment were included in this table. Septic sources discharge to groundwater and nontidal deposition refers to atmospheric deposition direct to nontidal surface waters.

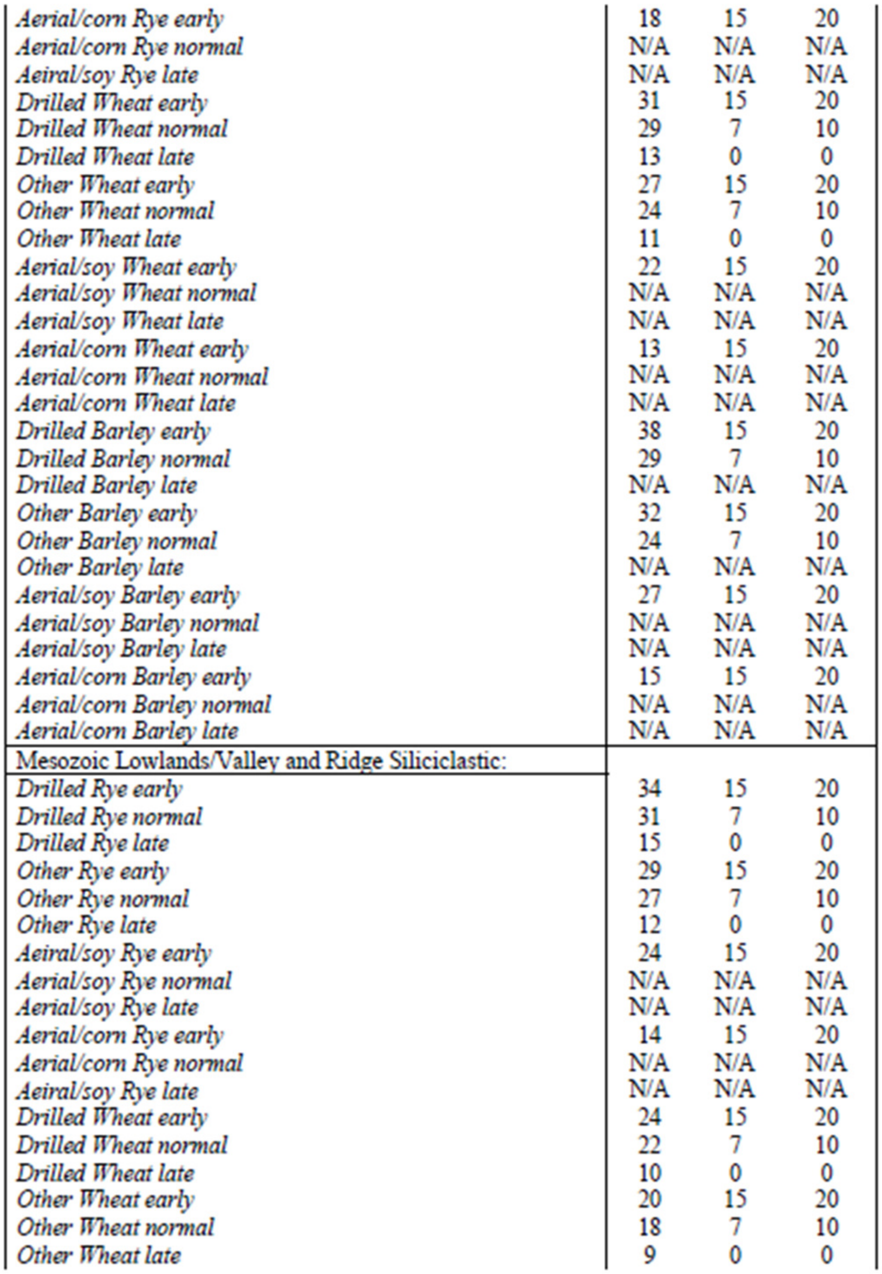
Table 5.2-2
Chesapeake Bay BMP Effectiveness Estimates
(Simpson and Weammert 2009)



UPDATED BMP EFFECTIVENESS ESTIMATES			
BMPs	**BMP Effectiveness Estimate (%)**		
	TN	**TP**	**TSS**
Conservation Plans			
Conventional tillage	8	15	25
Conservation tillage	3	5	8
Hayland	3	5	8
Pastureland	5	10	14
Conservation Tillage	8	22	30
Forest Buffer			
Inner Coastal Plain	65	42	56
Outer Coastal Plain Well Drained	31	45	60
Outer Coastal Plain Poorly Drained	56	39	52
Tidal Influenced	19	45	60
Piedmont Scnist/Gneiss	46	36	48
Piedmont Sandstone	56	42	56
Valley and Ridge - marble/limestone	34	30	40
Valley and Ridge - Sandstone/Shale	46	39	52
Appalachian Plateau	54	42	56
Grass Buffer			
Inner Coastal Plain	46	42	56
Outer Coastal Plain Well Drained	21	45	60
Outer Coastal Plain Poorly Drained	39	39	52
Tidal Influenced	13	45	60
Piedmont Scnist/Gneiss	32	36	48
Piedmont Sandstone	39	42	56
Valley and Ridge - marble/limestone	24	30	40
Valley and Ridge - Sandstone/Shale	32	39	52
Appalachian Plateau	38	42	56
Wetland Restoration and Creation			
Appalachian (1% of Watershed in wetlands)	7	12	15
Piedmont and Valley (2% of watershed in wetlands)	14	26	15
Coastal Plain (4% of watershed in wetlands)	25	50	15
Cover Crops			
Coastal Plain/Piedmont/Crystalline/Karst Settings:			
Drilled Rye early	45	15	20
Drilled Rye normal	41	7	10
Drilled Rye late	19	0	0
Other Rye early	38	15	20
Other Rye normal	35	7	10
Other Rye late	16	0	0
Aeiral/soy Rye early	31	15	20
Aerial/soy Rye normal	N/A	N/A	N/A
Aerial/soy Rye late	N/A	N/A	N/A

(cont.)

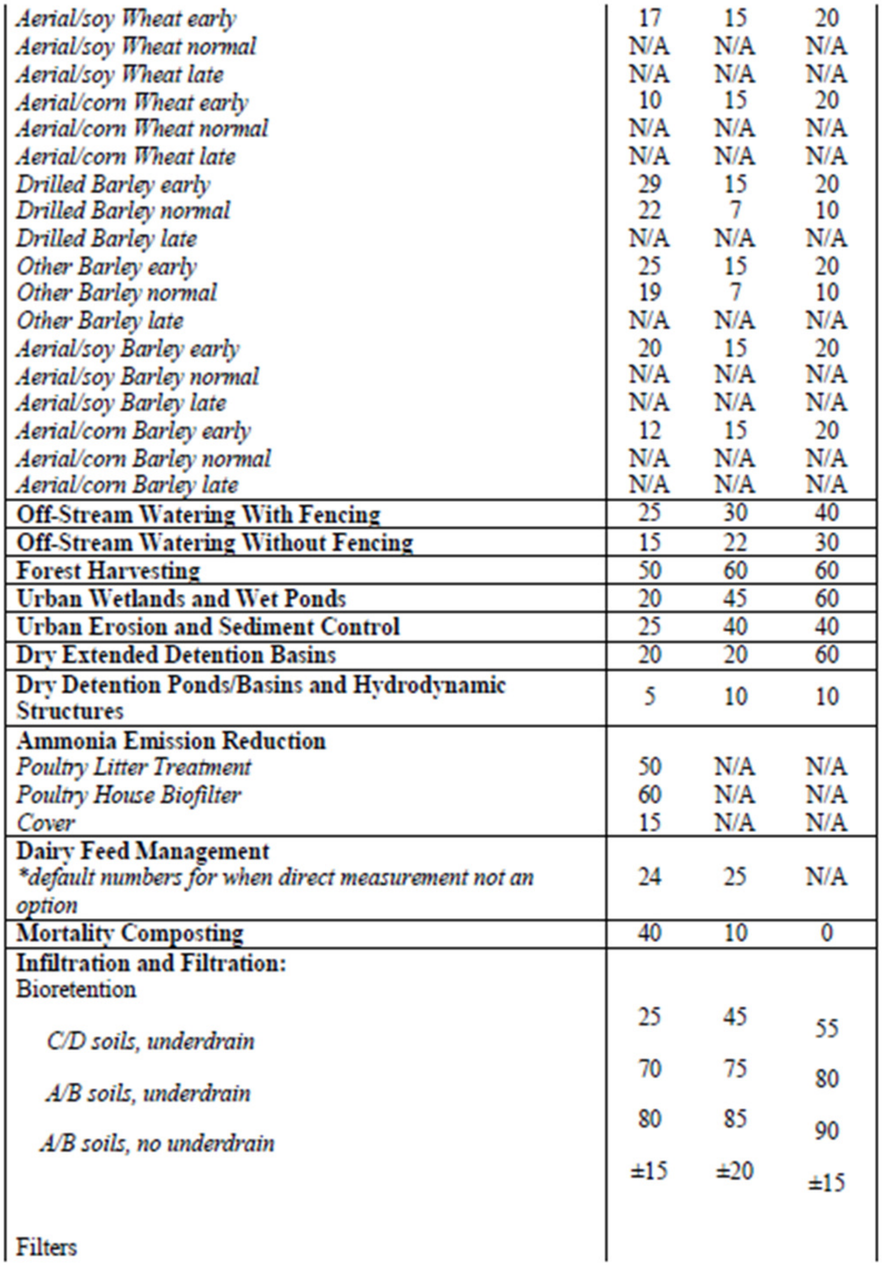
Table 5.2-2 (cont.)
Chesapeake Bay BMP Effectiveness Estimates
(Simpson and Weammert 2009)



Aerial/corn Rye early	18	15	20
Aerial/corn Rye normal	N/A	N/A	N/A
Aeiral/soy Rye late	N/A	N/A	N/A
Drilled Wheat early	31	15	20
Drilled Wheat normal	29	7	10
Drilled Wheat late	13	0	0
Other Wheat early	27	15	20
Other Wheat normal	24	7	10
Other Wheat late	11	0	0
Aerial/soy Wheat early	22	15	20
Aerial/soy Wheat normal	N/A	N/A	N/A
Aerial/soy Wheat late	N/A	N/A	N/A
Aerial/corn Wheat early	13	15	20
Aerial/corn Wheat normal	N/A	N/A	N/A
Aerial/corn Wheat late	N/A	N/A	N/A
Drilled Barley early	38	15	20
Drilled Barley normal	29	7	10
Drilled Barley late	N/A	N/A	N/A
Other Barley early	32	15	20
Other Barley normal	24	7	10
Other Barley late	N/A	N/A	N/A
Aerial/soy Barley early	27	15	20
Aerial/soy Barley normal	N/A	N/A	N/A
Aerial/soy Barley late	N/A	N/A	N/A
Aerial/corn Barley early	15	15	20
Aerial/corn Barley normal	N/A	N/A	N/A
Aerial/corn Barley late	N/A	N/A	N/A
Mesozoic Lowlands/Valley and Ridge Siliciclastic:			
Drilled Rye early	34	15	20
Drilled Rye normal	31	7	10
Drilled Rye late	15	0	0
Other Rye early	29	15	20
Other Rye normal	27	7	10
Other Rye late	12	0	0
Aeiral/soy Rye early	24	15	20
Aerial/soy Rye normal	N/A	N/A	N/A
Aerial/soy Rye late	N/A	N/A	N/A
Aerial/corn Rye early	14	15	20
Aerial/corn Rye normal	N/A	N/A	N/A
Aeiral/soy Rye late	N/A	N/A	N/A
Drilled Wheat early	24	15	20
Drilled Wheat normal	22	7	10
Drilled Wheat late	10	0	0
Other Wheat early	20	15	20
Other Wheat normal	18	7	10
Other Wheat late	9	0	0

(cont.)

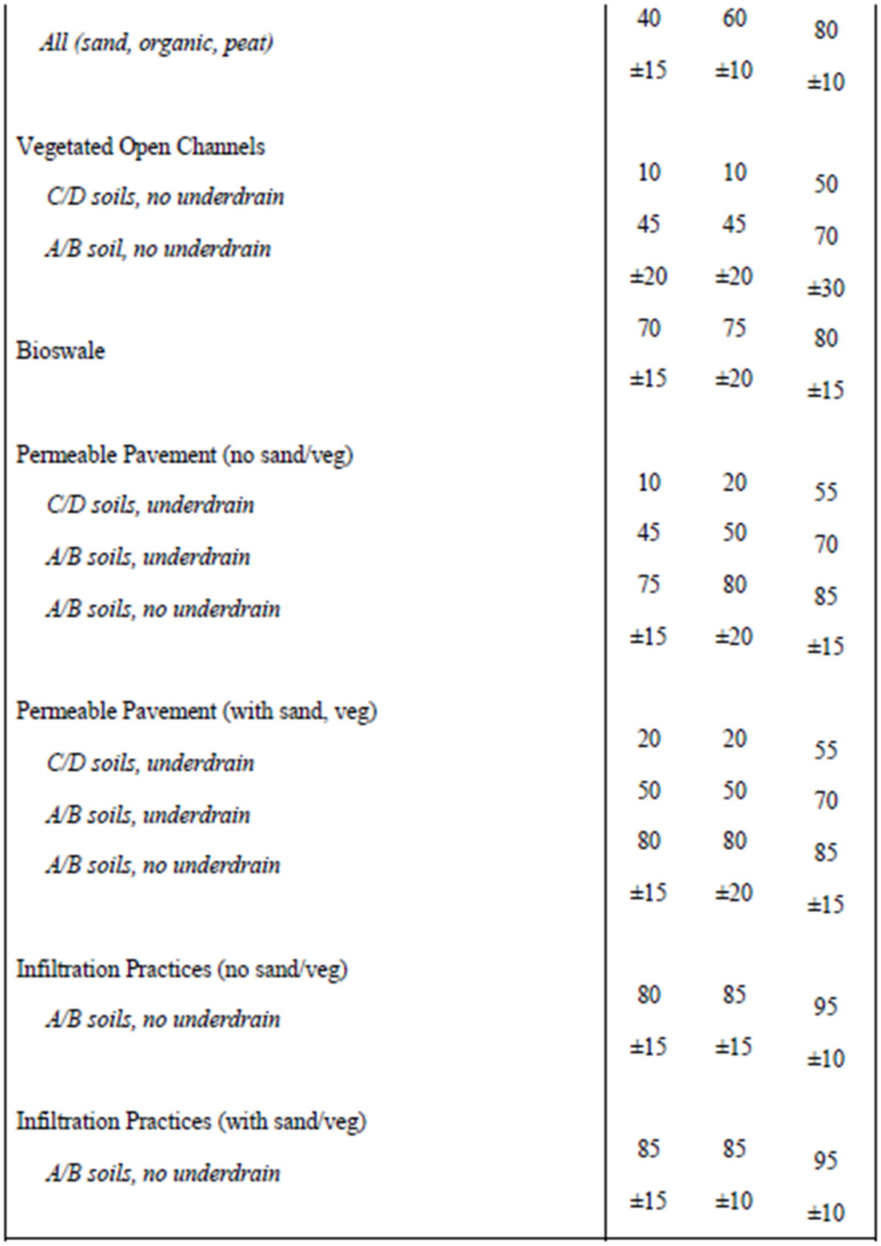
Table 5.2-2 (cont.)
Chesapeake Bay BMP Effectiveness Estimates
(Simpson and Weammert 2009)



Aerial/soy Wheat early	17	15	20
Aerial/soy Wheat normal	N/A	N/A	N/A
Aerial/soy Wheat late	N/A	N/A	N/A
Aerial/corn Wheat early	10	15	20
Aerial/corn Wheat normal	N/A	N/A	N/A
Aerial/corn Wheat late	N/A	N/A	N/A
Drilled Barley early	29	15	20
Drilled Barley normal	22	7	10
Drilled Barley late	N/A	N/A	N/A
Other Barley early	25	15	20
Other Barley normal	19	7	10
Other Barley late	N/A	N/A	N/A
Aerial/soy Barley early	20	15	20
Aerial/soy Barley normal	N/A	N/A	N/A
Aerial/soy Barley late	N/A	N/A	N/A
Aerial/corn Barley early	12	15	20
Aerial/corn Barley normal	N/A	N/A	N/A
Aerial/corn Barley late	N/A	N/A	N/A
Off-Stream Watering With Fencing	25	30	40
Off-Stream Watering Without Fencing	15	22	30
Forest Harvesting	50	60	60
Urban Wetlands and Wet Ponds	20	45	60
Urban Erosion and Sediment Control	25	40	40
Dry Extended Detention Basins	20	20	60
Dry Detention Ponds/Basins and Hydrodynamic Structures	5	10	10
Ammonia Emission Reduction			
Poultry Litter Treatment	50	N/A	N/A
Poultry House Biofilter	60	N/A	N/A
Cover	15	N/A	N/A
Dairy Feed Management **default numbers for when direct measurement not an option*	24	25	N/A
Mortality Composting	40	10	0
Infiltration and Filtration:			
Bioretention			
C/D soils, underdrain	25	45	55
A/B soils, underdrain	70	75	80
A/B soils, no underdrain	80	85	90
	±15	±20	±15
Filters			

(cont.)

Table 5.2-2 (cont.)
Chesapeake Bay BMP Effectiveness Estimates
(Simpson and Weammert 2009)



All (sand, organic, peat)	40	60	80
	±15	±10	±10
Vegetated Open Channels			
C/D soils, no underdrain	10	10	50
A/B soil, no underdrain	45	45	70
	±20	±20	±30
Bioswale	70	75	80
	±15	±20	±15
Permeable Pavement (no sand/veg)			
C/D soils, underdrain	10	20	55
A/B soils, underdrain	45	50	70
A/B soils, no underdrain	75	80	85
	±15	±20	±15
Permeable Pavement (with sand, veg)			
C/D soils, underdrain	20	20	55
A/B soils, underdrain	50	50	70
A/B soils, no underdrain	80	80	85
	±15	±20	±15
Infiltration Practices (no sand/veg)			
A/B soils, no underdrain	80	85	95
	±15	±15	±10
Infiltration Practices (with sand/veg)			
A/B soils, no underdrain	85	85	95
	±15	±10	±10

Table 5.2-3
Reductions to Sediment, Nitrogen, and Phosphorus Loads to Susquehanna River with BMPs on Cultivated Cropland (from NRCS 2011)

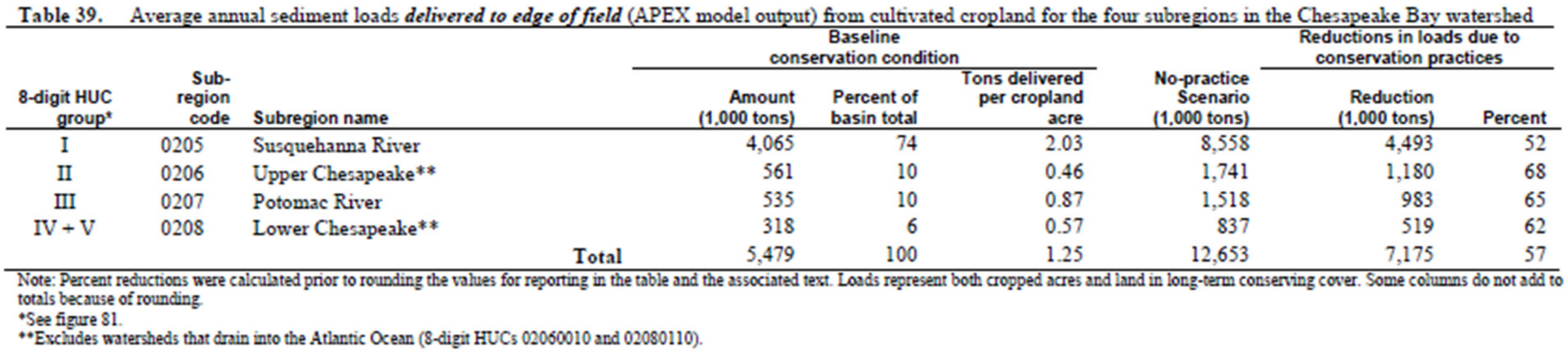


Table 39. Average annual sediment loads ***delivered to edge of field*** (APEX model output) from cultivated cropland for the four subregions in the Chesapeake Bay watershed

			Baseline conservation condition				Reductions in loads due to conservation practices	
8-digit HUC group*	Sub-region code	Subregion name	Amount (1,000 tons)	Percent of basin total	Tons delivered per cropland acre	No-practice Scenario (1,000 tons)	Reduction (1,000 tons)	Percent
I	0205	Susquehanna River	4,065	74	2.03	8,558	4,493	52
II	0206	Upper Chesapeake**	561	10	0.46	1,741	1,180	68
III	0207	Potomac River	535	10	0.87	1,518	983	65
IV + V	0208	Lower Chesapeake**	318	6	0.57	837	519	62
		Total	5,479	100	1.25	12,653	7,175	57

Note: Percent reductions were calculated prior to rounding the values for reporting in the table and the associated text. Loads represent both cropped acres and land in long-term conserving cover. Some columns do not add to totals because of rounding.

*See figure 81.

**Excludes watersheds that drain into the Atlantic Ocean (8-digit HUCs 02060010 and 02080110).

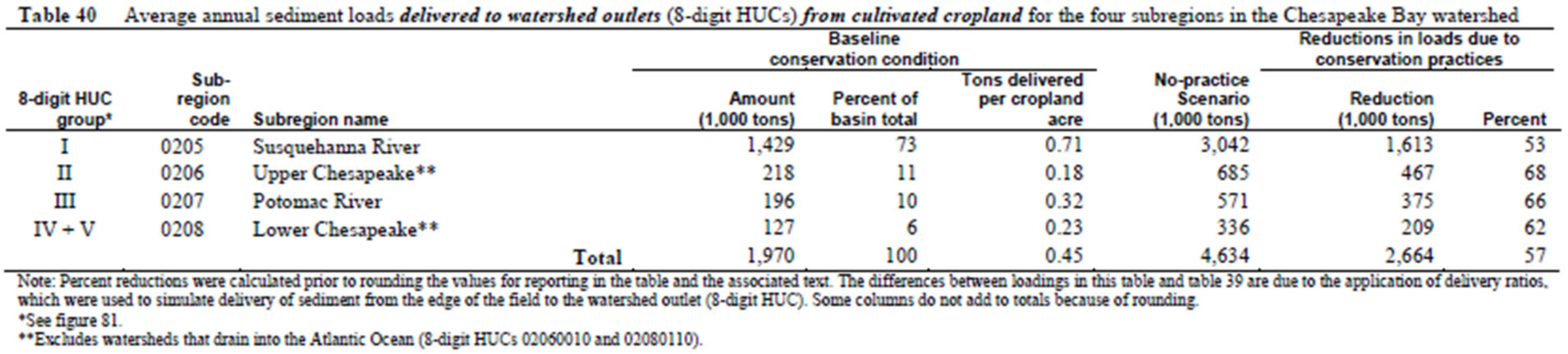


Table 40 Average annual sediment loads ***delivered to watershed outlets*** (8-digit HUCs) ***from cultivated cropland*** for the four subregions in the Chesapeake Bay watershed

			Baseline conservation condition				Reductions in loads due to conservation practices	
8-digit HUC group*	Sub-region code	Subregion name	Amount (1,000 tons)	Percent of basin total	Tons delivered per cropland acre	No-practice Scenario (1,000 tons)	Reduction (1,000 tons)	Percent
I	0205	Susquehanna River	1,429	73	0.71	3,042	1,613	53
II	0206	Upper Chesapeake**	218	11	0.18	685	467	68
III	0207	Potomac River	196	10	0.32	571	375	66
IV + V	0208	Lower Chesapeake**	127	6	0.23	336	209	62
		Total	1,970	100	0.45	4,634	2,664	57

Note: Percent reductions were calculated prior to rounding the values for reporting in the table and the associated text. The differences between loadings in this table and table 39 are due to the application of delivery ratios, which were used to simulate delivery of sediment from the edge of the field to the watershed outlet (8-digit HUC). Some columns do not add to totals because of rounding.

*See figure 81.

**Excludes watersheds that drain into the Atlantic Ocean (8-digit HUCs 02060010 and 02080110).

(cont.)

Table 5.2-3
Reductions to Sediment, Nitrogen, and Phosphorus Loads to Susquehanna River with BMPs on Cultivated Cropland (from NRCS 2011) (cont.)

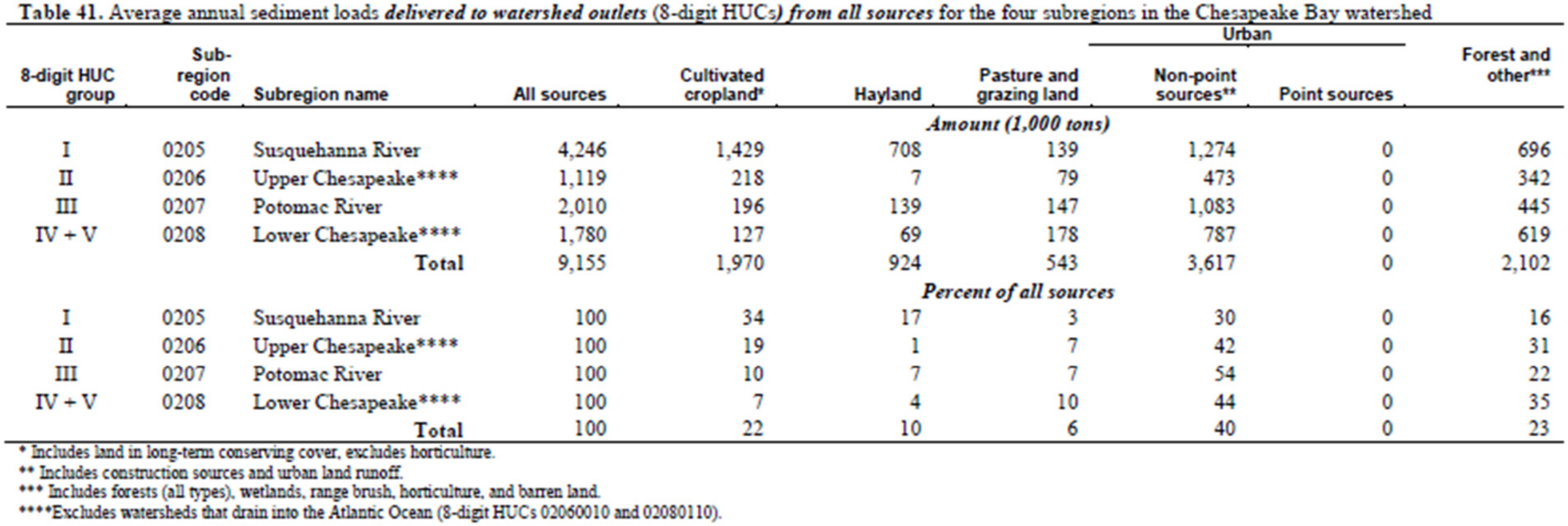


Table 41. Average annual sediment loads ***delivered to watershed outlets*** (8-digit HUCs) ***from all sources*** for the four subregions in the Chesapeake Bay watershed

8-digit HUC group	Sub-region code	Subregion name	All sources	Cultivated cropland*	Hayland	Pasture and grazing land	Urban		Forest and other***
							Non-point sources**	Point sources	
					Amount (1,000 tons)				
I	0205	Susquehanna River	4,246	1,429	708	139	1,274	0	696
II	0206	Upper Chesapeake****	1,119	218	7	79	473	0	342
III	0207	Potomac River	2,010	196	139	147	1,083	0	445
IV + V	0208	Lower Chesapeake****	1,780	127	69	178	787	0	619
		Total	9,155	1,970	924	543	3,617	0	2,102
					Percent of all sources				
I	0205	Susquehanna River	100	34	17	3	30	0	16
II	0206	Upper Chesapeake****	100	19	1	7	42	0	31
III	0207	Potomac River	100	10	7	7	54	0	22
IV + V	0208	Lower Chesapeake****	100	7	4	10	44	0	35
		Total	100	22	10	6	40	0	23

* Includes land in long-term conserving cover, excludes horticulture.

** Includes construction sources and urban land runoff.

*** Includes forests (all types), wetlands, range brush, horticulture, and barren land.

****Excludes watersheds that drain into the Atlantic Ocean (8-digit HUCs 02060010 and 02080110).

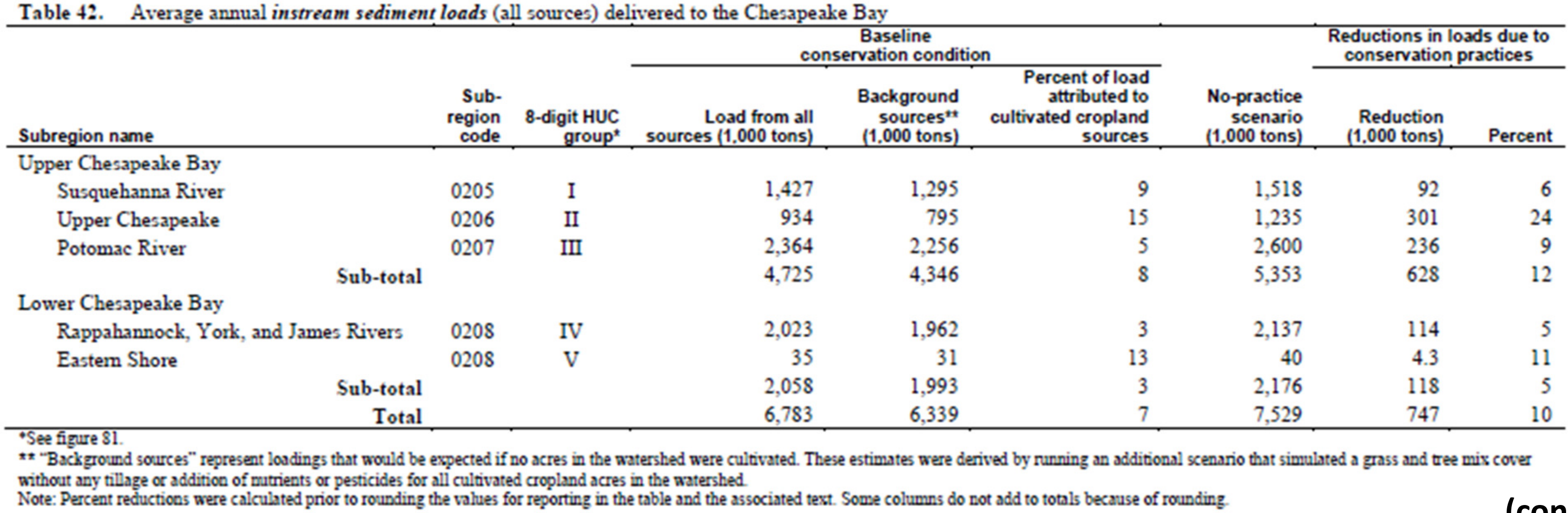


Table 42. Average annual ***instream sediment loads*** (all sources) delivered to the Chesapeake Bay

Subregion name	Sub-region code	8-digit HUC group*	Baseline conservation condition			No-practice scenario (1,000 tons)	Reductions in loads due to conservation practices	
			Load from all sources (1,000 tons)	Background sources** (1,000 tons)	Percent of load attributed to cultivated cropland sources		Reduction (1,000 tons)	Percent
Upper Chesapeake Bay								
Susquehanna River	0205	I	1,427	1,295	9	1,518	92	6
Upper Chesapeake	0206	II	934	795	15	1,235	301	24
Potomac River	0207	III	2,364	2,256	5	2,600	236	9
Sub-total			4,725	4,346	8	5,353	628	12
Lower Chesapeake Bay								
Rappahannock, York, and James Rivers	0208	IV	2,023	1,962	3	2,137	114	5
Eastern Shore	0208	V	35	31	13	40	4.3	11
Sub-total			2,058	1,993	3	2,176	118	5
Total			6,783	6,339	7	7,529	747	10

*See figure 81.

** "Background sources" represent loadings that would be expected if no acres in the watershed were cultivated. These estimates were derived by running an additional scenario that simulated a grass and tree mix cover without any tillage or addition of nutrients or pesticides for all cultivated cropland acres in the watershed.

Note: Percent reductions were calculated prior to rounding the values for reporting in the table and the associated text. Some columns do not add to totals because of rounding.

(cont.)

Table 5.2-3
Reductions to Sediment, Nitrogen, and Phosphorus Loads to Susquehanna River with BMPs on Cultivated Cropland (from NCRS 2011) (cont.)

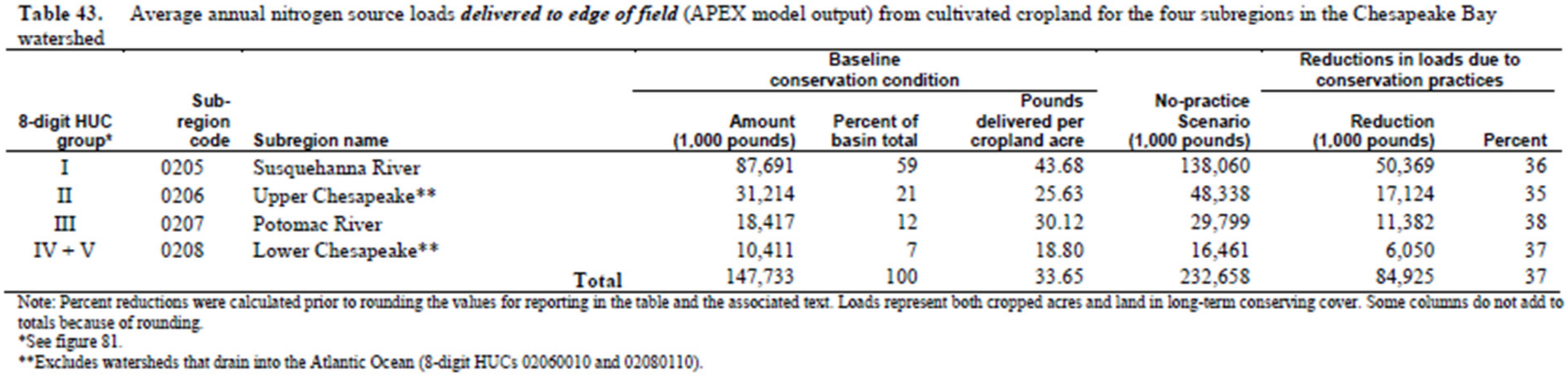


Table 43. Average annual nitrogen source loads ***delivered to edge of field*** (APEX model output) from cultivated cropland for the four subregions in the Chesapeake Bay watershed

			Baseline conservation condition				Reductions in loads due to conservation practices	
8-digit HUC group*	Sub-region code	Subregion name	Amount (1,000 pounds)	Percent of basin total	Pounds delivered per cropland acre	No-practice Scenario (1,000 pounds)	Reduction (1,000 pounds)	Percent
I	0205	Susquehanna River	87,691	59	43.68	138,060	50,369	36
II	0206	Upper Chesapeake**	31,214	21	25.63	48,338	17,124	35
III	0207	Potomac River	18,417	12	30.12	29,799	11,382	38
IV + V	0208	Lower Chesapeake**	10,411	7	18.80	16,461	6,050	37
		Total	147,733	100	33.65	232,658	84,925	37

Note: Percent reductions were calculated prior to rounding the values for reporting in the table and the associated text. Loads represent both cropped acres and land in long-term conserving cover. Some columns do not add to totals because of rounding.

*See figure 81.

**Excludes watersheds that drain into the Atlantic Ocean (8-digit HUCs 02060010 and 02080110).

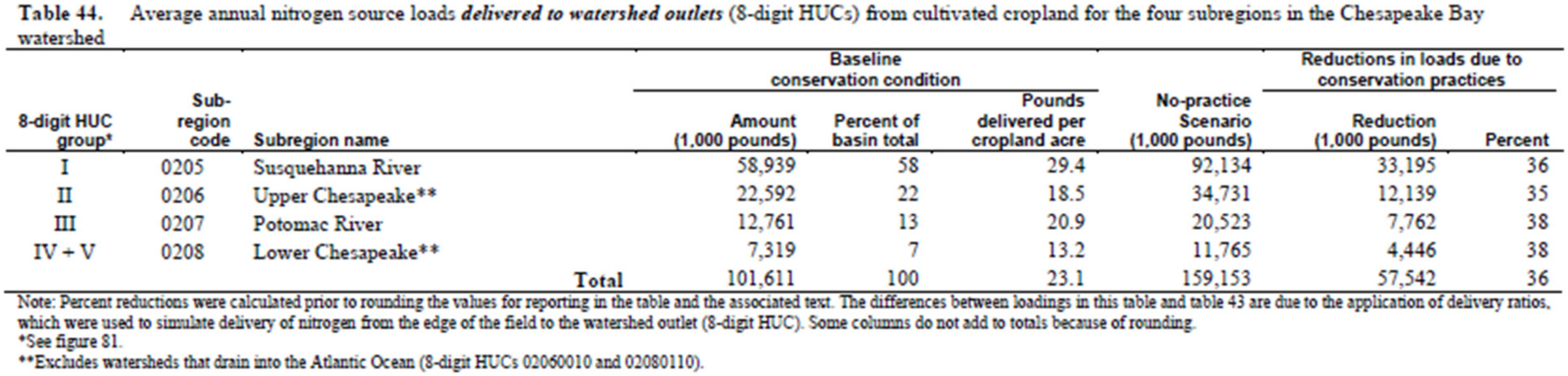


Table 44. Average annual nitrogen source loads ***delivered to watershed outlets*** (8-digit HUCs) from cultivated cropland for the four subregions in the Chesapeake Bay watershed

			Baseline conservation condition				Reductions in loads due to conservation practices	
8-digit HUC group*	Sub-region code	Subregion name	Amount (1,000 pounds)	Percent of basin total	Pounds delivered per cropland acre	No-practice Scenario (1,000 pounds)	Reduction (1,000 pounds)	Percent
I	0205	Susquehanna River	58,939	58	29.4	92,134	33,195	36
II	0206	Upper Chesapeake**	22,592	22	18.5	34,731	12,139	35
III	0207	Potomac River	12,761	13	20.9	20,523	7,762	38
IV + V	0208	Lower Chesapeake**	7,319	7	13.2	11,765	4,446	38
		Total	101,611	100	23.1	159,153	57,542	36

Note: Percent reductions were calculated prior to rounding the values for reporting in the table and the associated text. The differences between loadings in this table and table 43 are due to the application of delivery ratios, which were used to simulate delivery of nitrogen from the edge of the field to the watershed outlet (8-digit HUC). Some columns do not add to totals because of rounding.

*See figure 81.

**Excludes watersheds that drain into the Atlantic Ocean (8-digit HUCs 02060010 and 02080110).

(cont.)

Table 5.2-3
Reductions to Sediment, Nitrogen, and Phosphorus Loads to Susquehanna River with BMPs on Cultivated Cropland (from NRCS 2011) (cont.)

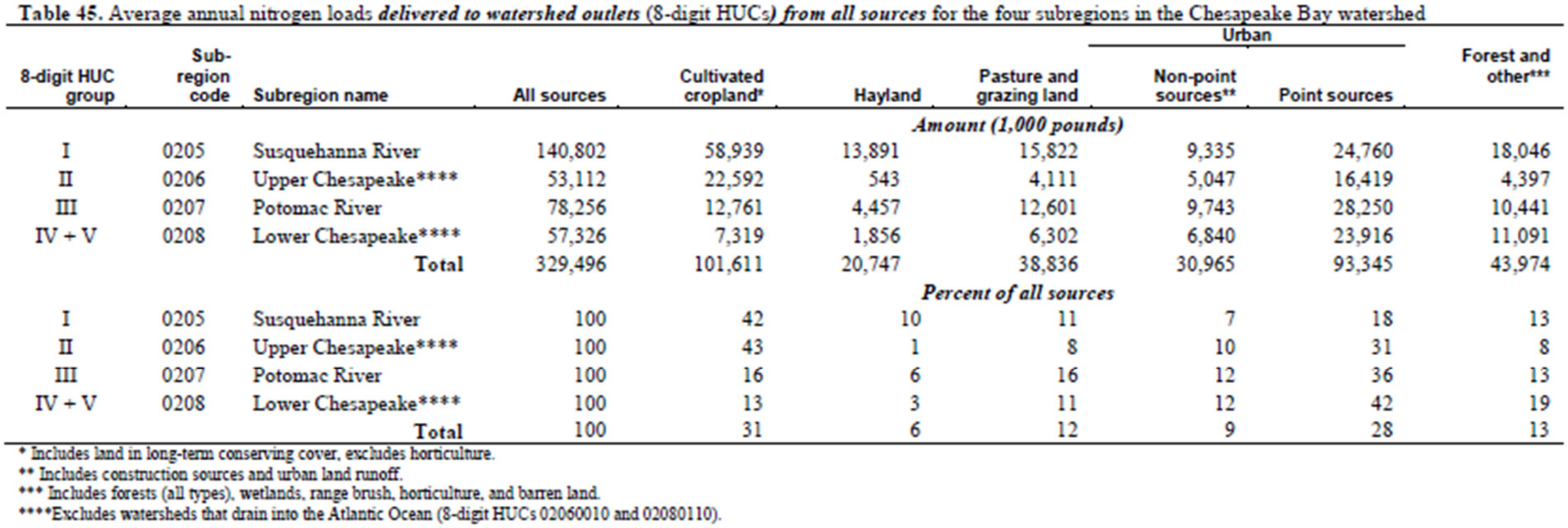


Table 45. Average annual nitrogen loads ***delivered to watershed outlets*** (8-digit HUCs***) from all sources*** for the four subregions in the Chesapeake Bay watershed

8-digit HUC group	Sub-region code	Subregion name	All sources	Cultivated cropland*	Hayland	Pasture and grazing land	Urban Non-point sources**	Urban Point sources	Forest and other***
						Amount (1,000 pounds)			
I	0205	Susquehanna River	140,802	58,939	13,891	15,822	9,335	24,760	18,046
II	0206	Upper Chesapeake****	53,112	22,592	543	4,111	5,047	16,419	4,397
III	0207	Potomac River	78,256	12,761	4,457	12,601	9,743	28,250	10,441
IV + V	0208	Lower Chesapeake****	57,326	7,319	1,856	6,302	6,840	23,916	11,091
		Total	329,496	101,611	20,747	38,836	30,965	93,345	43,974
						Percent of all sources			
I	0205	Susquehanna River	100	42	10	11	7	18	13
II	0206	Upper Chesapeake****	100	43	1	8	10	31	8
III	0207	Potomac River	100	16	6	16	12	36	13
IV + V	0208	Lower Chesapeake****	100	13	3	11	12	42	19
		Total	100	31	6	12	9	28	13

* Includes land in long-term conserving cover, excludes horticulture.
** Includes construction sources and urban land runoff.
*** Includes forests (all types), wetlands, range brush, horticulture, and barren land.
****Excludes watersheds that drain into the Atlantic Ocean (8-digit HUCs 02060010 and 02080110).

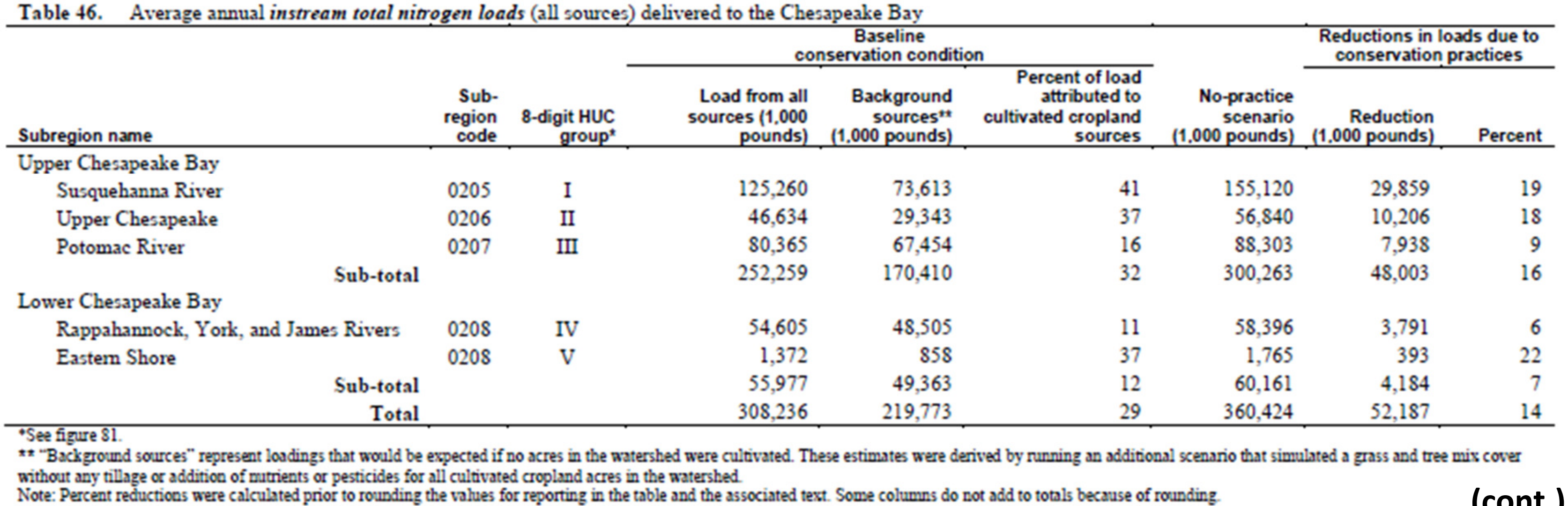


Table 46. Average annual ***instream total nitrogen loads*** (all sources) delivered to the Chesapeake Bay

Subregion name	Sub-region code	8-digit HUC group*	Baseline conservation condition Load from all sources (1,000 pounds)	Background sources** (1,000 pounds)	Percent of load attributed to cultivated cropland sources	No-practice scenario (1,000 pounds)	Reductions in loads due to conservation practices Reduction (1,000 pounds)	Percent
Upper Chesapeake Bay								
Susquehanna River	0205	I	125,260	73,613	41	155,120	29,859	19
Upper Chesapeake	0206	II	46,634	29,343	37	56,840	10,206	18
Potomac River	0207	III	80,365	67,454	16	88,303	7,938	9
Sub-total			252,259	170,410	32	300,263	48,003	16
Lower Chesapeake Bay								
Rappahannock, York, and James Rivers	0208	IV	54,605	48,505	11	58,396	3,791	6
Eastern Shore	0208	V	1,372	858	37	1,765	393	22
Sub-total			55,977	49,363	12	60,161	4,184	7
Total			308,236	219,773	29	360,424	52,187	14

*See figure 81.
** "Background sources" represent loadings that would be expected if no acres in the watershed were cultivated. These estimates were derived by running an additional scenario that simulated a grass and tree mix cover without any tillage or addition of nutrients or pesticides for all cultivated cropland acres in the watershed.
Note: Percent reductions were calculated prior to rounding the values for reporting in the table and the associated text. Some columns do not add to totals because of rounding.

(cont.)

Table 5.2-3
Reductions to Sediment, Nitrogen, and Phosphorus Loads to Susquehanna River with BMPs on Cultivated Cropland (from NRCS 2011) (cont.)

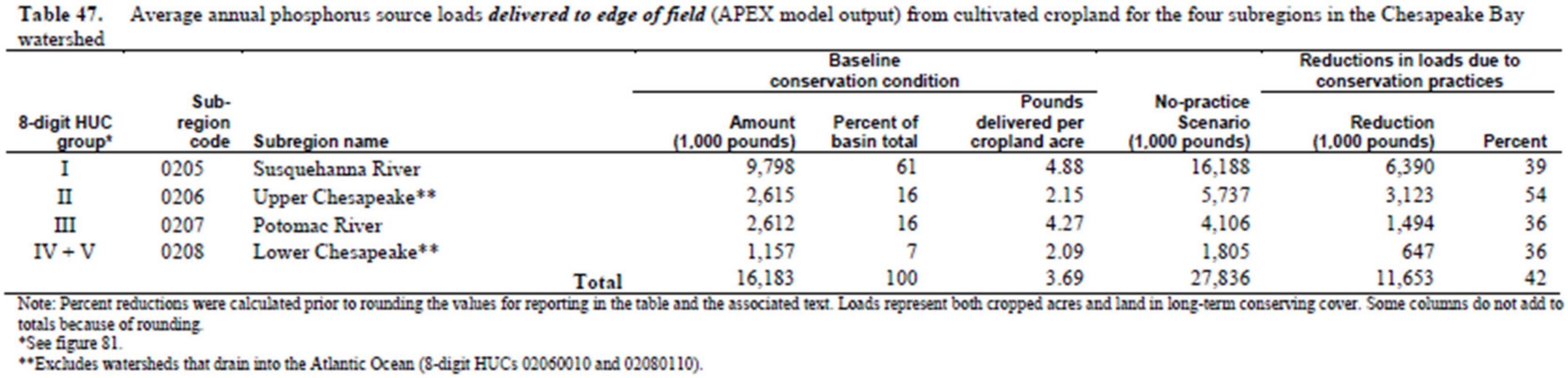


Table 47. Average annual phosphorus source loads ***delivered to edge of field*** (APEX model output) from cultivated cropland for the four subregions in the Chesapeake Bay watershed

			Baseline conservation condition				Reductions in loads due to conservation practices	
8-digit HUC group*	Sub-region code	Subregion name	Amount (1,000 pounds)	Percent of basin total	Pounds delivered per cropland acre	No-practice Scenario (1,000 pounds)	Reduction (1,000 pounds)	Percent
I	0205	Susquehanna River	9,798	61	4.88	16,188	6,390	39
II	0206	Upper Chesapeake**	2,615	16	2.15	5,737	3,123	54
III	0207	Potomac River	2,612	16	4.27	4,106	1,494	36
IV + V	0208	Lower Chesapeake**	1,157	7	2.09	1,805	647	36
		Total	16,183	100	3.69	27,836	11,653	42

Note: Percent reductions were calculated prior to rounding the values for reporting in the table and the associated text. Loads represent both cropped acres and land in long-term conserving cover. Some columns do not add to totals because of rounding.

*See figure 81.

**Excludes watersheds that drain into the Atlantic Ocean (8-digit HUCs 02060010 and 02080110).

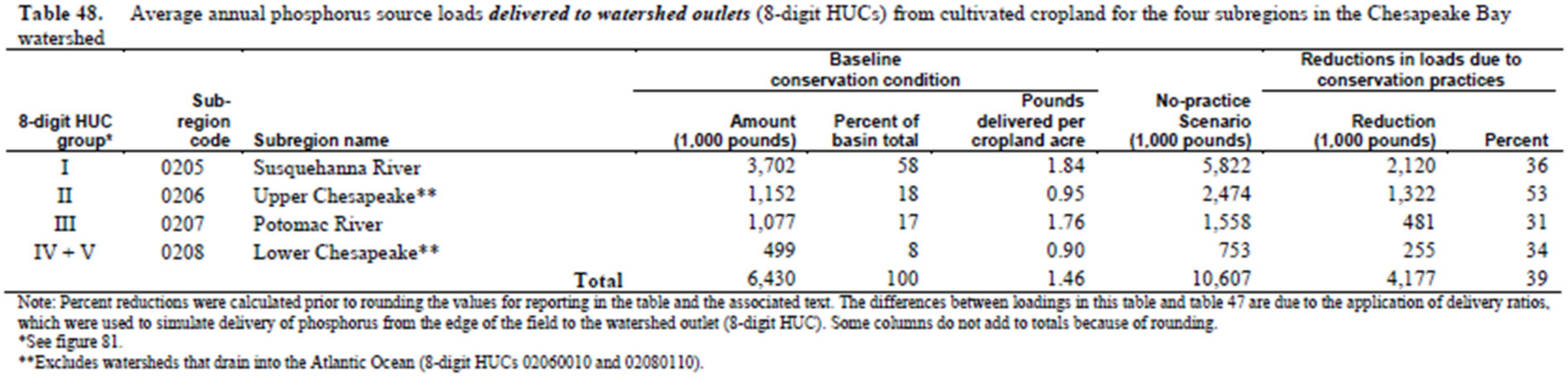


Table 48. Average annual phosphorus source loads ***delivered to watershed outlets*** (8-digit HUCs) from cultivated cropland for the four subregions in the Chesapeake Bay watershed

			Baseline conservation condition				Reductions in loads due to conservation practices	
8-digit HUC group*	Sub-region code	Subregion name	Amount (1,000 pounds)	Percent of basin total	Pounds delivered per cropland acre	No-practice Scenario (1,000 pounds)	Reduction (1,000 pounds)	Percent
I	0205	Susquehanna River	3,702	58	1.84	5,822	2,120	36
II	0206	Upper Chesapeake**	1,152	18	0.95	2,474	1,322	53
III	0207	Potomac River	1,077	17	1.76	1,558	481	31
IV + V	0208	Lower Chesapeake**	499	8	0.90	753	255	34
		Total	6,430	100	1.46	10,607	4,177	39

Note: Percent reductions were calculated prior to rounding the values for reporting in the table and the associated text. The differences between loadings in this table and table 47 are due to the application of delivery ratios, which were used to simulate delivery of phosphorus from the edge of the field to the watershed outlet (8-digit HUC). Some columns do not add to totals because of rounding.

*See figure 81.

**Excludes watersheds that drain into the Atlantic Ocean (8-digit HUCs 02060010 and 02080110).

(cont.)

Table 5.2-3
Reductions to Sediment, Nitrogen, and Phosphorus Loads to Susquehanna River with BMPs on Cultivated Cropland (from NRCS 2011) (cont.)

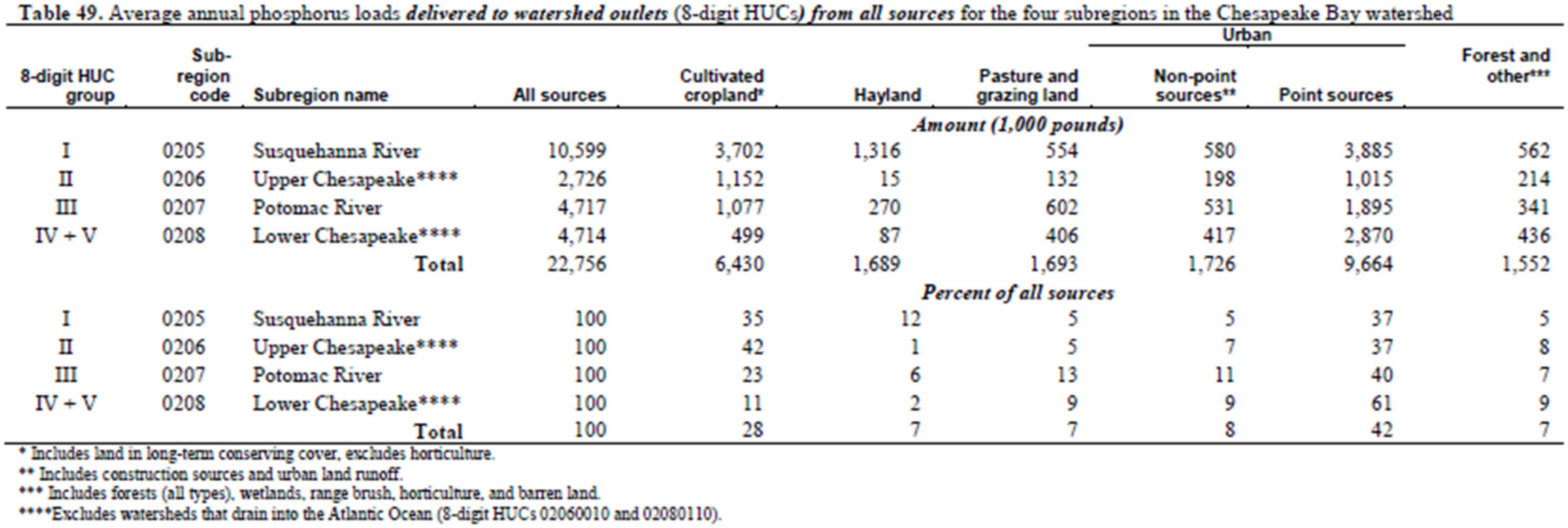


Table 49. Average annual phosphorus loads ***delivered to watershed outlets*** (8-digit HUCs***) from all sources*** for the four subregions in the Chesapeake Bay watershed

8-digit HUC group	Sub-region code	Subregion name	All sources	Cultivated cropland*	Hayland	Pasture and grazing land	Urban: Non-point sources**	Urban: Point sources	Forest and other***
			Amount (1,000 pounds)						
I	0205	Susquehanna River	10,599	3,702	1,316	554	580	3,885	562
II	0206	Upper Chesapeake****	2,726	1,152	15	132	198	1,015	214
III	0207	Potomac River	4,717	1,077	270	602	531	1,895	341
IV + V	0208	Lower Chesapeake****	4,714	499	87	406	417	2,870	436
		Total	22,756	6,430	1,689	1,693	1,726	9,664	1,552
			Percent of all sources						
I	0205	Susquehanna River	100	35	12	5	5	37	5
II	0206	Upper Chesapeake****	100	42	1	5	7	37	8
III	0207	Potomac River	100	23	6	13	11	40	7
IV + V	0208	Lower Chesapeake****	100	11	2	9	9	61	9
		Total	100	28	7	7	8	42	7

* Includes land in long-term conserving cover, excludes horticulture.
** Includes construction sources and urban land runoff.
*** Includes forests (all types), wetlands, range brush, horticulture, and barren land.
****Excludes watersheds that drain into the Atlantic Ocean (8-digit HUCs 02060010 and 02080110).

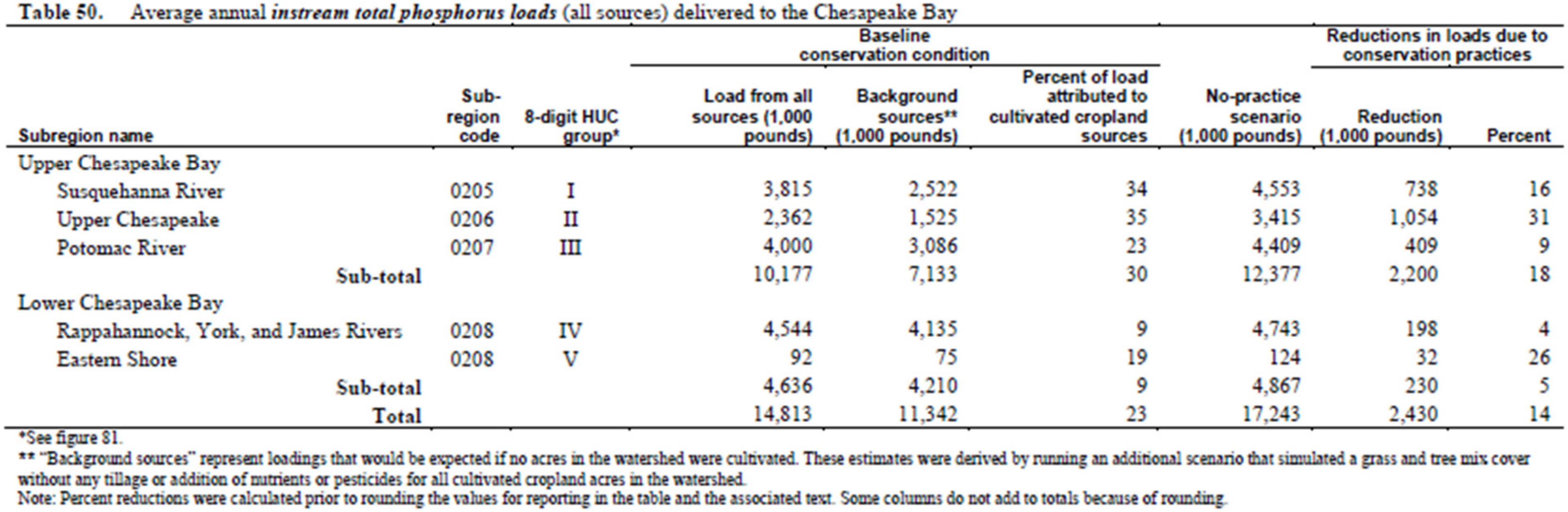


Table 50. Average annual ***instream total phosphorus loads*** (all sources) delivered to the Chesapeake Bay

Subregion name	Sub-region code	8-digit HUC group*	Baseline conservation condition: Load from all sources (1,000 pounds)	Baseline conservation condition: Background sources** (1,000 pounds)	Baseline conservation condition: Percent of load attributed to cultivated cropland sources	No-practice scenario (1,000 pounds)	Reductions in loads due to conservation practices: Reduction (1,000 pounds)	Reductions in loads due to conservation practices: Percent
Upper Chesapeake Bay								
Susquehanna River	0205	I	3,815	2,522	34	4,553	738	16
Upper Chesapeake	0206	II	2,362	1,525	35	3,415	1,054	31
Potomac River	0207	III	4,000	3,086	23	4,409	409	9
Sub-total			10,177	7,133	30	12,377	2,200	18
Lower Chesapeake Bay								
Rappahannock, York, and James Rivers	0208	IV	4,544	4,135	9	4,743	198	4
Eastern Shore	0208	V	92	75	19	124	32	26
Sub-total			4,636	4,210	9	4,867	230	5
Total			14,813	11,342	23	17,243	2,430	14

*See figure 81.
** "Background sources" represent loadings that would be expected if no acres in the watershed were cultivated. These estimates were derived by running an additional scenario that simulated a grass and tree mix cover without any tillage or addition of nutrients or pesticides for all cultivated cropland acres in the watershed.
Note: Percent reductions were calculated prior to rounding the values for reporting in the table and the associated text. Some columns do not add to totals because of rounding.

Table 5.4-1

Chesapeake Bay Program Recommended Sediment Best Management Practices

BMP[1]	Description
Riparian Buffers	A riparian buffer is an area of trees, shrubs, grasses or other vegetation that is (i) at least 35 feet wide, (ii) adjacent to a body of water, and (iii) managed to maintain the integrity of stream channels and shorelines. A riparian buffer reduces the effects of upland sources of pollution by trapping, filtering, and converting sediments, nutrients, and other chemicals.
Stream Restoration	Stream restoration is a term used to cover a "broad range of actions and measures designed to enable stream corridors to recover dynamic equilibrium and function at a self-sustaining level." The objectives for stream restoration include, but are not limited to, reducing stream channel erosion, promoting physical channel stability, reducing the transport of pollutants downstream, and working towards a stable habitat with a self-sustaining, diverse aquatic community.
Urban Stormwater Management	The CBP's Urban Stormwater Workgroup (USWG) developed a list of BMP categories and specific BMPs with associated pollutant removal efficiencies and hydrologic effects. This list is quite extensive and includes an overview of: the construction of wet ponds and wetlands, dry detention hydrodynamic structures, and dry extended detention systems; infiltration practices; filtering practices; roadway systems; impervious surface reduction; street sweeping; and catch basin inserts.
Structural Shoreline Erosion Controls	Structural shoreline erosion controls are designed to protect eroding shorelines by armoring the shoreline to dissipate incoming wave energy while protecting unconsolidated bank sediments. These practices are applicable in areas of higher erosion rates or where wave energy is too strong for vegetative alternatives. They include: shoreline hardening, offshore breakwaters, headland controls, and breakwater systems.
Restoring Submerged Aquatic Vegetation	The benefits of restoring submerged aquatic vegetation (SAV) to the Chesapeake are fairly well documented and publicized. SAV specifically filters and traps sediment and nutrients from the water column and also reduces shoreline erosion by dampening water velocity and turbulence.

Source: Chesapeake Bay Program (2006)

[1] Oyster Restoration and Oyster Aquaculture have been excluded because of their limited applicability to the Conowingo Project.

Table 5.5-1
Traditional Methods to Preserve Reservoir Storage Capacity

METHOD	EXPLANATION	FEASIBILITY *
Control Volume of Sediment Entering Reservoir		
Watershed Management	Implementation of management practices throughout the watershed to reduce sediment loads reaching the reservoir.	**yes**
Upstream Check Structures	Placement of structure designed to interrupt flows of tributaries, reduce velocity, and promote deposition.	**-**
Reservoir Bypass	Divert sediment-laden flows around reservoir by construction of conveyance channel.	**maybe**
Off-Channel Storage	Main channel water is diverted to off-channel storage reservoirs; appropriate option of new projects but not for existing projects.	**-**
Create Flow Conditions Within Reservoir to Prevent Accumulation		
Sluicing	Pass incoming sediment load through reservoir and dam before sediment can settle.	**no** [1]
Density Current Venting	Density, viscosity, and turbulence differences in a reservoir may trigger the sinking of dense highly suspended sediment-lade inflow and development of a coherent current of sediment-laden water transporting large amounts of sediment towards the dam. Sediment accumulation is prevented by venting the density current through low-level outlets.	**-**
Remove Sediment That Has Already Been Deposited		
Flushing	Remobilize accumulated sediment by increasing flow velocities to scour and transport through low-level outlets in dam.	**maybe**[2]
Mechanical Removal (dredging)	Hydraulic dredging Mechanical dredging Dry excavation Hydrosuction (siphon) dredging	**no**

***Refers to discussions specific to use in Conowingo Pond (see Section 5.6 in text).**

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[1] This is termed *flushing* by source cited in Section 5.6

[2] This is termed *sluicing* by source cited in Section 5.6

Table 5.6-1: In-Reservoir Sediment Management Options

Option	Citation	Pros	Cons	Cost	Finding	Comments/Questions
Dredging behind dam	SRBC (1995) SRBC (2002) USGS/Corps (2006)	○ Regain lost capacity ○ Reduces sediment scour	○ Increased turbidity ○ Large disposal site(s) ○ Environmental permitting ○ Cost	1995 estimate of $28 million per year to keep pace with new sediment deposited	Corps needs to conduct a feasibility study	○ Which reservoirs to dredge? ○ Quantity? ○ Selective dredging of fines in combination with bypassing of coarse sediment suggested in 2006 ○ Army Corps seeking non-federal partners to support feasibility study
Flushing sediment laden storm flows over spillway or through low-level outlets in dam	SRBC (1995)	○ Reduces deposition behind dam	○ Does not regain lost capacity ○ Does not address high flow scour loads ○ Limited upstream effectiveness ○ Does not reduce sediment load to Bay	moderate	Dismissed from further consideration	○ Scour loads already flow over spillway ○ Use turbine units as low-level outlets ○ Alters timing or variability of loadings to Bay
Siphoning bottom sediment from reservoir side to toe of dam Sediment bypassing	SRBC (1995) SRBC (2002) Corps (2006)	○ Regain lost capacity ○ Transport coarser, habitat forming sediment to Bay	○ Increases downstream deposition for given flow if operated under non-storm flows ○ May increase oxygen demand downstream ○ Does not reduce sediment load to Bay ○ Limited effect during storms that scour	moderate	Dismissed from further consideration in SRBC reports Corps found idea worth pursuing	○ Can operates during non-storm flows ○ Alters timing or variability of loadings to Bay
In situ sediment capping with clean sediment	SRBC (1995) SRBC (2002)	NA	NA	NA	Not applicable – reservoir sediment not contaminated	
In situ sediment fixing (stabilizing or hardening) by physical or chemical treatment	SRBC (1995) SRBC (2002)	○ Prevents scouring	○ Does not reduce sediment load to Bay ○ Does not regain lost capacity	1995 estimate of $40-80 million	Dismissed from further consideration	○ Alters timing or variability of loadings to Bay ○ No information presented on methods to stabilize without need to address contamination
Modified dam operations	SRBC (2002)	○ None	○ Conflicts with primary purpose to generate electricity	NA	Dismissed from further consideration	

SRBC (1995): Managing Sediment and Nutrients in the Susquehanna River Basin. Final Report. Publication No. 164. September 1995.
SRBC (2002): Sediment Task Force Recommendations. Publication No. 221. June 2002.
USGS/Corps (2006): from Lower Susquehanna Riverkeeper website, http://www.lowersusquehannariverkeeper.org/issues.html#3, Summary of Conowingo Dam Sediment Science Meeting (October 2006): Mike Langland (USGS) & Kevin Luebke (Corps).

TABLE A.1.3-1

Mt. Johnson Island – Littoral Zone Substrate

Sample ID	**GPS**	**Depth (feet below normal pool elevation)**	**Predominant Grains**		**Coal**		**Other**
			Approx. Size * (Φ-scale)	**Roundness**	**Approx. Size * (Φ-scale)**	**Roundness**	
MJ-1	39° 46.243' N 76° 14.981' W	3.8	silt	—	2.5	—	biotite flakes
MJ-2	39° 45.983' N 76° 14.882' W	6.3	1.0-2.5	sub-angular to sub-rounded	0-0.5	—	—
MJ-3	39° 45.792' N 76° 14.694' W	4.0	0.0-2.5	sub-angular to well-rounded	0-0.5	angular	—
MJ-4	39° 46.297' N 76° 14.994' W	9.8	silt	—	0-4.0	angular	biotite flakes
MJ-5	39° 46.522' N 76° 15.215' W	12.5	1.0-2.0	sub-rounded to rounded	0-1.0	angular	—

* PHI (Φ)-scale = $\log_2$ (diameter in millimeters)

Example: $\frac{1}{16}$ millimeter diameter grain = -4Φ

TABLE A.1.3-2

Peters Creek – Littoral Zone Substrate

Sample ID	GPS	Depth (feet below normal pool elevation)	Predominant Grains		Coal		Other
			Approx. Size * (Φ-scale)	Roundness	Approx. Size * (Φ-scale)	Roundness	
PC-1	39° 45.460' N 76° 14.213' W	5.4	1.5-2.0	sub-rounded to rounded	- 0.5-1.0	angular	sand mostly quartz; coal 40%
PC-2	39° 45.364' N 76° 14.086' W	4.7	1.0-2.0	sub-angular to rounded	0.5-1.0	angular	sand mostly quartz; coal 5-10%; biotite flakes
PC-3	39° 45.084' N 76° 13.793' W	—	silt / mud	—	—	—	minor coal; minor sand

* PHI (Φ)-scale = $\log_2$ (diameter in millimeters)

Example: $\frac{1}{16}$ millimeter diameter grain = -4Φ

TABLE A.1.3-3

Fishing Creek – Littoral Zone Substrate

Sample ID	GPS	Depth (feet below normal pool elevation)	Predominant Grains		Coal		Other
			Approx. Size * (Φ-scale)	Roundness	Approx. Size * (Φ-scale)	Roundness	
FC-1	39° 47.181' N 76° 15.701' W	3.8	silt	—	2	sub-rounded	contains quartz sand (2Φ)
FC-2	39° 47.347' N 76° 15.992' W	6.3	0.5-1.5	sub-angular to sub-rounded	0.5-1.5	sub-angular to sub-rounded	predominantly coal
FC-3	39° 47.512' N 76° 16.158' W	3.6	silt	—	0-1.5	sub-angular to sub-rounded	contains quartz sand (1.5-3.0 Φ)

* PHI (Φ)-scale = $\log_2$ (diameter in millimeters)

Example: $\frac{1}{16}$ millimeter diameter grain = -4Φ

Table B.2.1-1
Significant Storm Events

Event	Date	Season[1]	Total Precipitation (inches)[2]	Conowingo Peak Flow (cfs)[3]	Flow Frequency[4]
1933	August 23-24	Summer	6.70	290,000	~2 year
1936	March 18	Winter	1.45	798,000	~100 year
1954 - Hurricane Hazel	October 16	Fall	1.06	<100,000	<1 year
1955 - Hurricane Connie	August 12-13	Summer	6.0	114,000	<1 year
1955 - Hurricane Diane	August 18-19	Summer	2.60	<100,000	<1 year
1972 - Hurricane Agnes	June 22-24	Summer	6.51	1,130,000	~525 year
1975 - Hurricane Eloise	September 23-27	Fall	6.86	710,000	~53 year
1993	April 2	Spring	1.32	442,000	~10 year
1996	January 20	Winter	1.00	909,000	~178 year
2004 - Hurricane Ivan	September 18-19	Summer	1.97[5]	620,000	~29 year
2011	March 7, 10-11	Winter	5.08	487,000	~10 year

[1] Seasons determined as follows – December 21-March 20 (winter); March 21-June 20 (spring); June 21-September 20 (summer); and September 21-December 20 (fall)

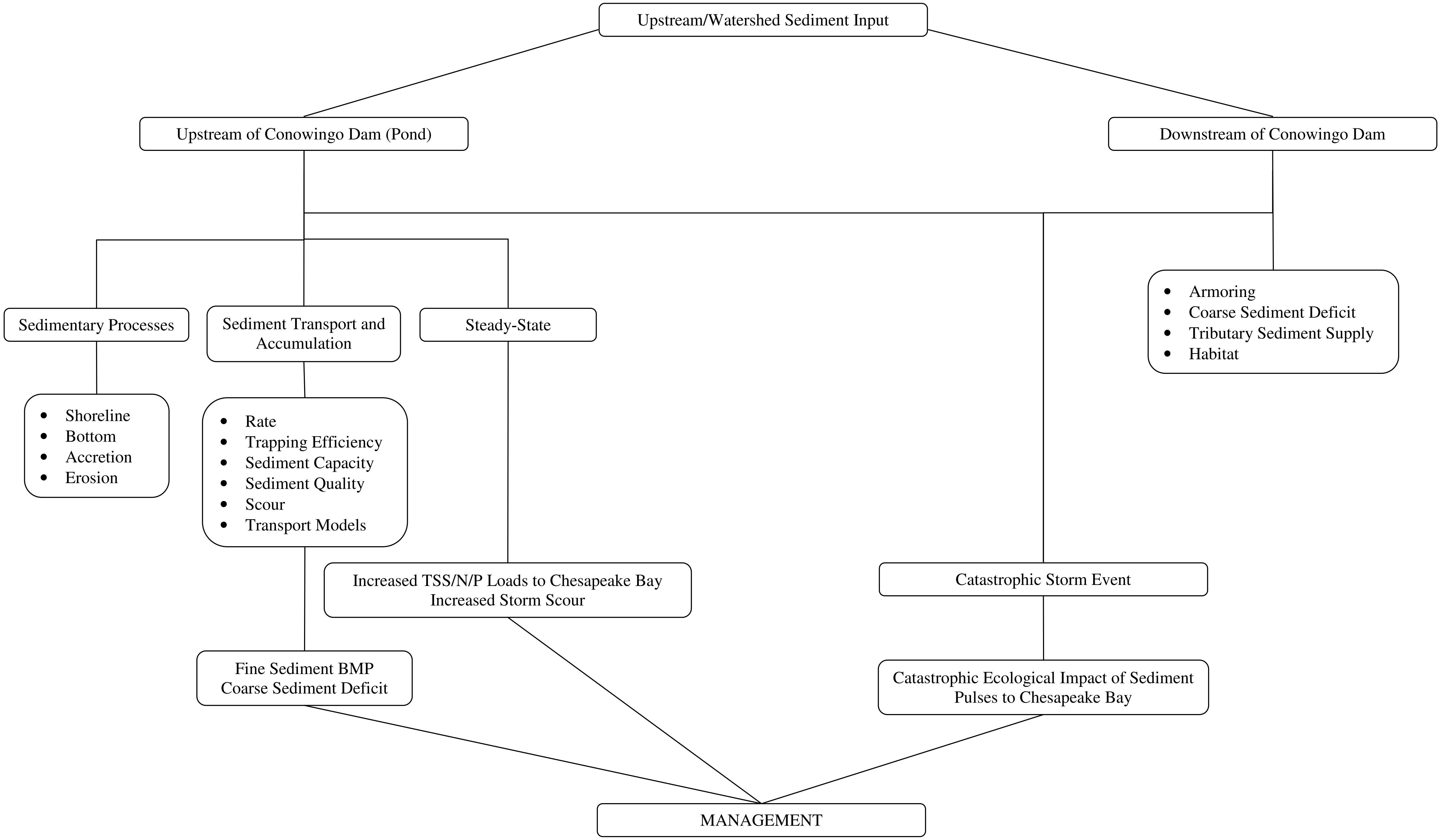
[2] Measured at Holtwood, PA station HLTP1, unless otherwise noted (http://climate.met.psu.edu)

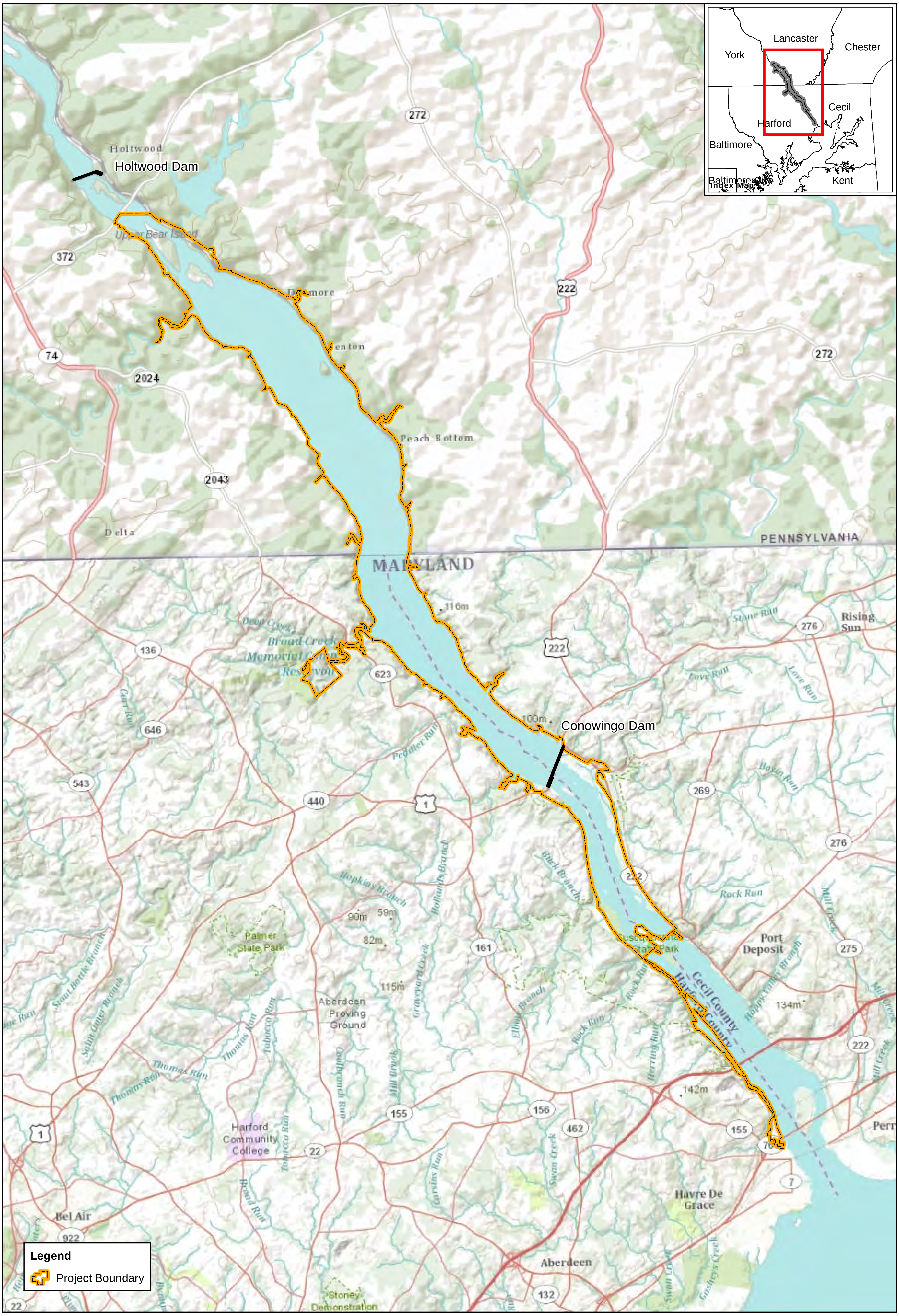
[3] All measurements prior to 1967 were scaled from the Harrisburg USGS gage using a 1.078 scaling factor; after 1967 measurements were recorded at the Conowingo USGS gage

[4] Based on Harrisburg USGS gage flow using a 1.078 scaling factor, due to a longer period of record for this gage

[5] Data were not available from the Holtwood station; data were collected from the station located at Safe Harbor Dam

Figure 2.0-1
Sediment Transport Issues Overview





EXELON GENERATION COMPANY, LLC

CONOWINGO HYDROELECTRIC PROJECT
PROJECT NO. 405

N

1 inch = 1.8 miles

0 0.875 1.75 3.5
Miles

Figure 3.0 - 1
Project Area

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Fig 3.0-1.mxd

Figure 3.1.1-1
USGS Map (1900)

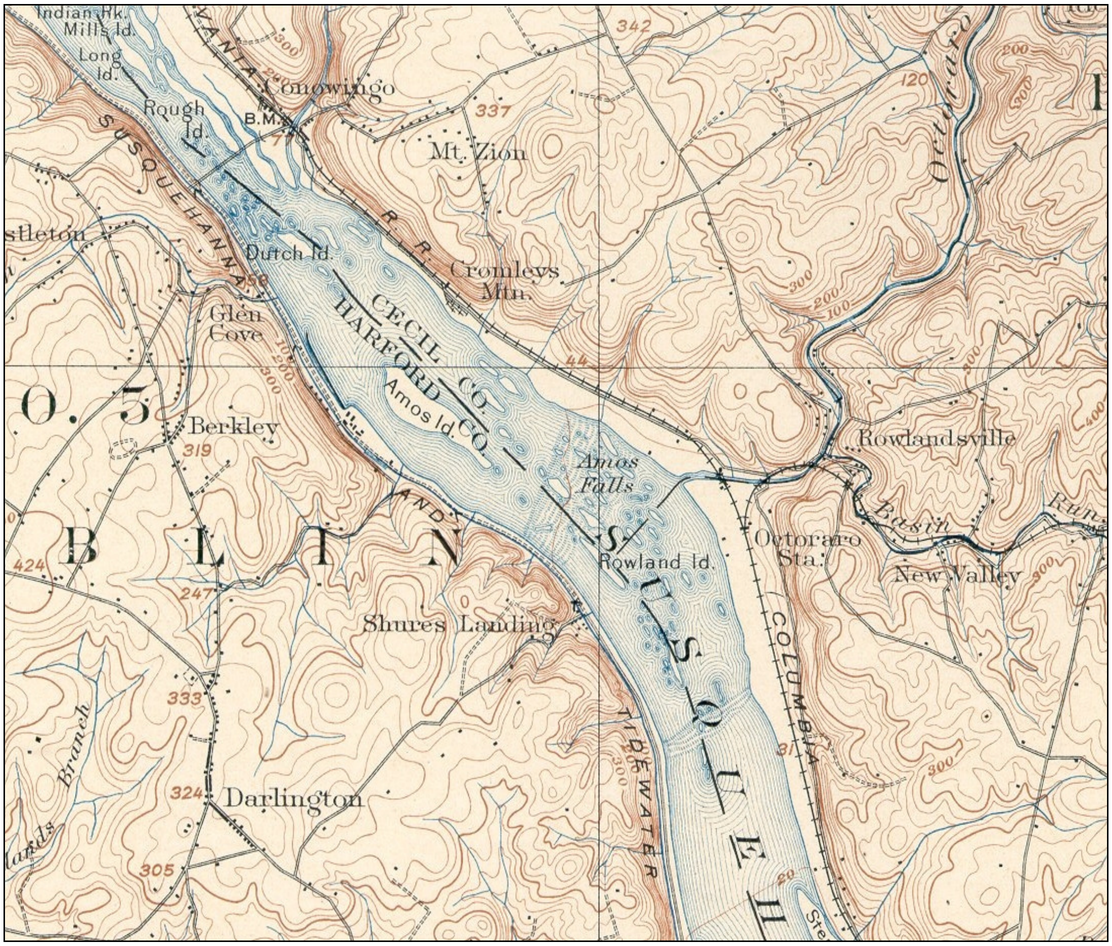


Figure 3.1.1-2

. . River Profile (from Pratt 1909)

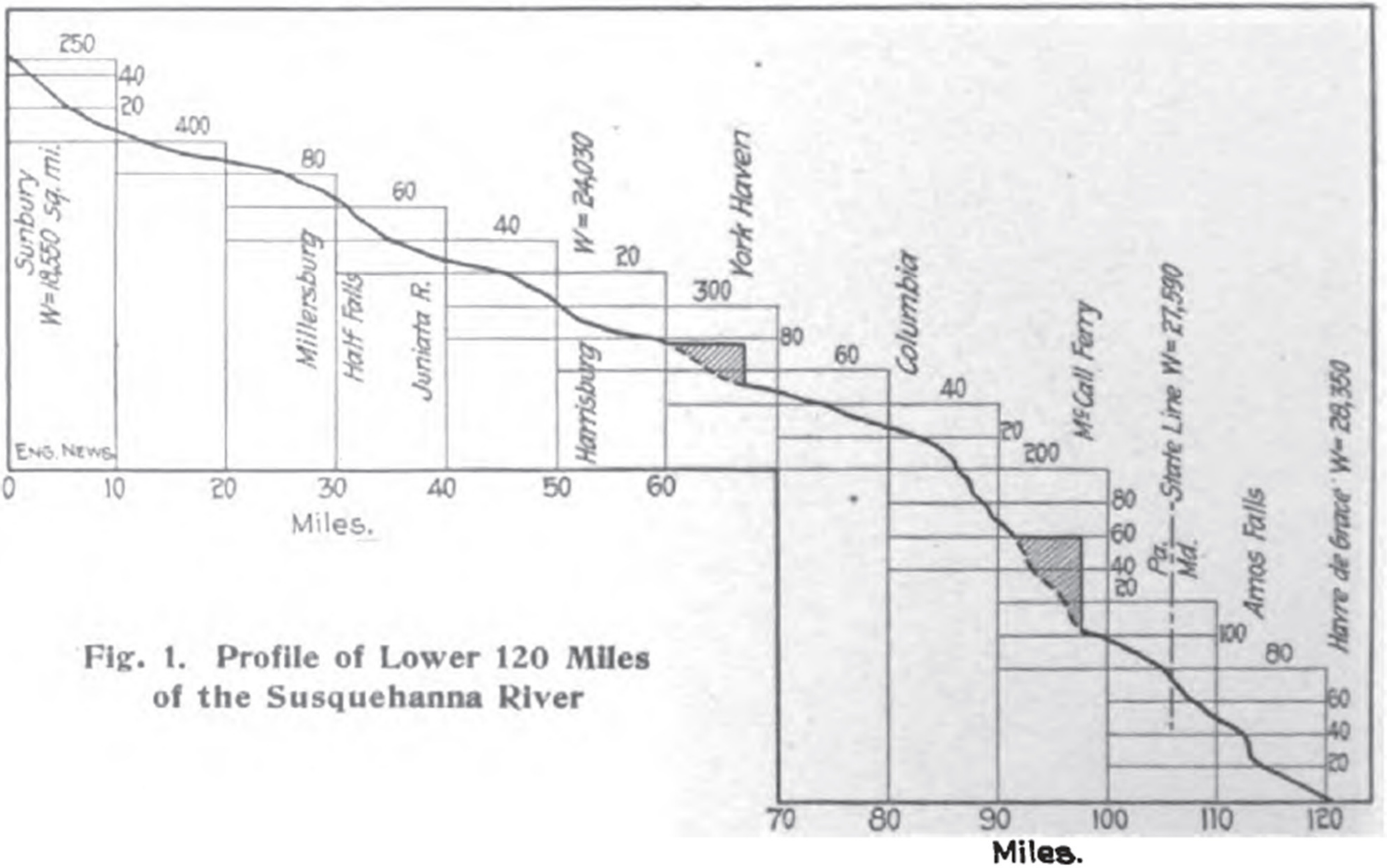
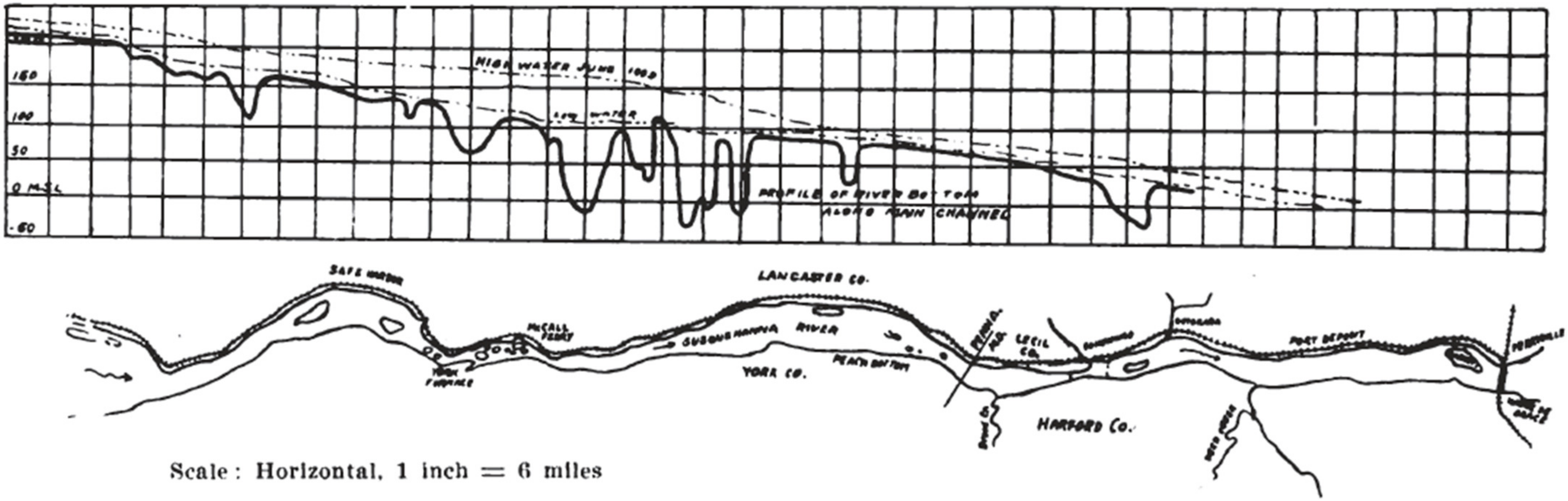


Fig. 1. Profile of Lower 120 Miles of the Susquehanna River

Figure 3.1.1-3

River Profile (from Matthews 1917)



Scale: Horizontal, 1 inch = 6 miles

FIGURE 1.—*Plan and Profile of Susquehanna River, showing Location of "Deeps"*

Figure 3.1.1-4

River Profile (from Knopf and Jonas 1929)

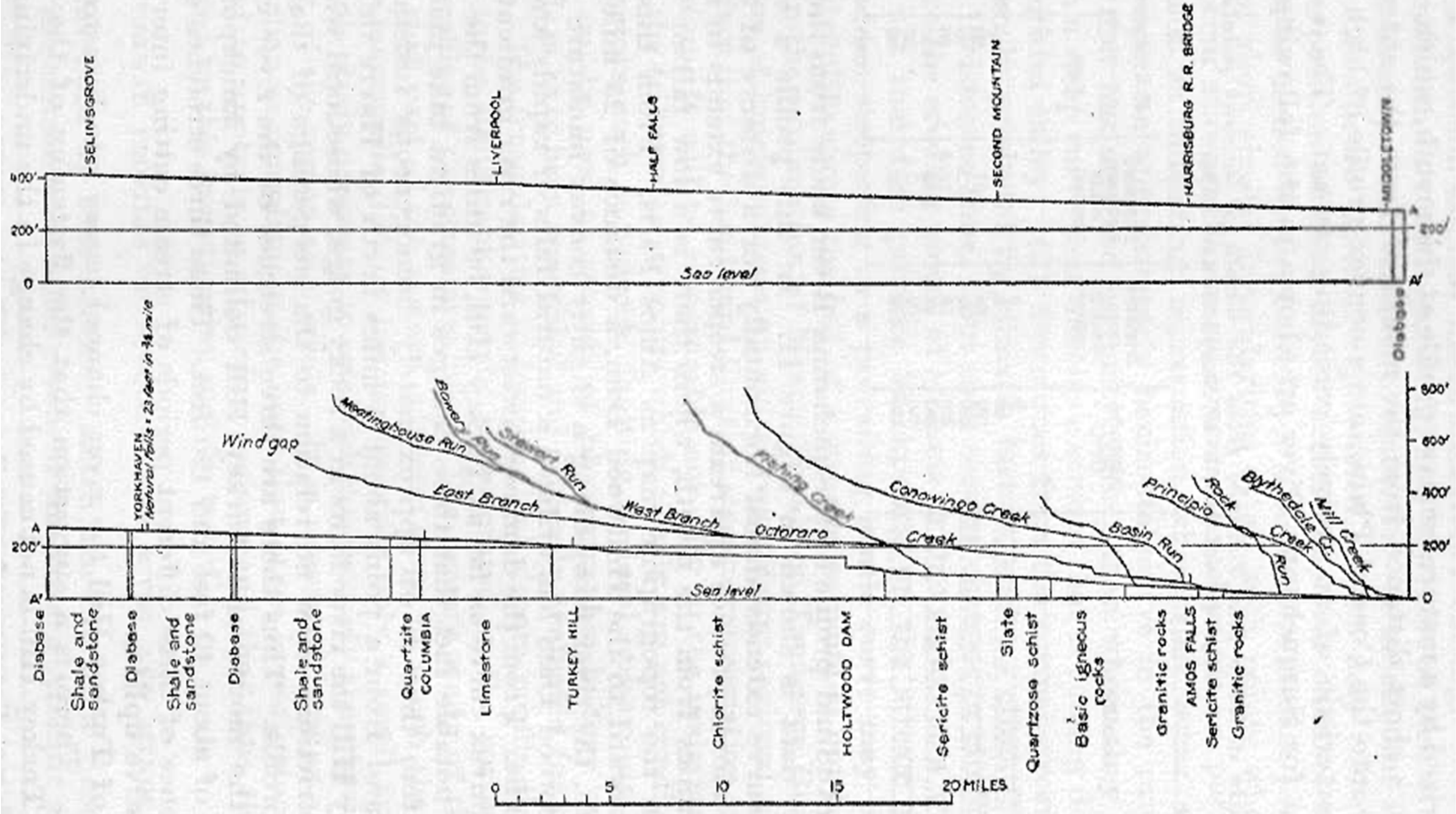


FIGURE 11.—Longitudinal profiles of Susquehanna River from its mouth to a point 3 miles southwest of Sunbury, Pa., and of eight minor streams

Figure 3.1.1-5
River Map (from Hauducoeur 1799)

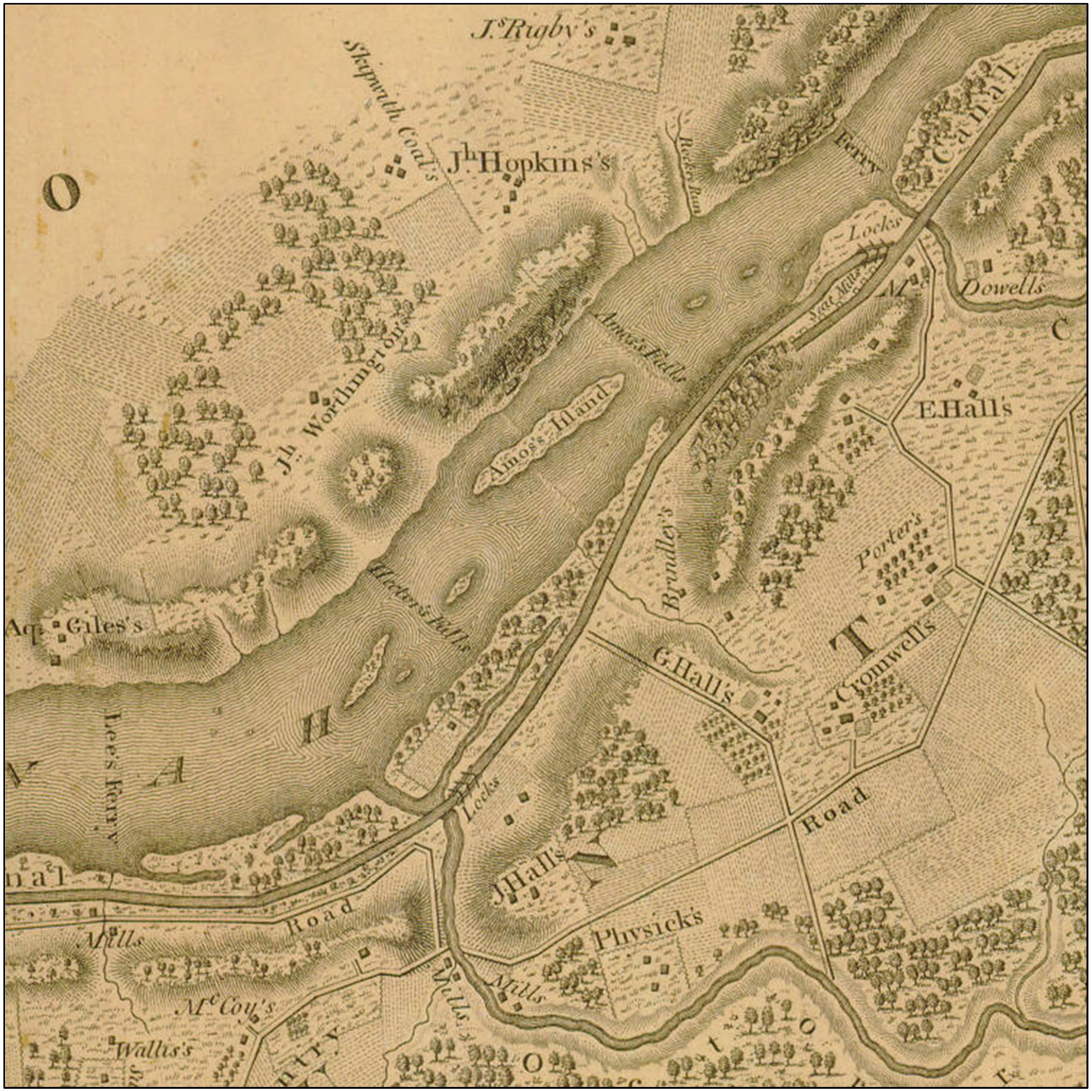


Figure 3.1.1-6: Labelle Survey (1920) Hector's Falls

Figure 3.1.1-7: Labelle Survey (1920) Rapids at Glen Cove

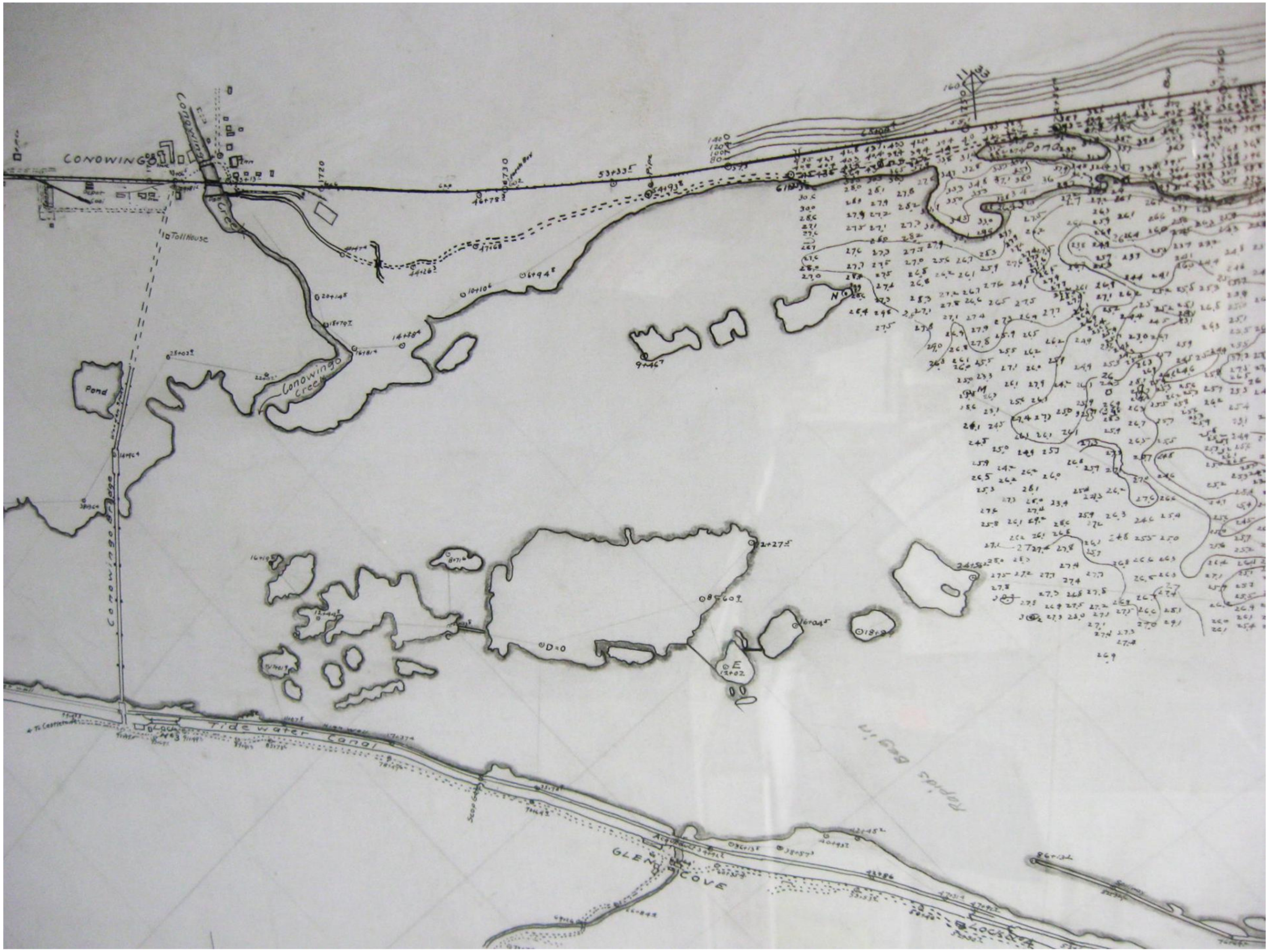


Figure 3.2.2-1
Suspended Sediment Transport (1979-1981) (from Lang 1982)

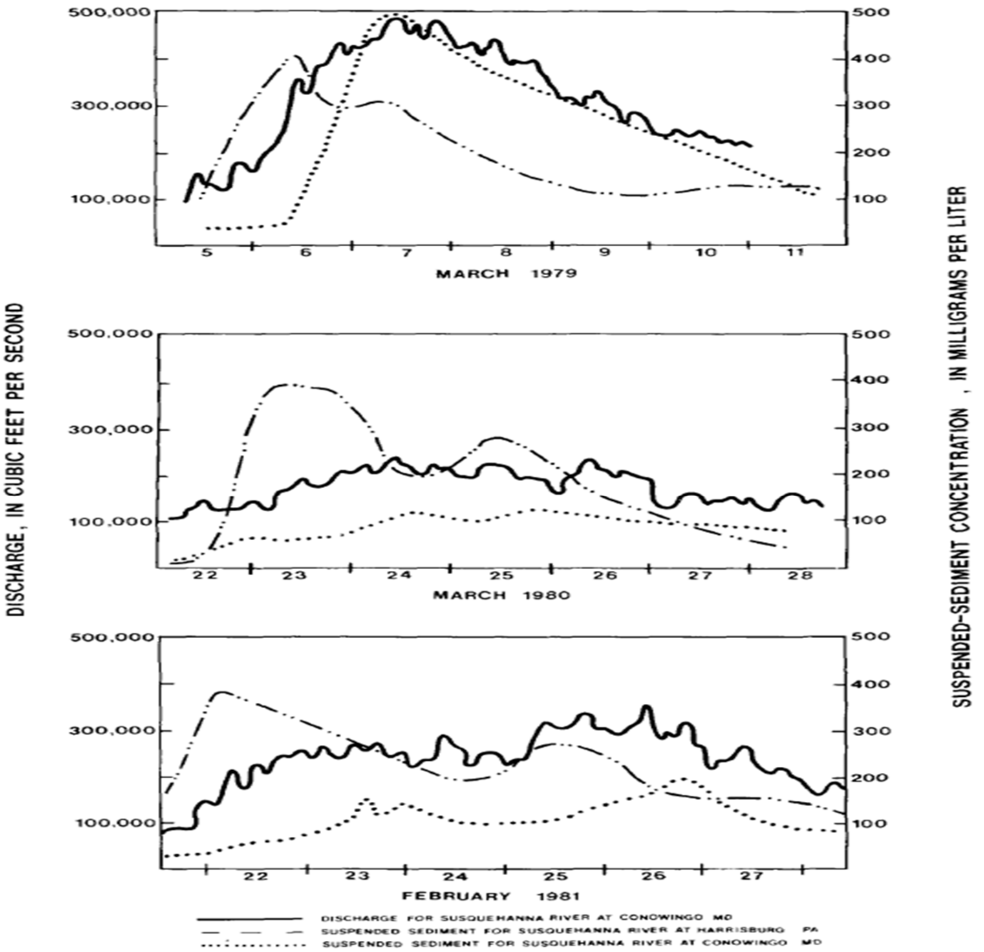


Figure 16.--Suspended-sediment transport for three high flows at the Susquehanna River at Harrisburg, Pa., and Conowingo, Md.

Figure 3.2.6.2-1
USGS Scour Regression Model (from Langland and Hainly 1997)

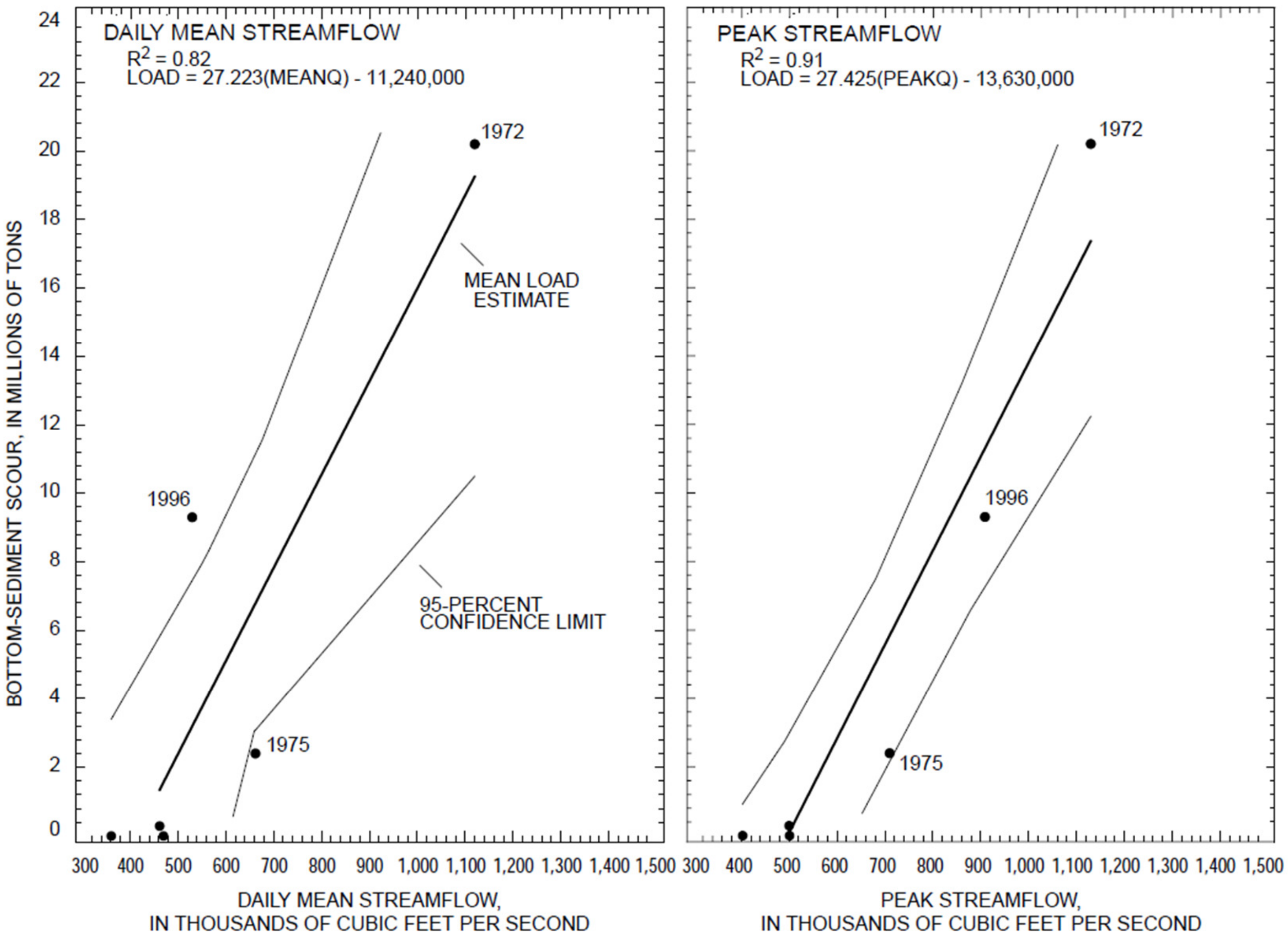
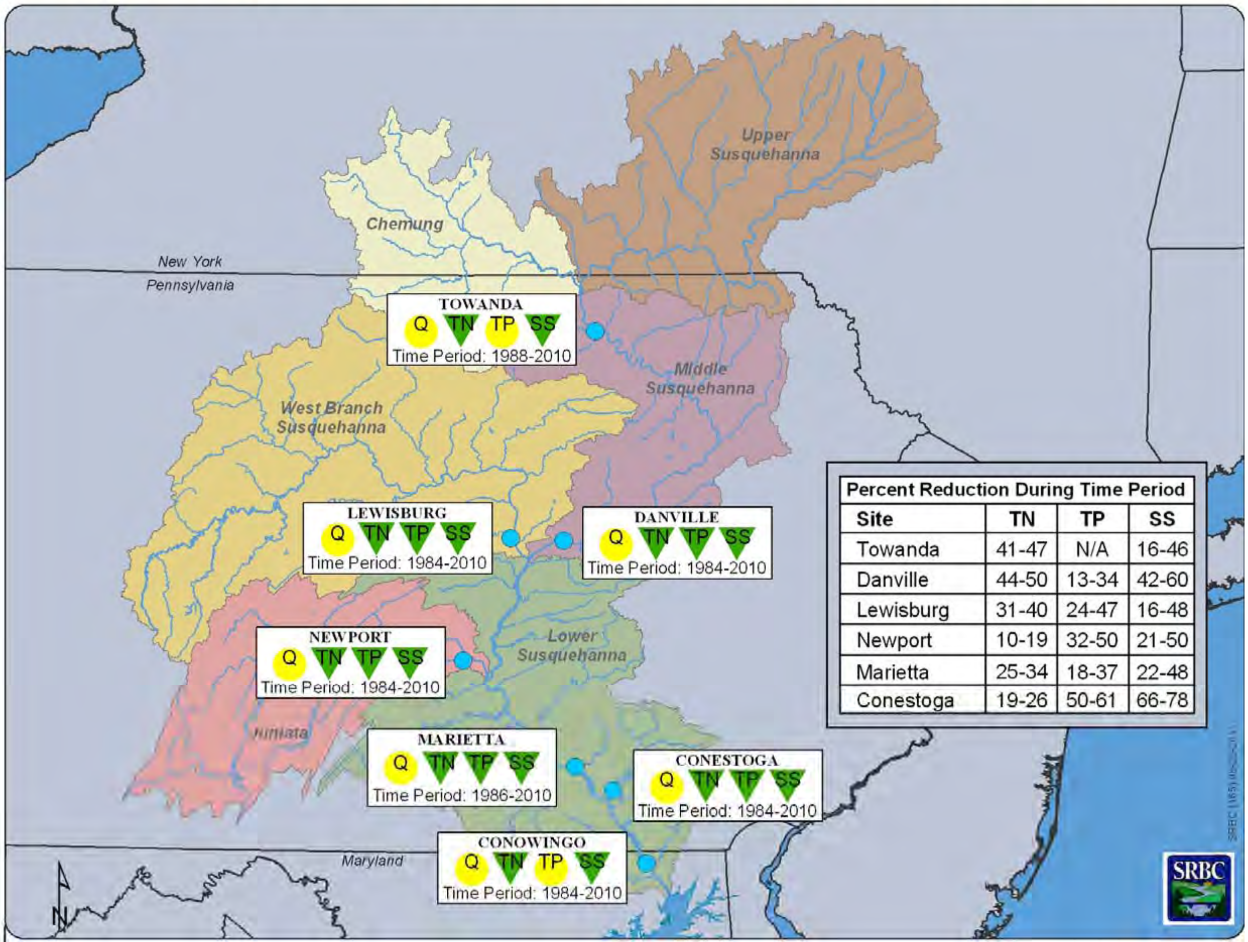


Figure 7. Estimates of scour from Conowingo Reservoir based on daily mean streamflow and peak streamflow of floods from 1972 to 1996 at Conowingo Dam, Maryland.

Figure 3.2.7-1
Flow-Adjusted TP, TN, SS Concentrations (1984-2010)
(SRBC 2011)

Susquehanna River Basin Commission

FLOW-ADJUSTED CONCENTRATION TRENDS THROUGH 2010



Percent Reduction During Time Period

Site	TN	TP	SS
Towanda	41-47	N/A	16-46
Danville	44-50	13-34	42-60
Lewisburg	31-40	24-47	16-48
Newport	10-19	32-50	21-50
Marietta	25-34	18-37	22-48
Conestoga	19-26	50-61	66-78

TRENDS IN FLOW, NITROGEN, PHOSPHORUS AND SUSPENDED SEDIMENT IN THE SUSQUEHANNA RIVER BASIN THROUGH 2010

The Susquehanna River Basin Commission estimates trends in nutrients, sediment, and flow as part of the Chesapeake Bay Program's annual trend update. Trends are calculated based on the USGS water year, October 1 to September 30, using the USGS 7-parameter, log-linear regression model (ESTIMATOR) for nutrient trends and the Seasonal Kendall test for trends in flow.

Trends in flow indicate the natural changes in hydrology. Changes in flow and the cumulative sources of flow (base flow and overland runoff) affect the observed concentrations and the estimated loads of nutrients and suspended sediment. The Flow Adjusted Concentration (FAC) is the concentration after the effects of flow are removed. Trends in FAC indicate that changes have occurred in the processes that deliver constituents to the stream system. This is the concentration that relates to the effects of nutrient-reduction activities and other actions taking place in the watershed.

FAC trends for 2010 remained unchanged from 2009 trends. The chart shows the range in percentage of reductions that have occurred at each site since the beginning of monitoring at the site. For example, TN values at Towanda for 2010 are between 41% and 47% less than 1989 values of TN.

● STATION LOCATION

TREND CHANGE

● - No change over Dated Time Period

▼ - Decreasing Concentration over Dated Time Period

30 0 30 60 Miles

TREND EXPLANATION

Q - Flow

TN - Total Nitrogen

TP - Total Phosphorus

SS - Suspended Sediment

MAJOR RIVER

WATER BODY

STATE BOUNDARY

SUSQUEHANNA RIVER BASIN

Source: Susquehanna River Basin Commission and Conowingo results from USGS Baltimore, Maryland; DISCLAIMER: Intended for Educational Display Purposes Only.

Figure 3.3.2-1
Suspended Sediment Concentrations During Tropical Storm Agnes
(Schubel 1976)

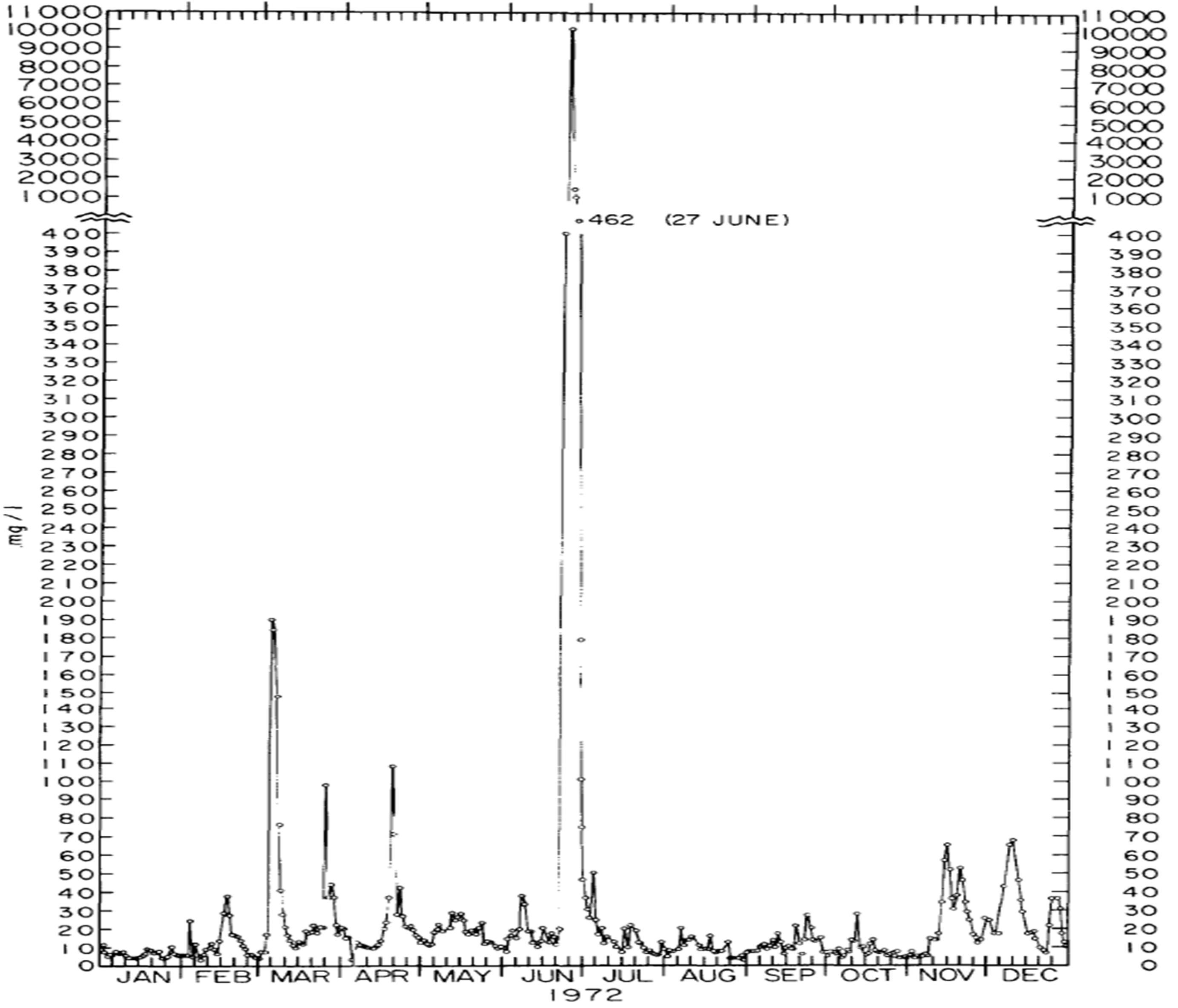


Figure 4. Concentration of total suspended solids (mg/l) in the Susquehanna River at Conowingo, Md., during 1972.

Figure 3.3.2-2

Sediment Deposition in Chesapeake Bay from Tropical Storm Agnes

(Schubel and Zabawa 1976)

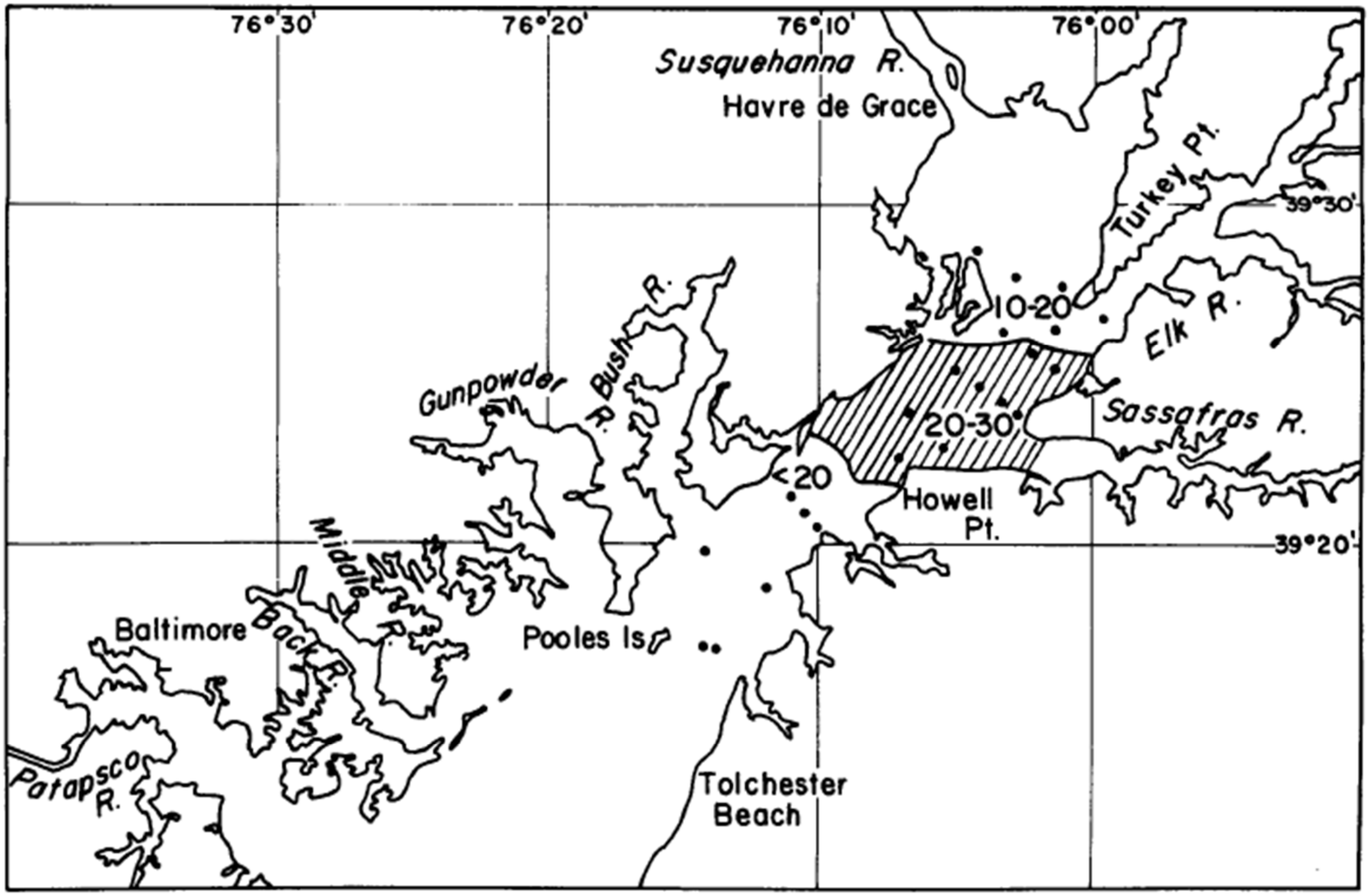
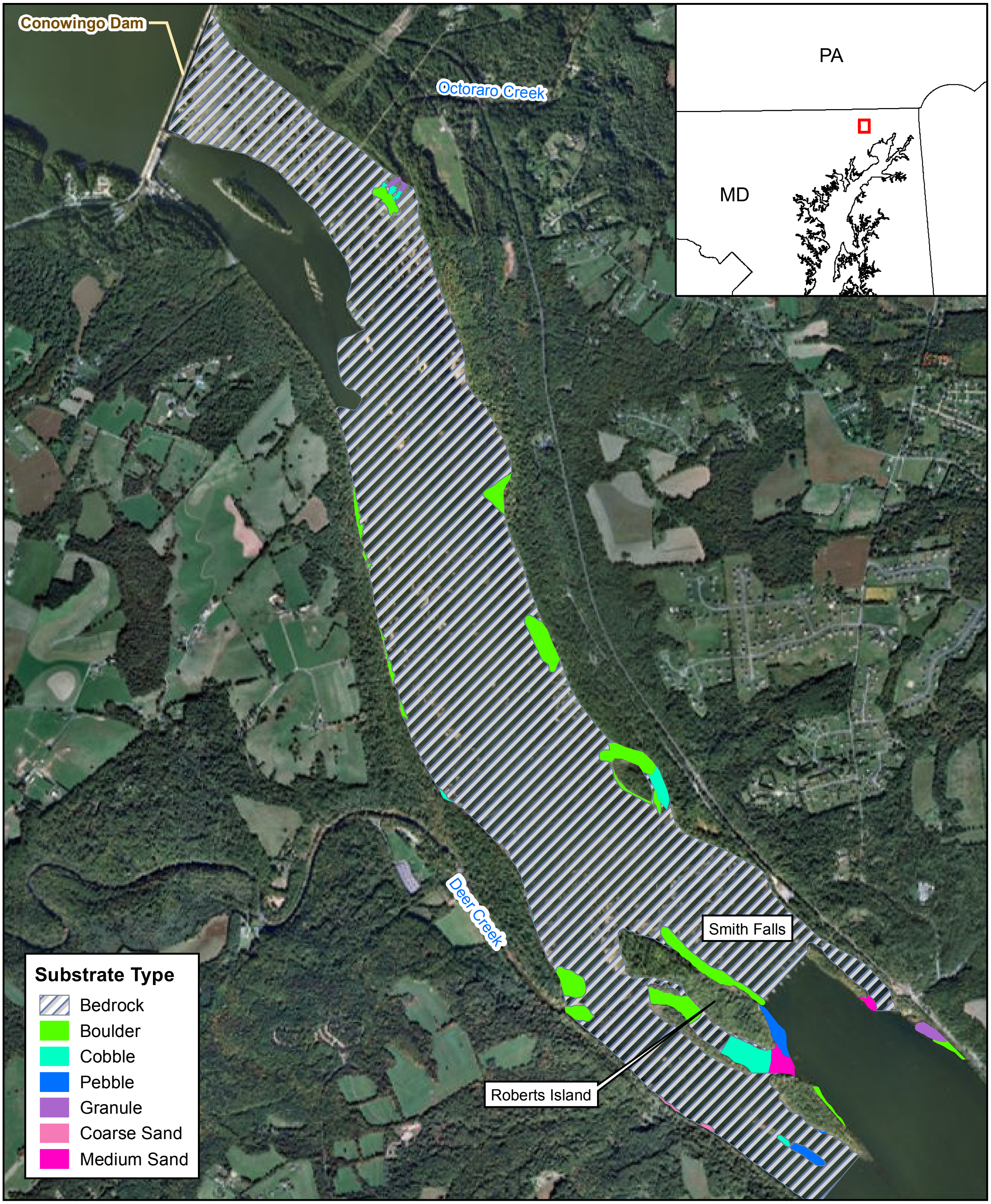


Figure 2. Map of study area showing estimated thickness of Agnes sedimentary layer (cm). Estimates were made from X-radiographs of cores taken in August 1972.



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N

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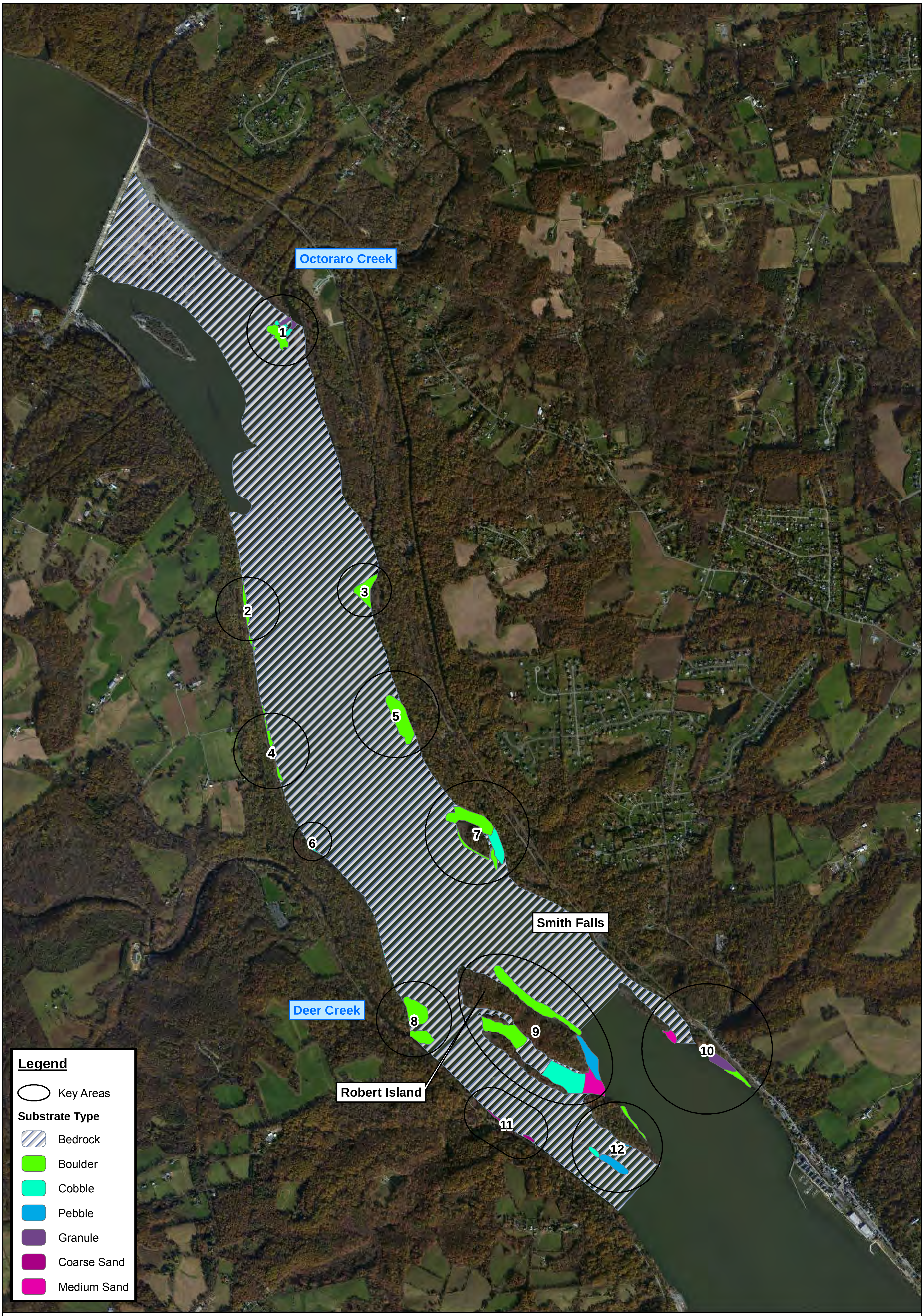
FERC PROJECT NO. 405

Figure 4.1.1-1
Downstream Grain Size Distribution

0 0.25 0.5 1 Miles

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Downstream Grain Size 4.1.1-1.mxd



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1:24,000

0 1,000 2,000 4,000 Feet

N

Figure 4.1.4-1
Mobile Substrate Areas for Shear Stress Analysis

Source: Bing Maps™ Imagery
URS Custom Data

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Fig 4.1.4-1_Mobile subs areas.mxd

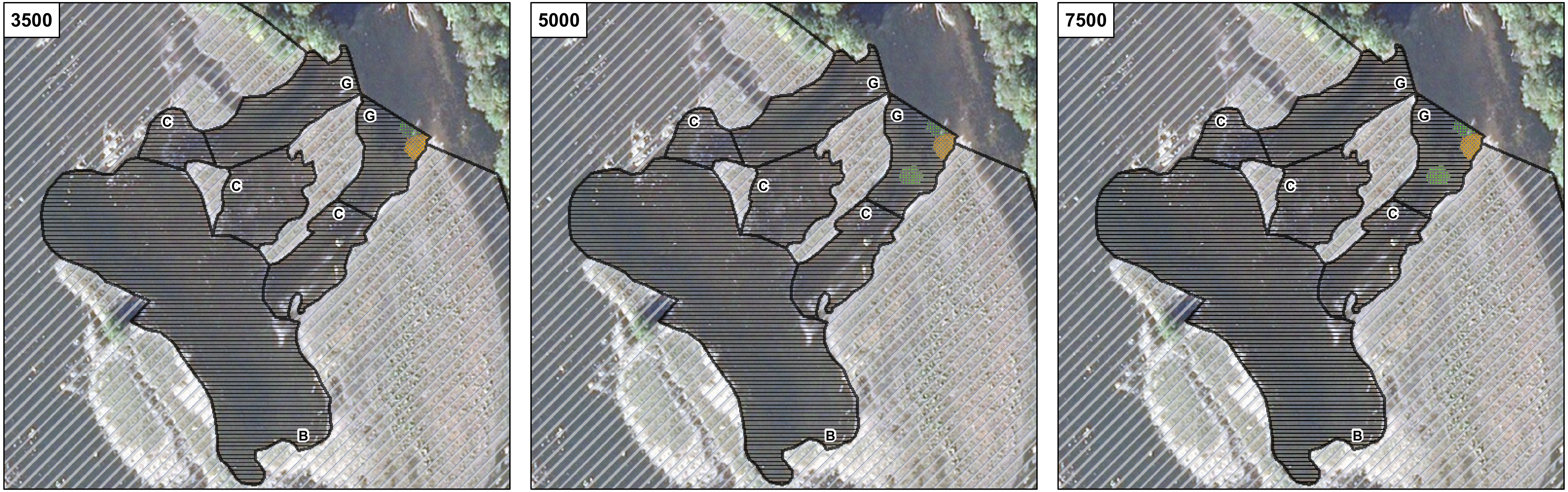

Figure 4.1.4.1-1
Entrainment Potential
Key Area 1

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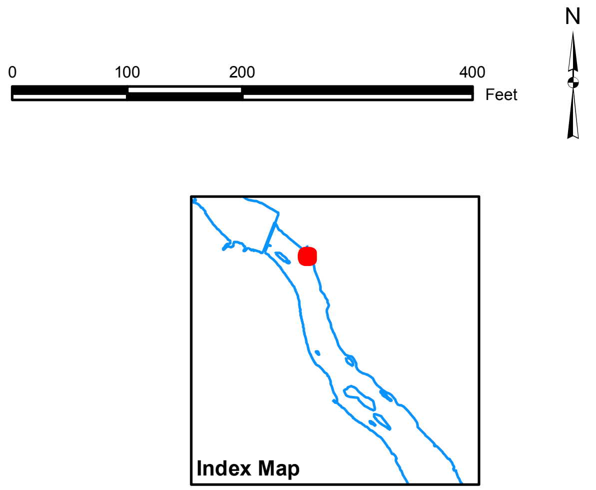

Legend

Erosion Potential

- ☰ < 1
- ▨ 1 - 2
- ▨ > 2

Substrate Type

- ▨ Bedrock
- ▭ Boulder - B
- ▭ Cobble - C
- ▭ Pebble - P
- ▭ Granule - G
- ▭ Coarse Sand - CS
- ▭ Medium Sand - MS

Q:\GIS_Data\GOMEZSULLIVAN\EXELONCONO\Maps\Sediment Introduction and Transport Study\KeyArea1 EP Fig 4.1.4.1-1.mxd

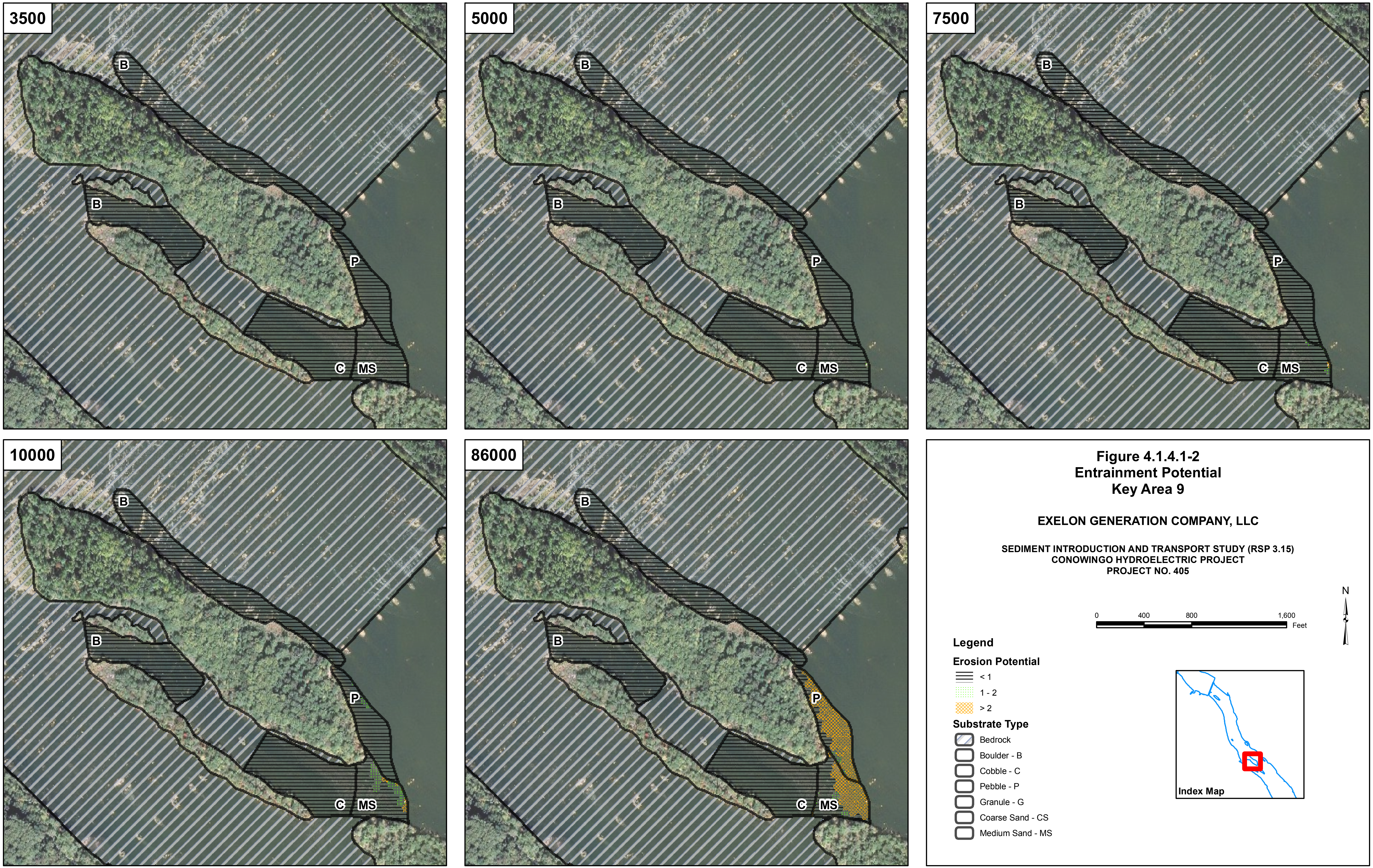

Figure 4.1.4.1-2
Entrainment Potential
Key Area 9

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PROJECT NO. 405

Q:\GIS_Data\GOMEZSULLIVAN\EXELONCONO\Maps\Sediment Introduction and Transport Study\KeyArea9 EP Fig 4.1.4.1-2.mxd

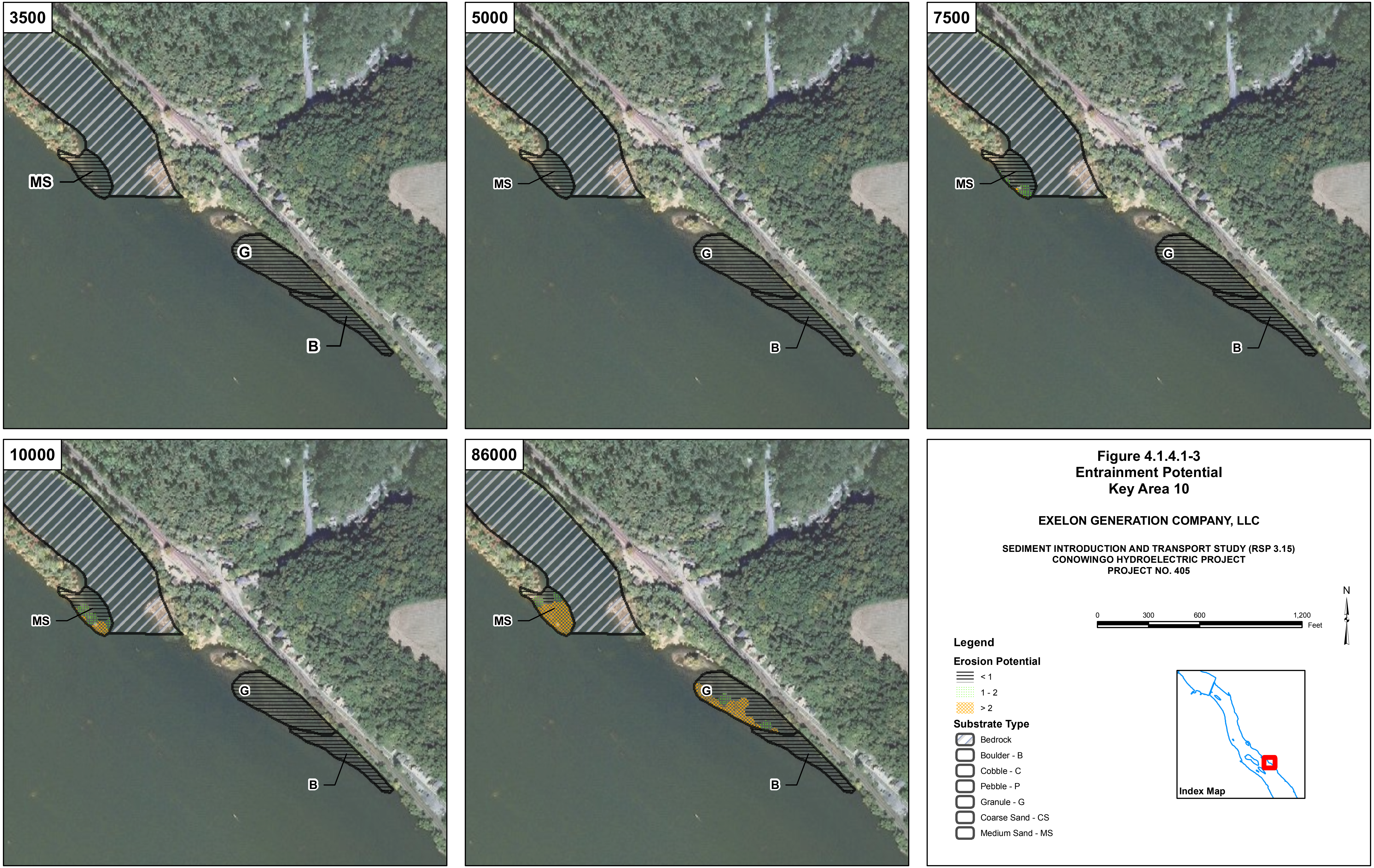

Figure 4.1.4.1-3
Entrainment Potential
Key Area 10

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PROJECT NO. 405

Q:\GIS_Data\GOMEZSULLIVAN\EXELONCONO\Maps\Sediment Introduction and Transport Study\KeyArea10 EP Fig 4.1.4.1-3.mxd

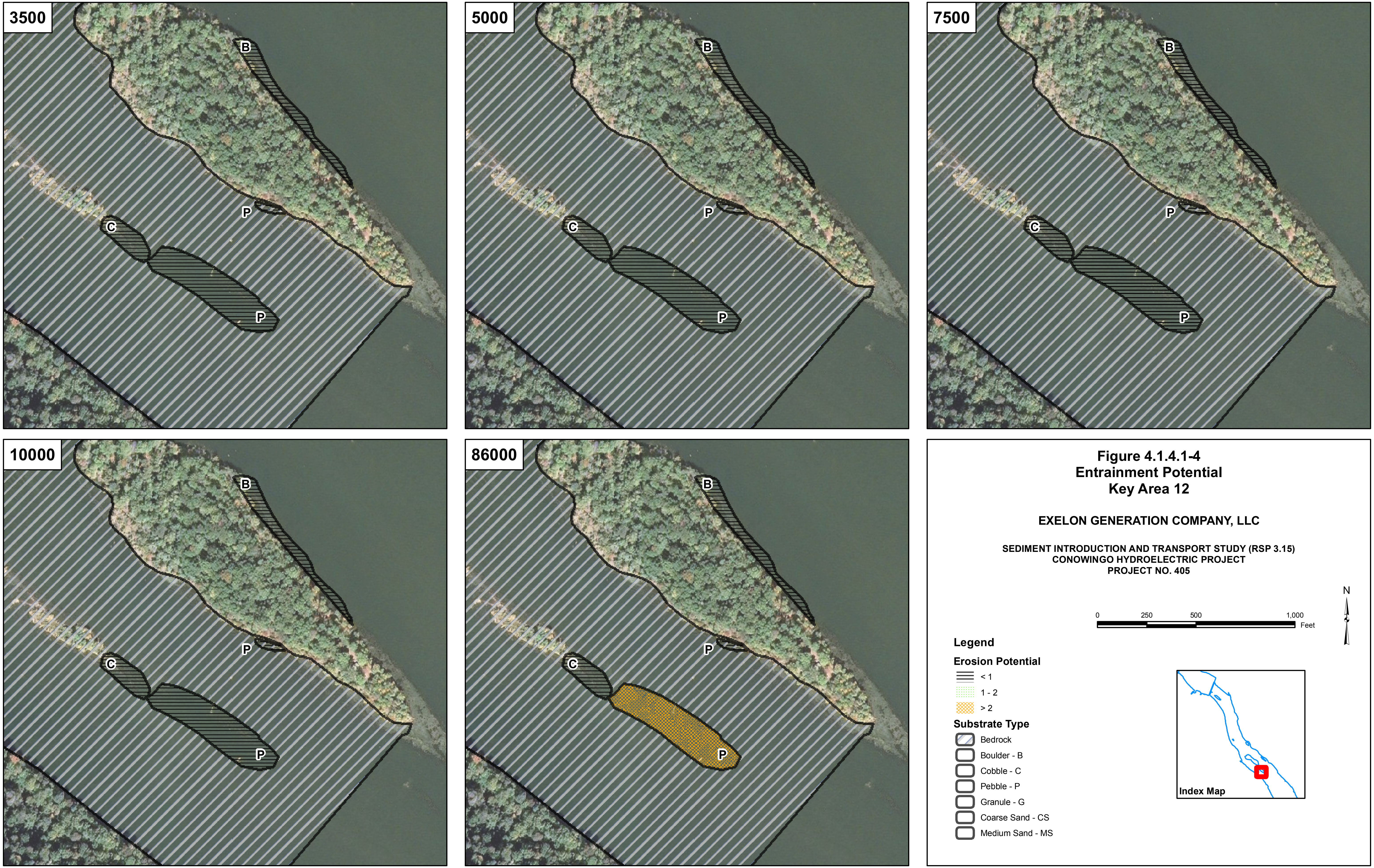

Figure 4.1.4.1-4
Entrainment Potential
Key Area 12

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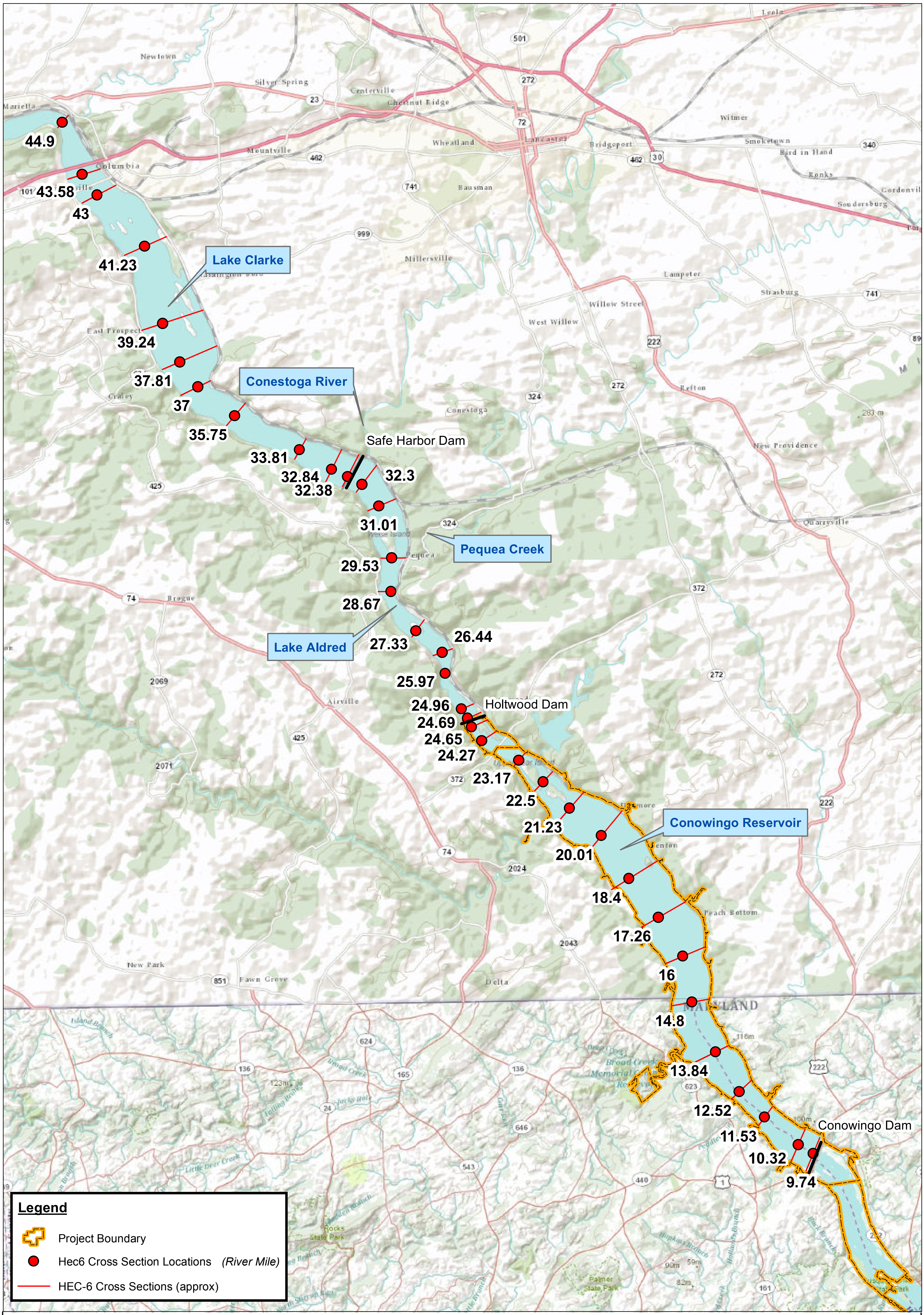
PROJECT NO. 405

Q:\GIS_Data\GOMEZSULLIVAN\EXELONCONO\Maps\Sediment Introduction and Transport Study\KeyArea12 EP Fig 4.1.4.1-4.mxd



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PROJECT NO. 405

1:150,000

0 1 2 4 Miles

Figure 4.2.2.1-1
Reservoir Cross Sections of HEC-6 Analysis

Source: ESRI - World Topo Map

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\F4.2.2.1-1_HEC cxsec.mxd

Figure 4.2.3-1
Daily Mean Discharge (January 1996)

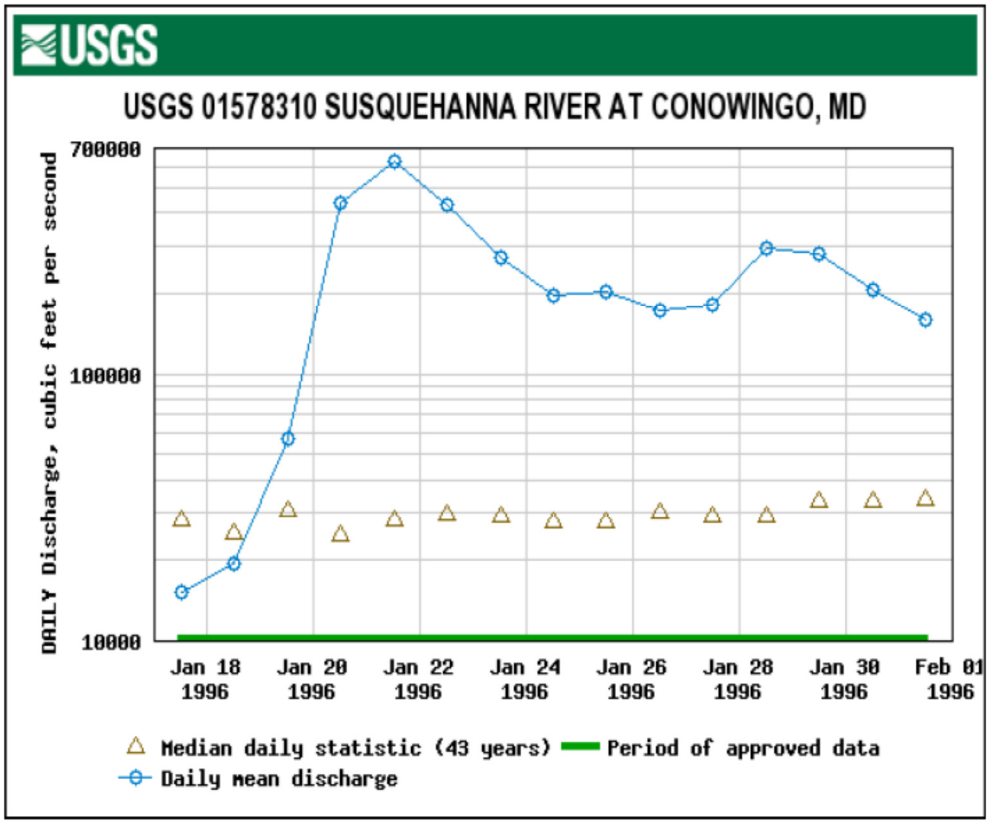


Figure 4.3-1: Sediment Transport Models for Lower Susquehanna River Watershed Assessment Study

Data Source: USACE (2010)

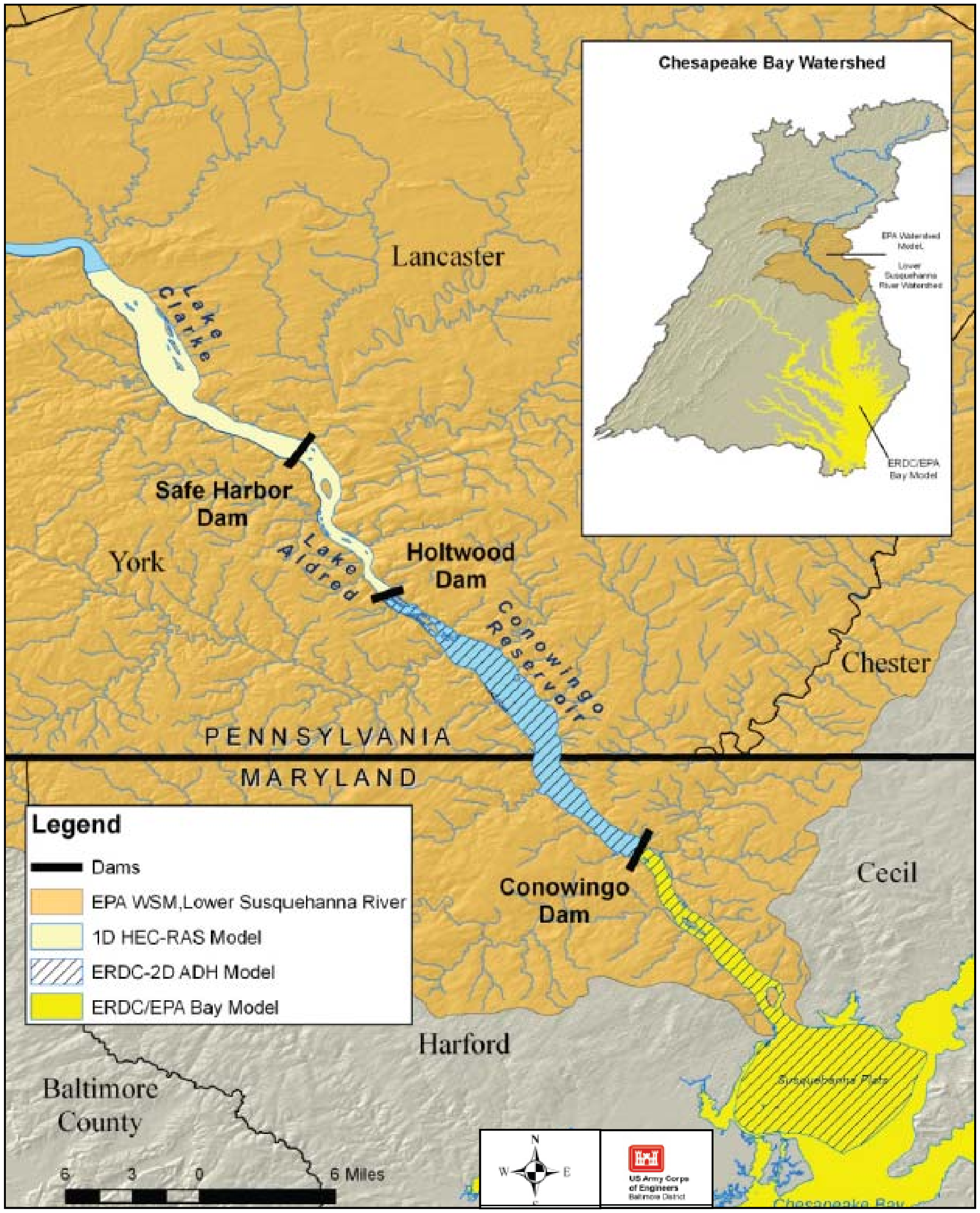
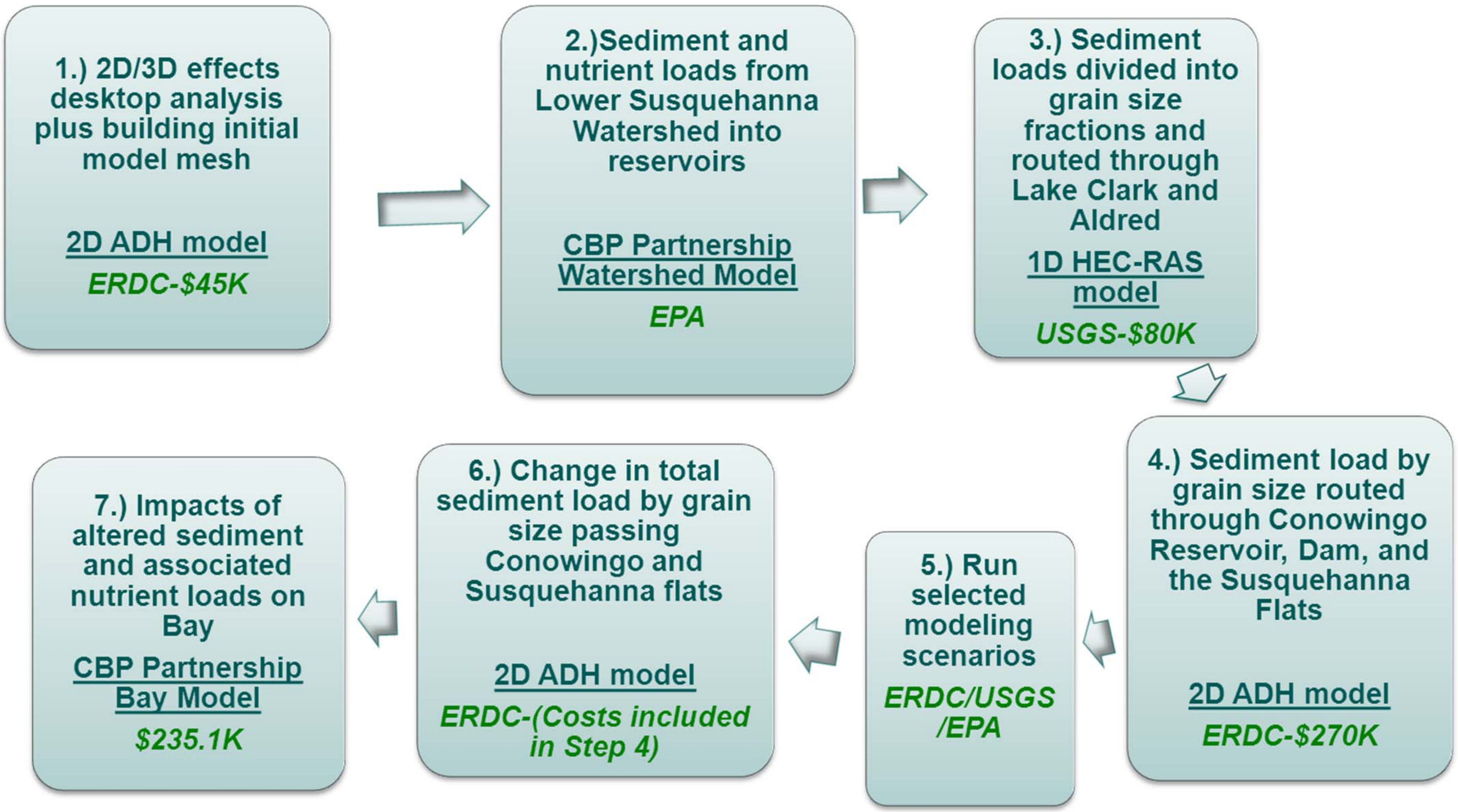


Figure 4.3-2 Corps Step-Wise Sediment Transport Analysis Approach



Data Source: USACE (2012)

Figure 6.0-1
Sediment Equilibrium in Lower Susquehanna River Reservoirs
(from Academy of Natural Sciences of Philadelphia 1994)

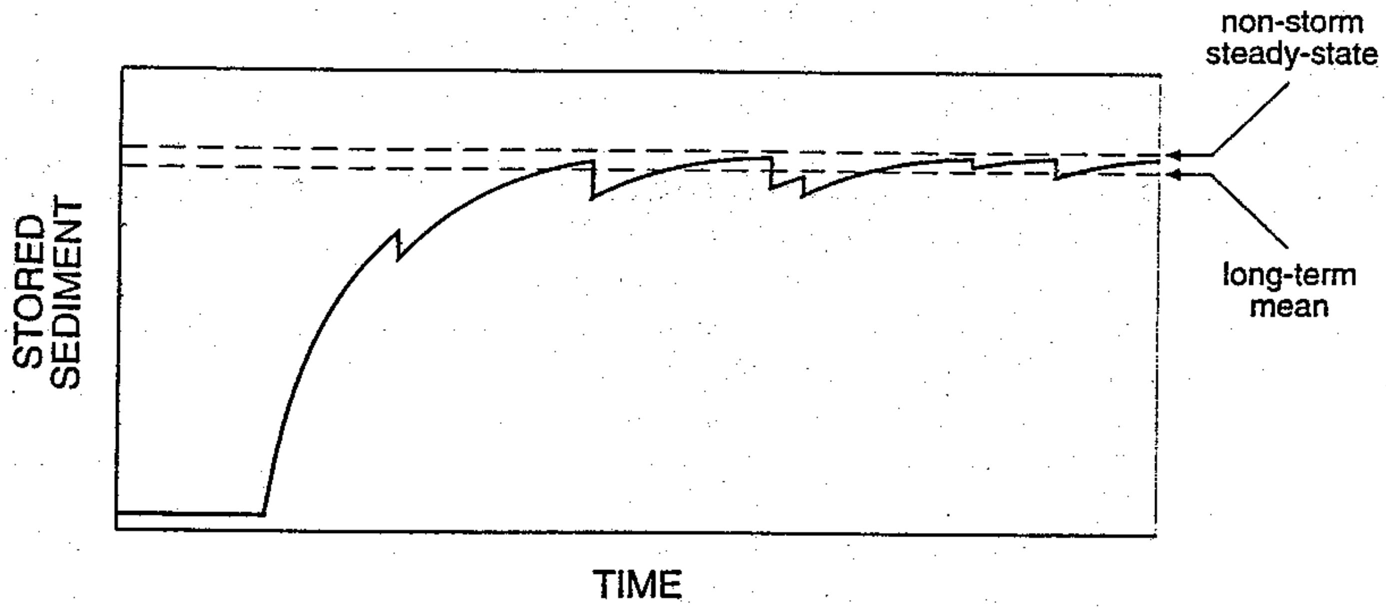
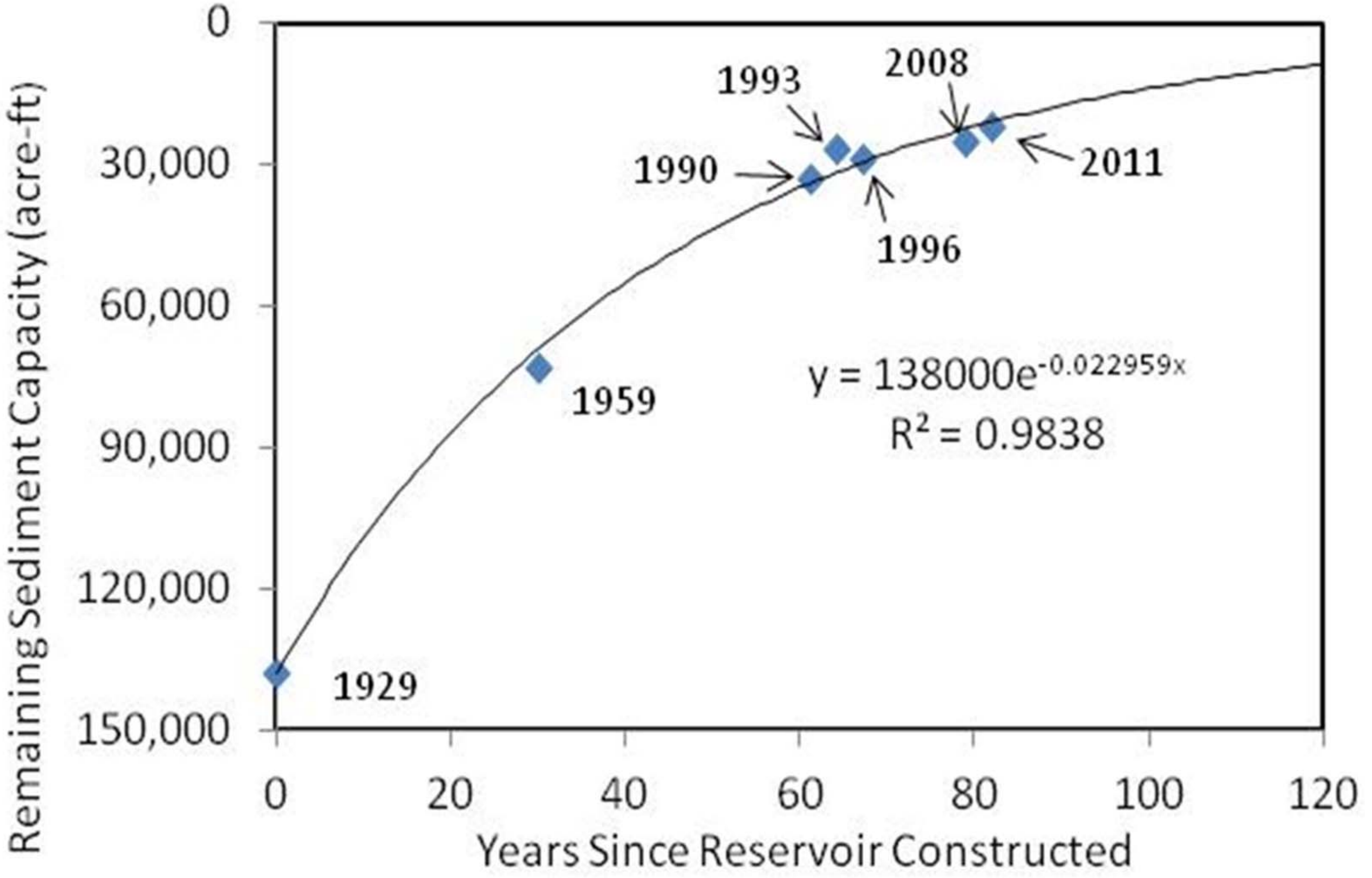
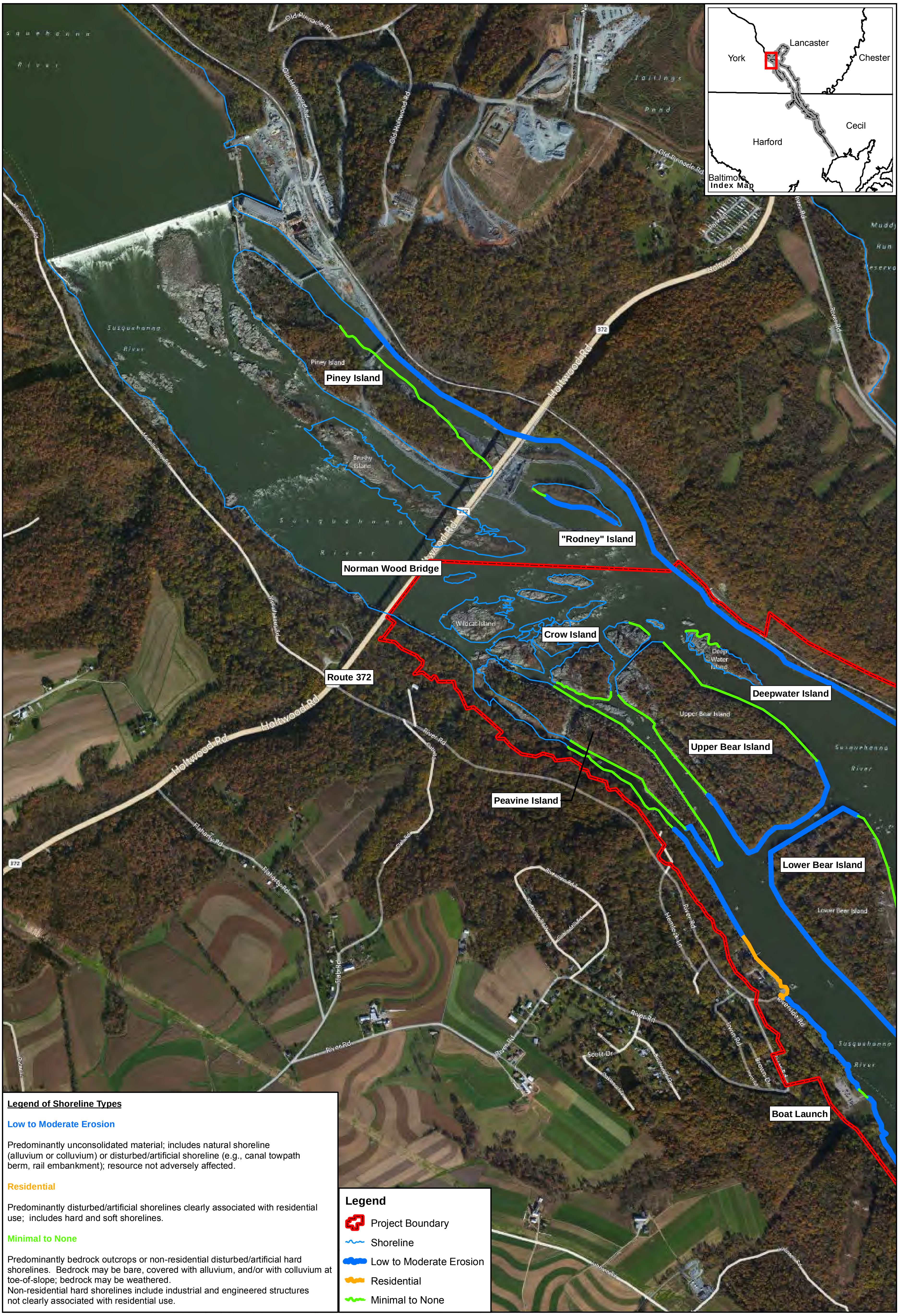


FIGURE 4. Schematic of the long-term temporal dynamics of stored sediment in the reservoir system. Periods of gradual accumulation (net deposition) are punctuated by scouring events (major floods) which remove small fractions (≤10%) of the sediment stored in the reservoirs. The quantity of stored sediment is therefore a stochastic process; "steady state" properly refers to the stationary probability distribution for this process. Note that the long-term mean sediment content is less than the steady state that would exist if there were no major storms.

Figure 6.0-2
Sediment Storage versus Time
Conowingo Pond



*Calculations assume the steady state reservoir water volume is 142,000 acre-ft



Legend of Shoreline Types

Low to Moderate Erosion

Predominantly unconsolidated material; includes natural shoreline (alluvium or colluvium) or disturbed/artificial shoreline (e.g., canal towpath berm, rail embankment); resource not adversely affected.

Residential

Predominantly disturbed/artificial shorelines clearly associated with residential use; includes hard and soft shorelines.

Minimal to None

Predominantly bedrock outcrops or non-residential disturbed/artificial hard shorelines. Bedrock may be bare, covered with alluvium, and/or with colluvium at toe-of-slope; bedrock may be weathered.
Non-residential hard shorelines include industrial and engineered structures not clearly associated with residential use.

Legend

- 🟥 Project Boundary
- ～ Shoreline
- ━ Low to Moderate Erosion
- ━ Residential
- ━ Minimal to None

N

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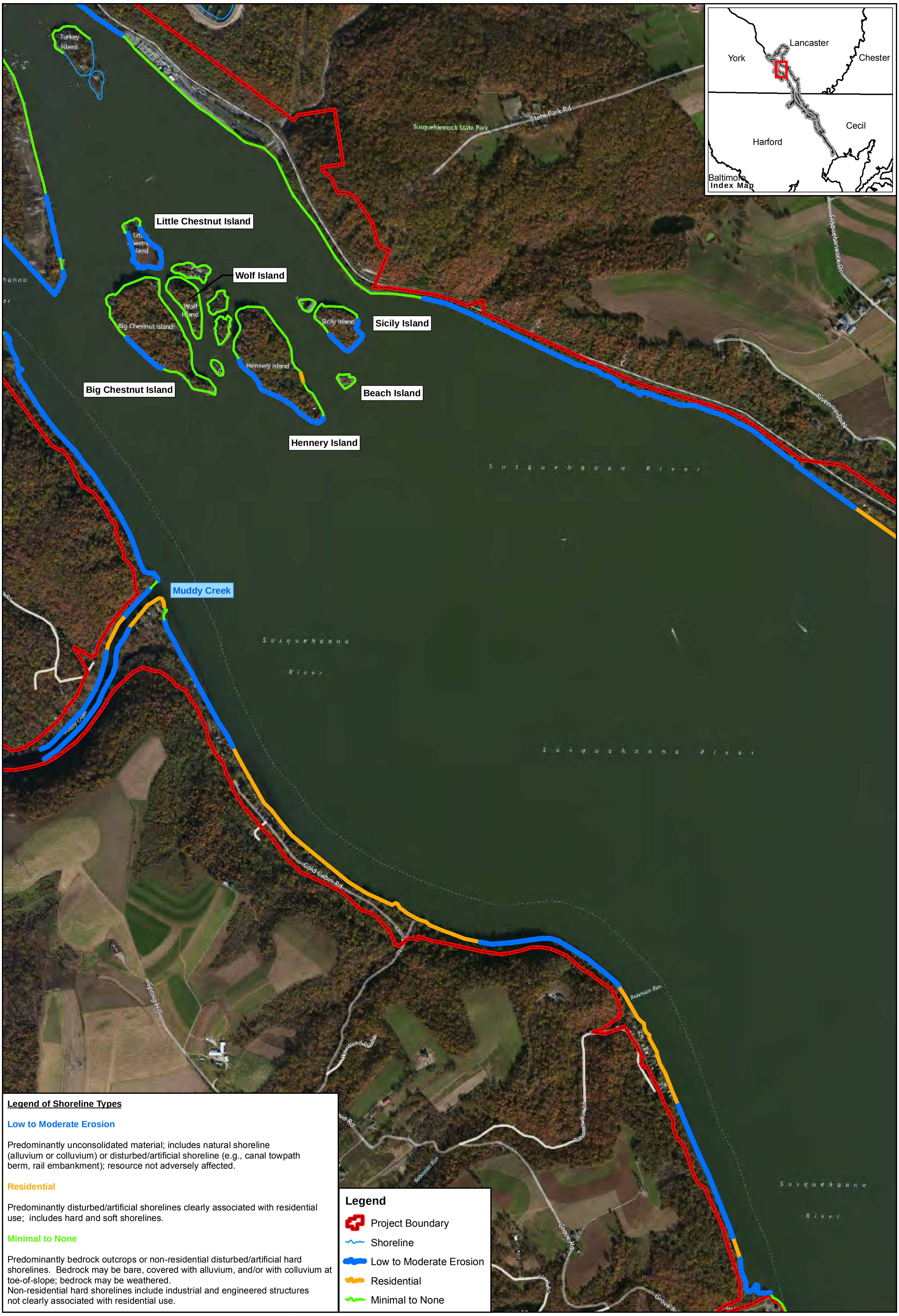
1 inch = 1,100 feet
0 550 1,100 2,200 Feet

Figure A.1.2 - 1
Shoreline Erosion Study - Extent 1

Source: ESRI Data & Maps CD, Bing Maps ™ Imagery, URS Shoreline Study Data

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Extent 1 Fig A.1.2-1.mxd



Legend of Shoreline Types

Low to Moderate Erosion

Predominantly unconsolidated material; includes natural shoreline (alluvium or colluvium) or disturbed/artificial shoreline (e.g., canal towpath berm, rail embankment); resource not adversely affected.

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Non-residential hard shorelines include industrial and engineered structures not clearly associated with residential use.

Legend

- Project Boundary
- Shoreline
- Low to Moderate Erosion
- Residential
- Minimal to None

Exelon.

N

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FERC PROJECT NO. 405

1 inch = 1,100 feet
0 550 1,100 2,200
Feet

Figure A.1.2 - 1
Shoreline Erosion Study - Extent 2

Source: ESRI Data & Maps CD, Bing Maps ™ Imagery, URS Shoreline Study Data

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Extent 2 Fig A.1.2-1.mxd

Legend of Shoreline Types

Low to Moderate Erosion

Predominantly unconsolidated material; includes natural shoreline (alluvium or colluvium) or disturbed/artificial shoreline (e.g., canal towpath berm, rail embankment); resource not adversely affected.

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Minimal to None

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Non-residential hard shorelines include industrial and engineered structures not clearly associated with residential use.

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Figure A.1.2 - 1
Shoreline Erosion Study - Extent 3

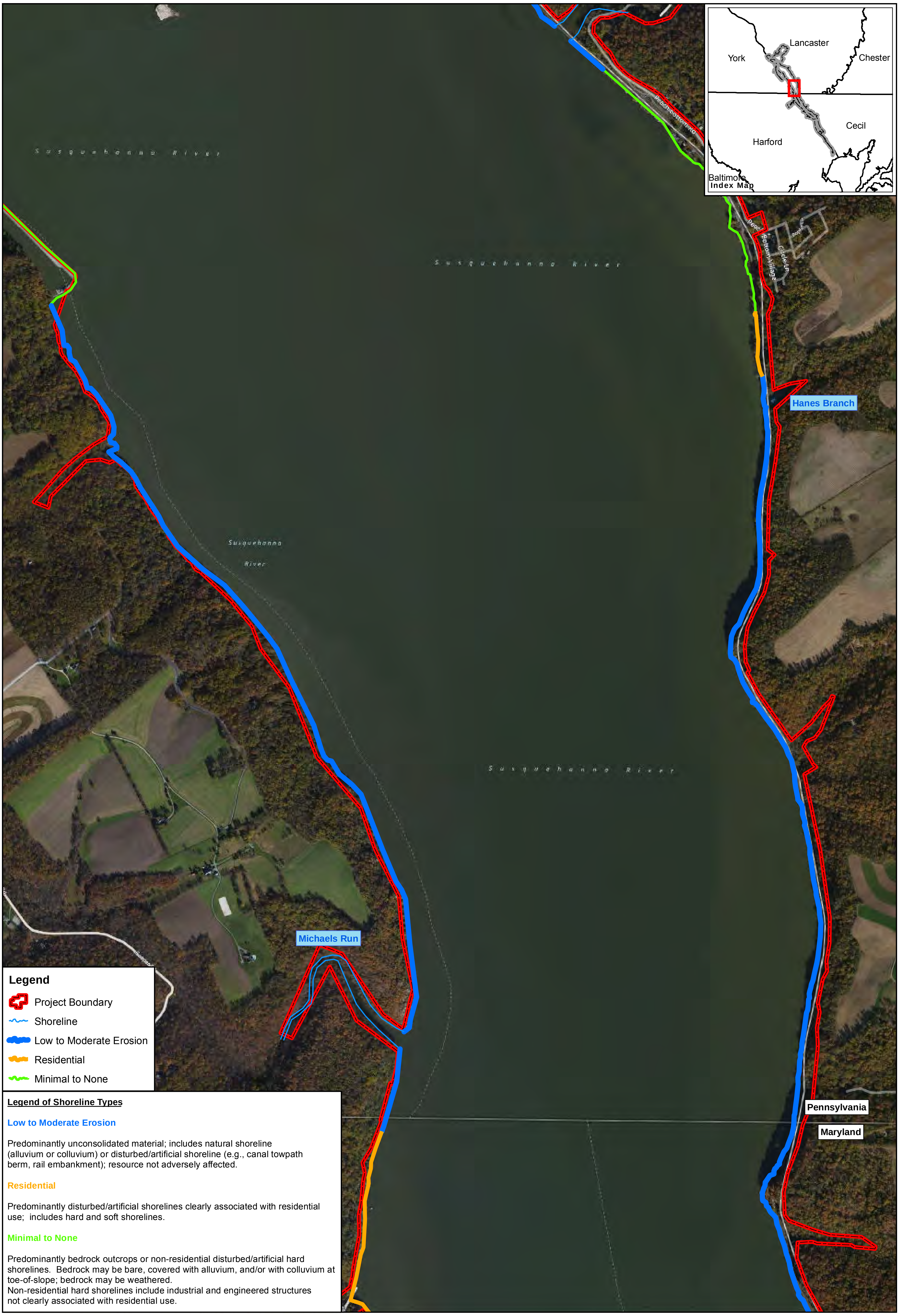
N

1 inch = 1,100 feet

0 550 1,100 2,200 Feet

Source: ESRI Data & Maps CD, Bing Maps ™ Imagery, URS Shoreline Study Data

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Extent 3 Fig A.1.2-1.mxd



Legend of Shoreline Types

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PROJECT NO. 405

Figure A.1.2 - 1
Shoreline Erosion Study - Extent 4

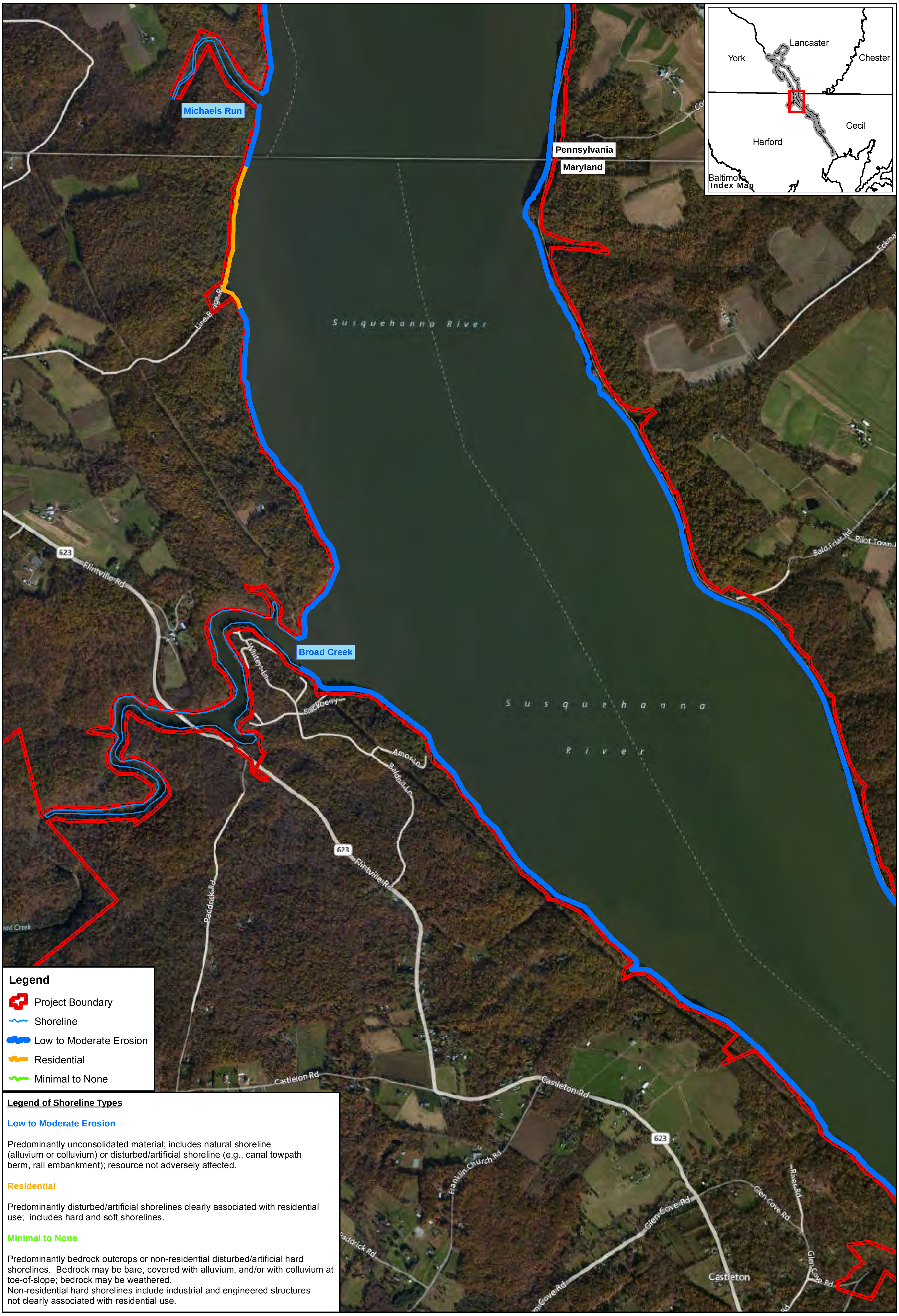
N

1 inch = 1,100 feet

0 550 1,100 2,200 Feet

Source: ESRI Data & Maps CD, Bing Maps™ Imagery, URS Shoreline Study Data

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Extent 4 Fig A.1.2-1.mxd



Legend of Shoreline Types

Low to Moderate Erosion

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Non-residential hard shorelines include industrial and engineered structures not clearly associated with residential use.

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Source: ESRI Data & Maps CD, Bing Maps™ Imagery, URS Shoreline Study Data

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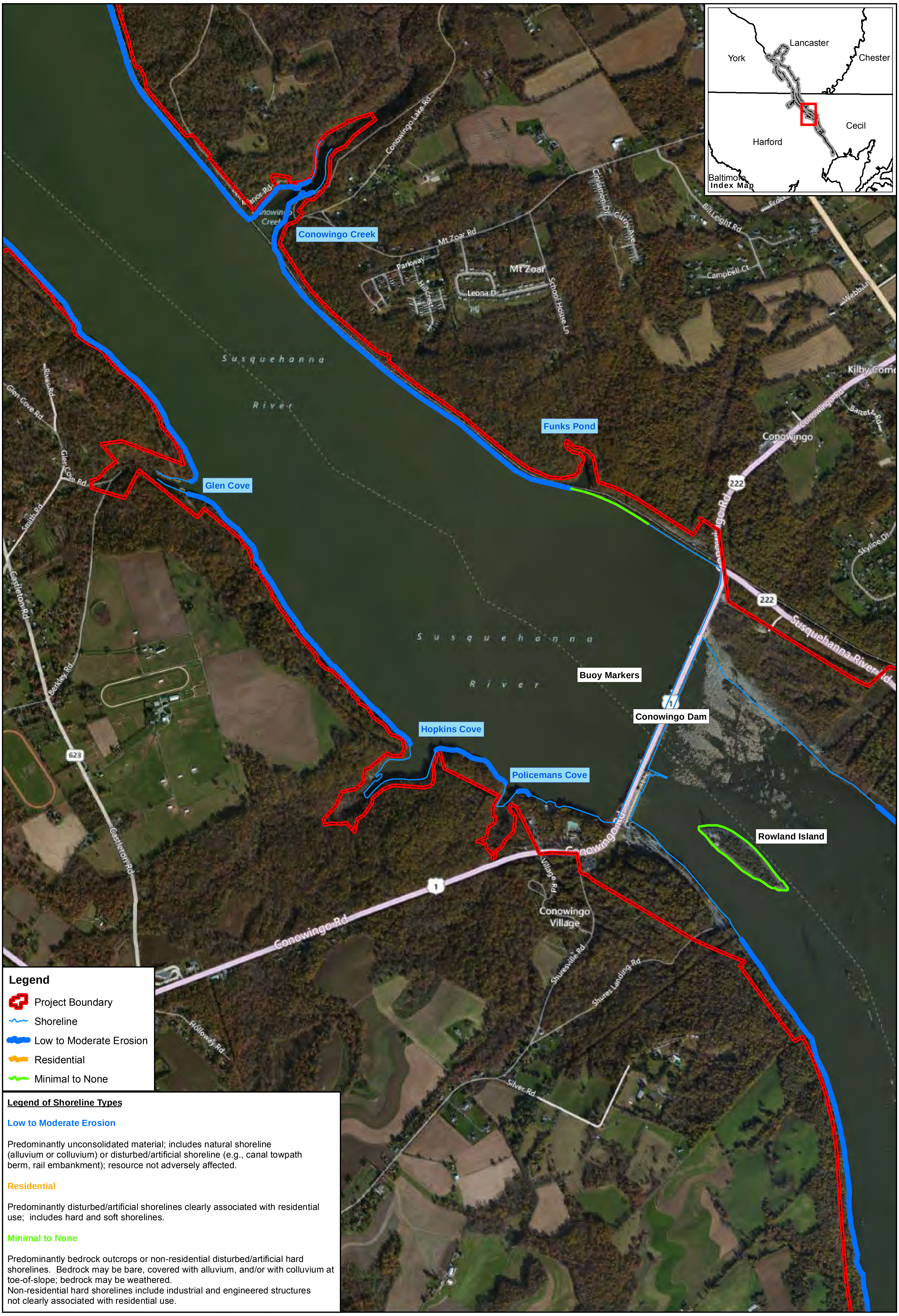
1 inch = 1,500 feet
0 750 1,500 3,000 Feet

Figure A.1.2 - 1
Shoreline Erosion Study - Extent 5

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Extent 5 Fig A.1.2-1.mxd



Legend of Shoreline Types

Low to Moderate Erosion

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Non-residential hard shorelines include industrial and engineered structures not clearly associated with residential use.

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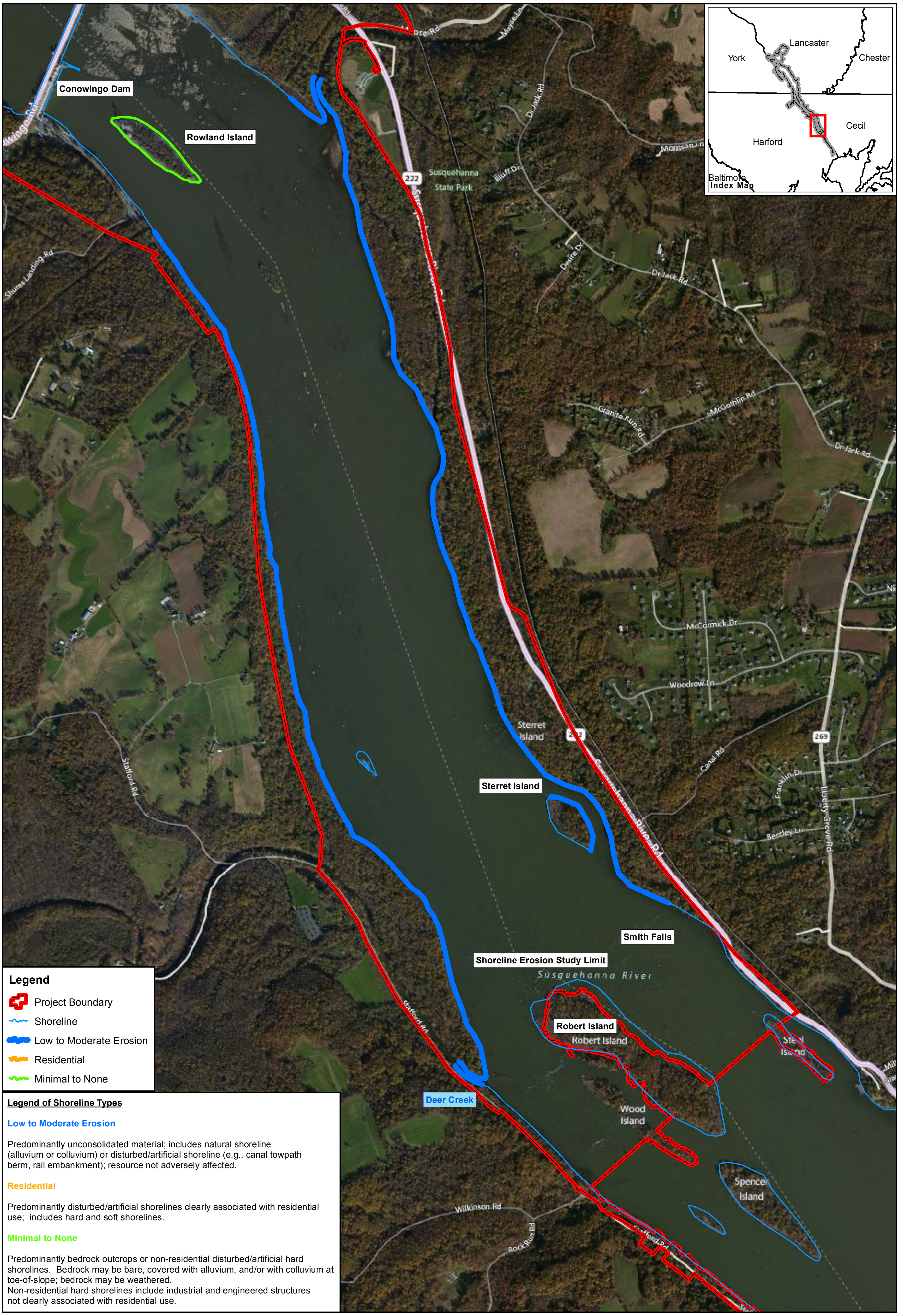
1 inch = 1,500 feet

0 750 1,500 3,000 Feet

N

Figure A.1.2 - 1
Shoreline Erosion Study - Extent 6

Source: ESRI Data & Maps CD, Bing Maps™ Imagery, URS Shoreline Study Data



Legend

🟥 Project Boundary

〰 Shoreline

▬ Low to Moderate Erosion

▬ Residential

▬ Minimal to None

Legend of Shoreline Types

Low to Moderate Erosion

Predominantly unconsolidated material; includes natural shoreline (alluvium or colluvium) or disturbed/artificial shoreline (e.g., canal towpath berm, rail embankment); resource not adversely affected.

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Non-residential hard shorelines include industrial and engineered structures not clearly associated with residential use.

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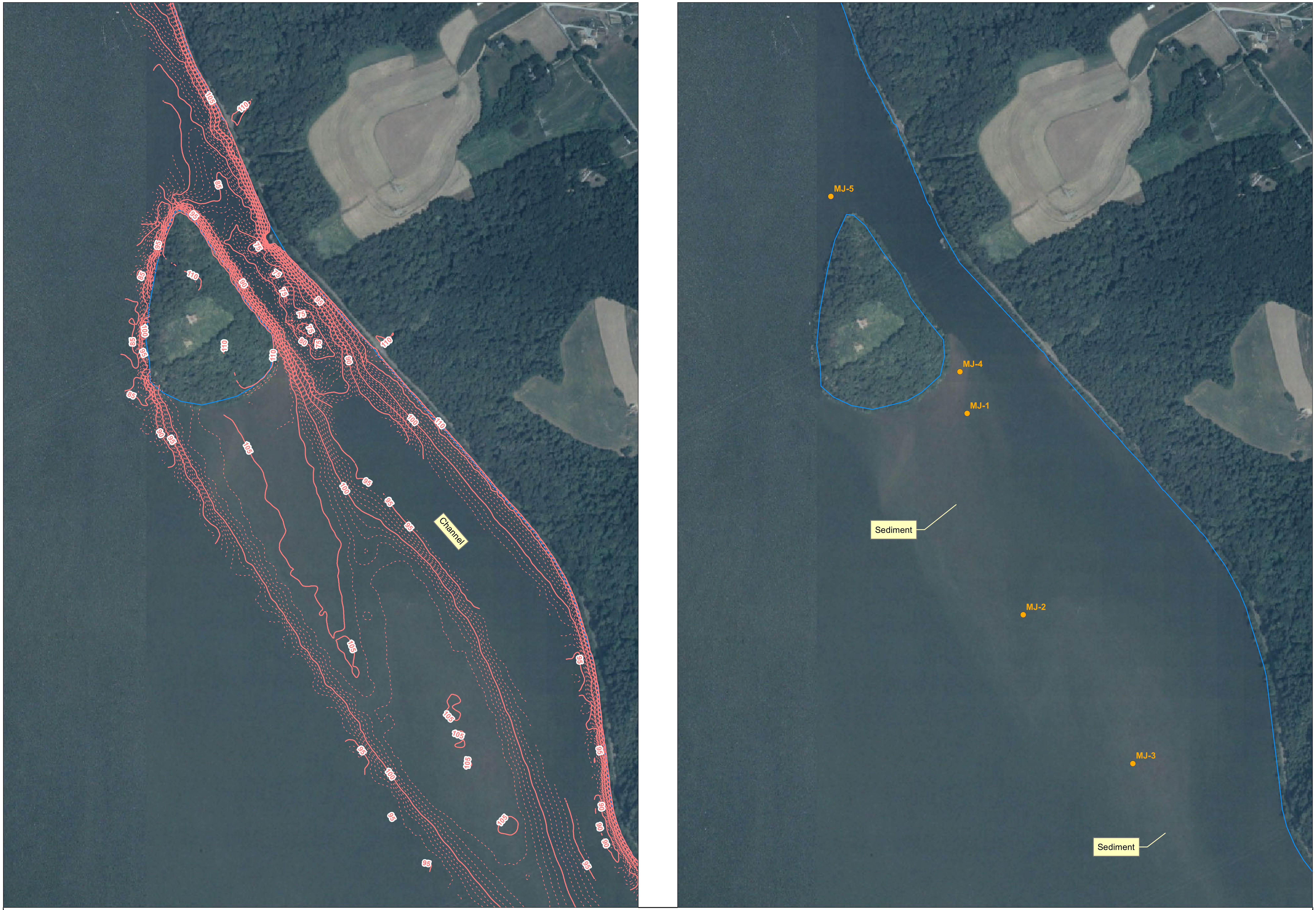
Figure A.1.2 - 1
Shoreline Erosion Study - Extent 7

N

1 inch = 1,500 feet

0 750 1,500 3,000 Feet

Source: ESRI Data & Maps CD, Bing Maps ™ Imagery, URS Shoreline Study Data



N

Legend

—	5-ft Depth Contour (below normal pool elevation 108.5 feet)	●	Sediment Samples
- - -	1-ft Depth Contour (below normal pool elevation 108.5 feet)	〜	Shoreline

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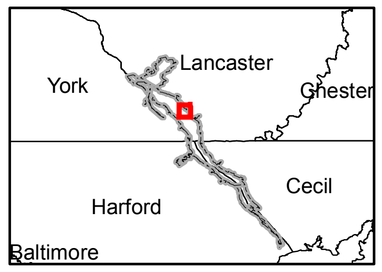
1:6,000

0 250 500 1,000 1,500 Feet

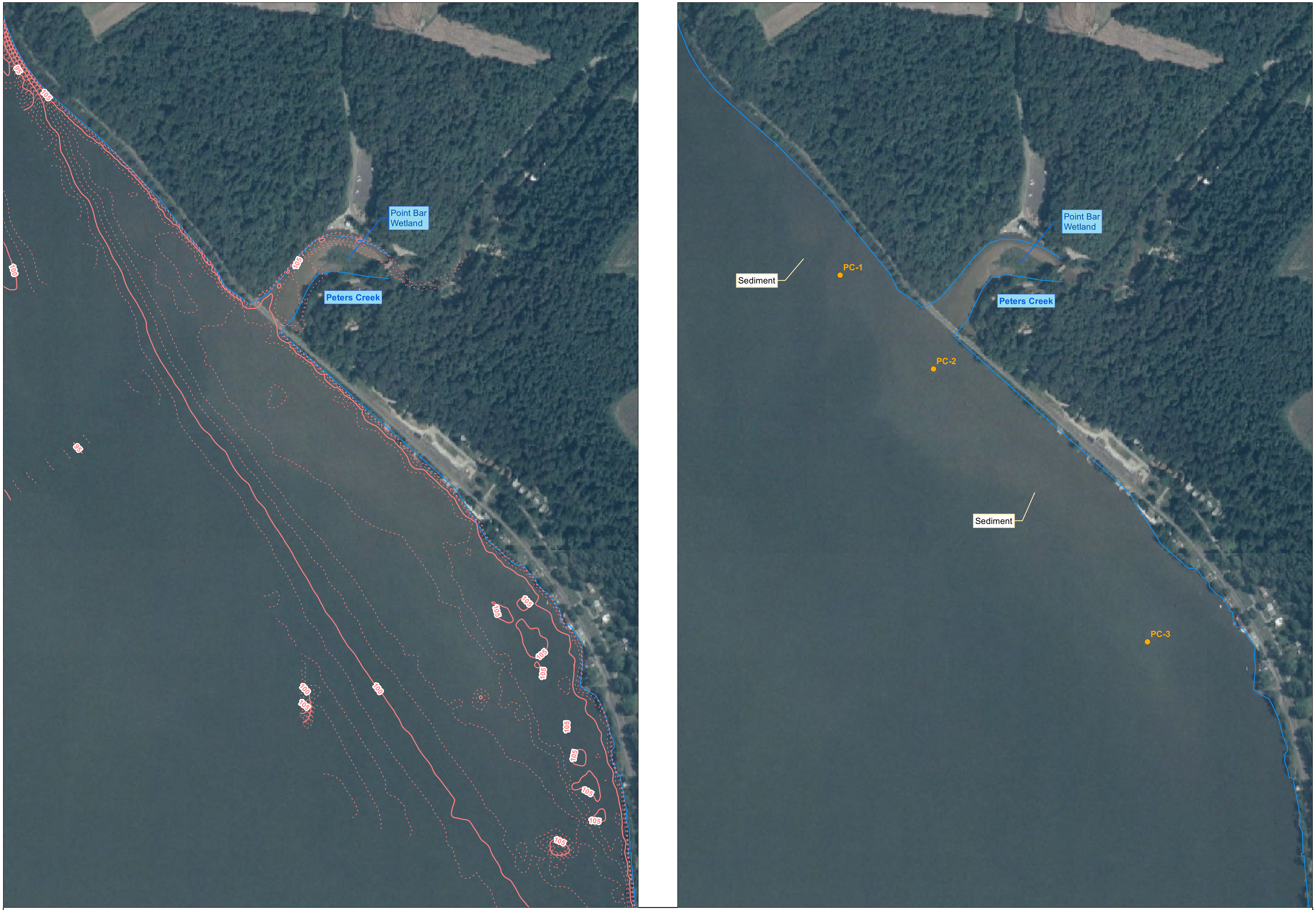


Index Map

Figure A.1.3 - 1
Mt. Johnson Island Area
Depth Contours and Sampling Locations

Source: ESRI Data & Maps CD
Bing Maps™ Imagery
URS Shoreline Study Data

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Mt Johnson Fig A.1.3-1.mxd



Legend

- 5-ft Depth Contour (below normal pool elevation 108.5 feet.)
- 1-ft Depth Contour (below normal pool elevation 108.5 feet.)
- ● Sediment Samples
- Shoreline

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SEDIMENT INTRODUCTION AND TRANSPORT STUDY (RSP 3.15)
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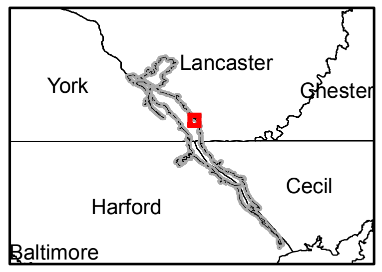
1:4,800

0 200 400 800 1,200 Feet

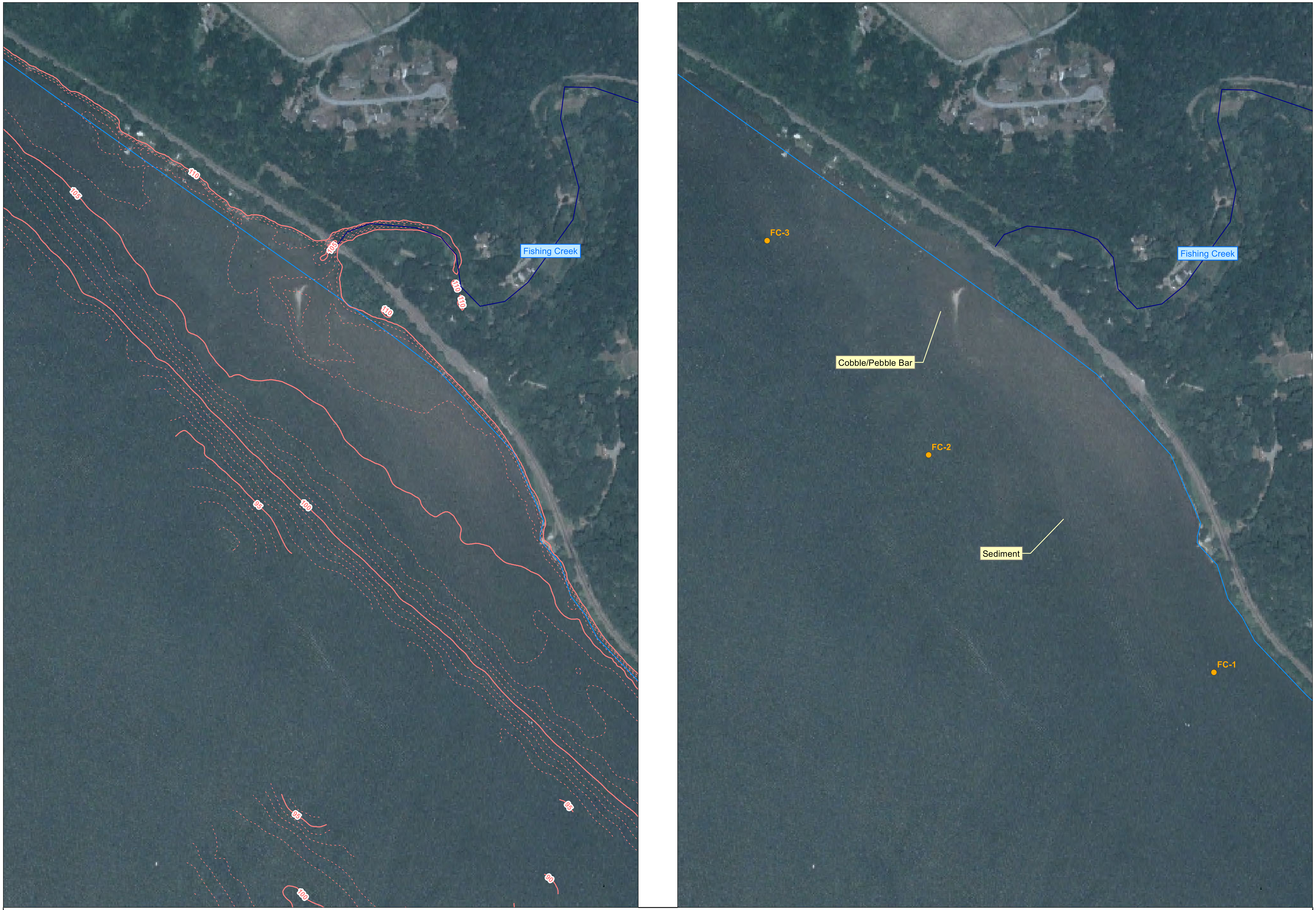


Index Map

Figure A.1.3 - 2
Peter's Creek Area
Depth Contours and Sampling Locations

Source: ESRI Data & Maps CD
Bing Maps™ Imagery
URS Shoreline Study Data

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Peters Creek Fig A.1.3-2.mxd



Legend

- 5-ft Depth Contour (below normal pool elevation 108.5 feet)
- 1-ft Depth Contour (below normal pool elevation 108.5 feet)
- ● Sediment Samples
- Shoreline

N

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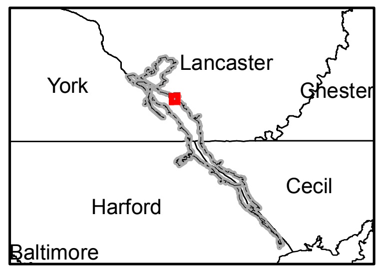
CONOWINGO HYDROELECTRIC PROJECT
PROJECT NO. 405

1:3,600



Index Map

Figure A.1.3 - 3
Fishing Creek Area
Depth Contours and Sampling Locations

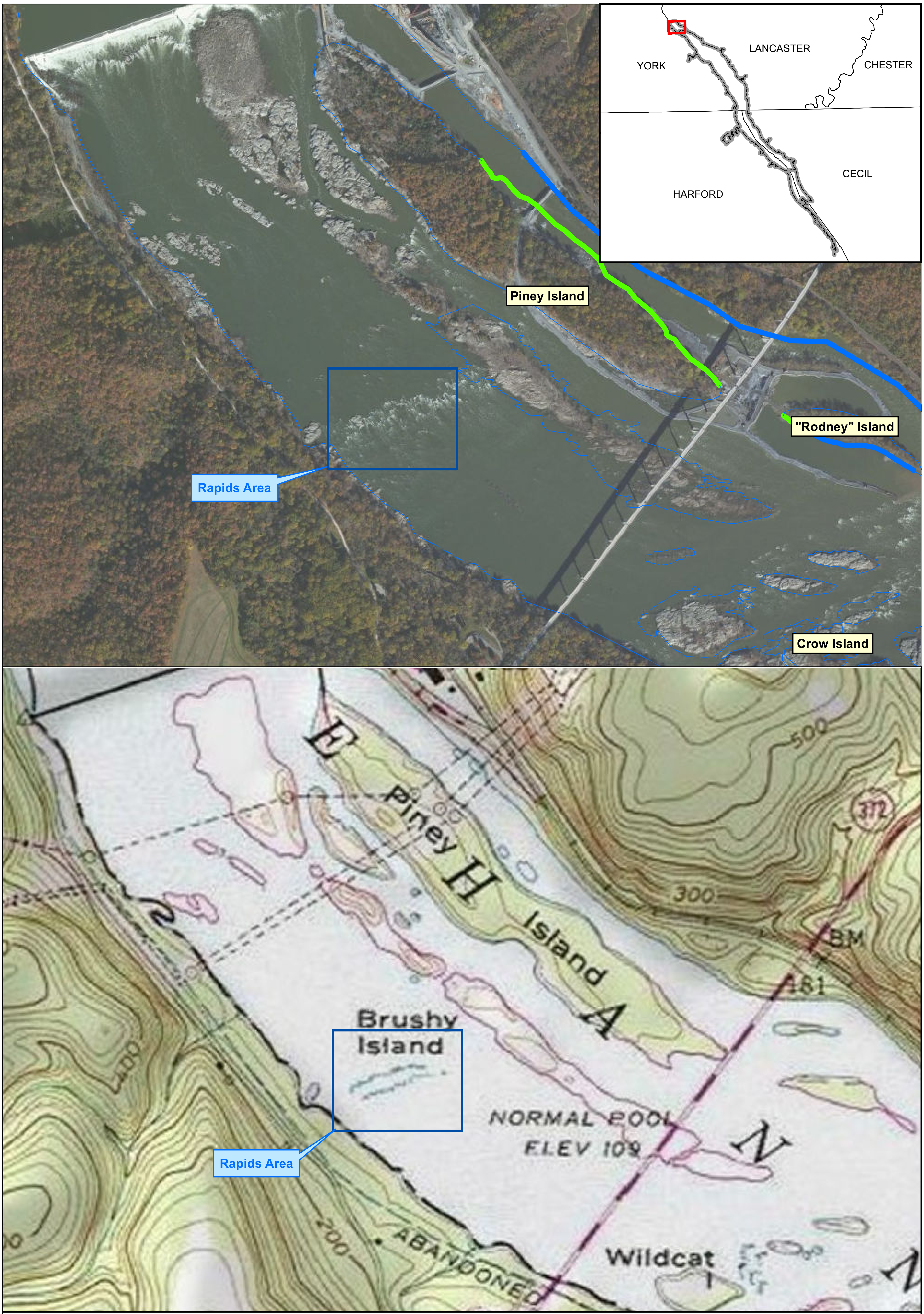
Source: ESRI Data & Maps CD
Bing Maps™ Imagery
URS Shoreline Study Data

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Fishing Creek Fig A.1.3-3.mxd

Figure A.2.1-1

Riverbed Emergent Wetlands

View of Holtwood Dam from Norman Wood Bridge – riverbed emergent marsh with scrub-shrub island margin wetland in center of photo.



EXELON GENERATION COMPANY, LLC

SEDIMENT INTRODUCTION AND TRANSPORT STUDY (RSP 3.15)
CONOWINGO HYDROELECTRIC PROJECT
PROJECT NO. 405
1:8,400

N

0 350 700 1,400 Feet

Figure A.2.1-2
Rapids Area Below Holtwood Dam

Source: ESRI I3 Imagery Prime World
URS Custom Data

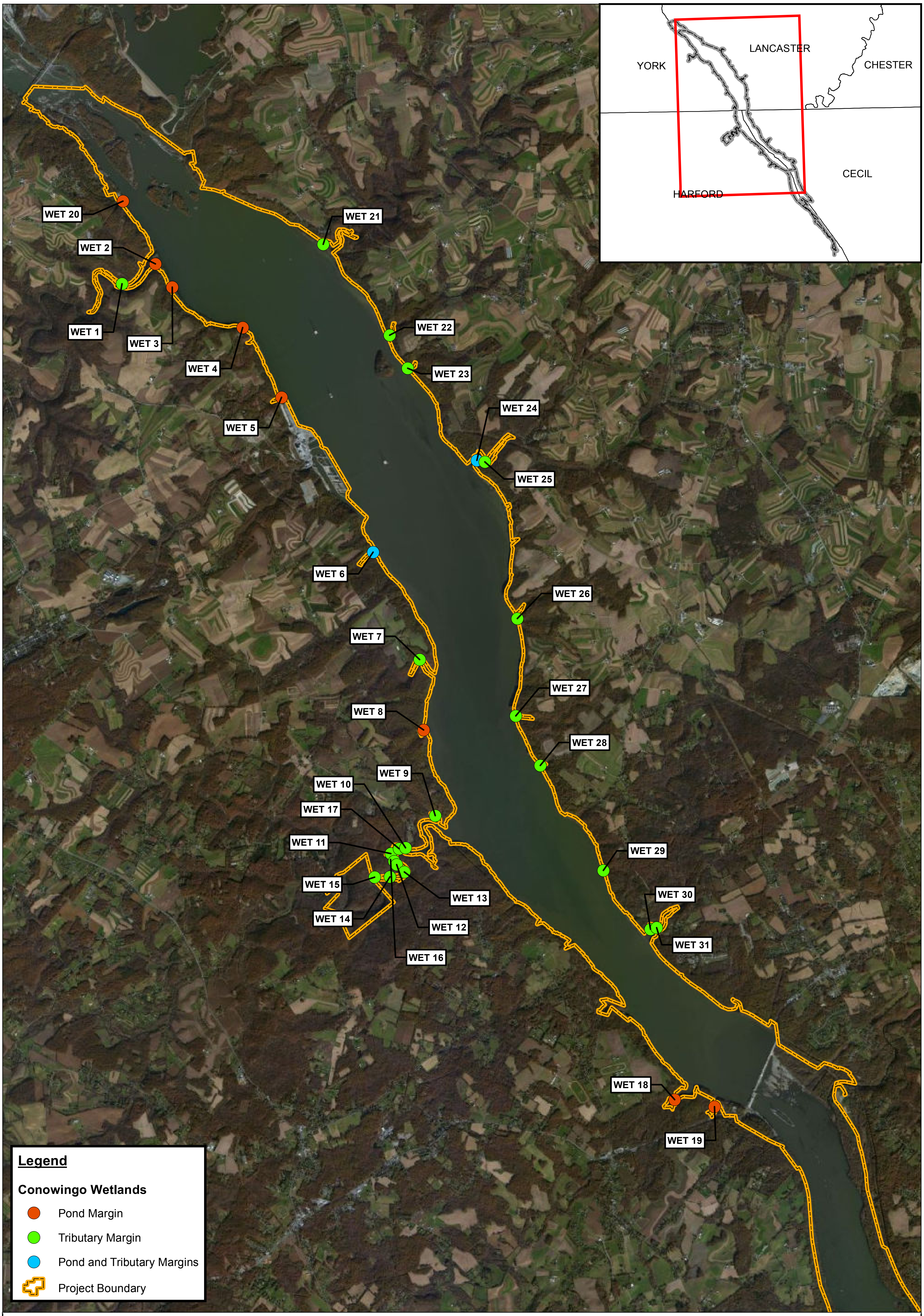
Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Figure_A.2.1-2_rapids.mxd

Figure A.2.1-3

Water willow and purple loosestrife in rock crevasses.

Figure A.2.1-4

Riverbed emergent wetland zones – water willow transition to sedges.



EXELON GENERATION COMPANY, LLC

Exelon.

N

SEDIMENT INTRODUCTION AND TRANSPORT STUDY (RSP 3.15)
CONOWINGO HYDROELECTRIC PROJECT
PROJECT NO. 405
1:63,360

0 0.5 1 2 Miles

Figure A.2.2-1
Conowingo Wetlands
Hydrogeomorphic Position

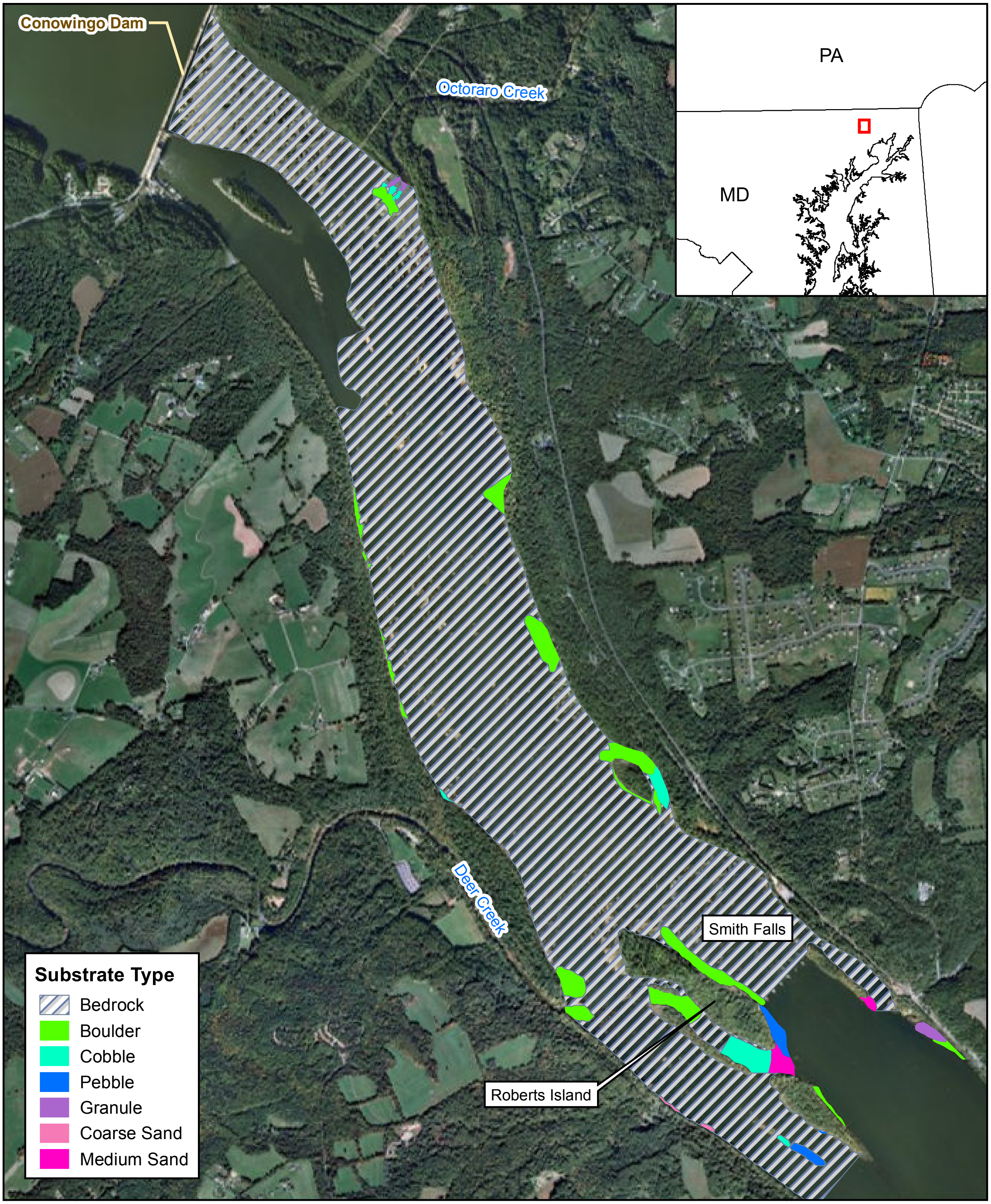
Source: ESRI I3 Imagery Prime World
URS Custom Data

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Figure_A.2.2-1_HGM.mxd

Figure A.2.2-2

Cobble/pebble Bar at Fishing Creek

Waves break on incipient island accreting at mouth of Fishing Creek.



EXELON GENERATION COMPANY, LLC

CONOWINGO HYDROELECTRIC PROJECT
FERC PROJECT NO. 405

Figure A.2.3-1
Downstream Grain Size Distribution

N

0 0.25 0.5 1
Miles

Path: X:\GISMaps\project_maps\study_plan\conowingo\study_3.15\Downstream Grain Size A.2.3-1.mxd

Figure B.2.1-1
SAV Fluctuations 1958-1975
(Orth and Moore 1982)

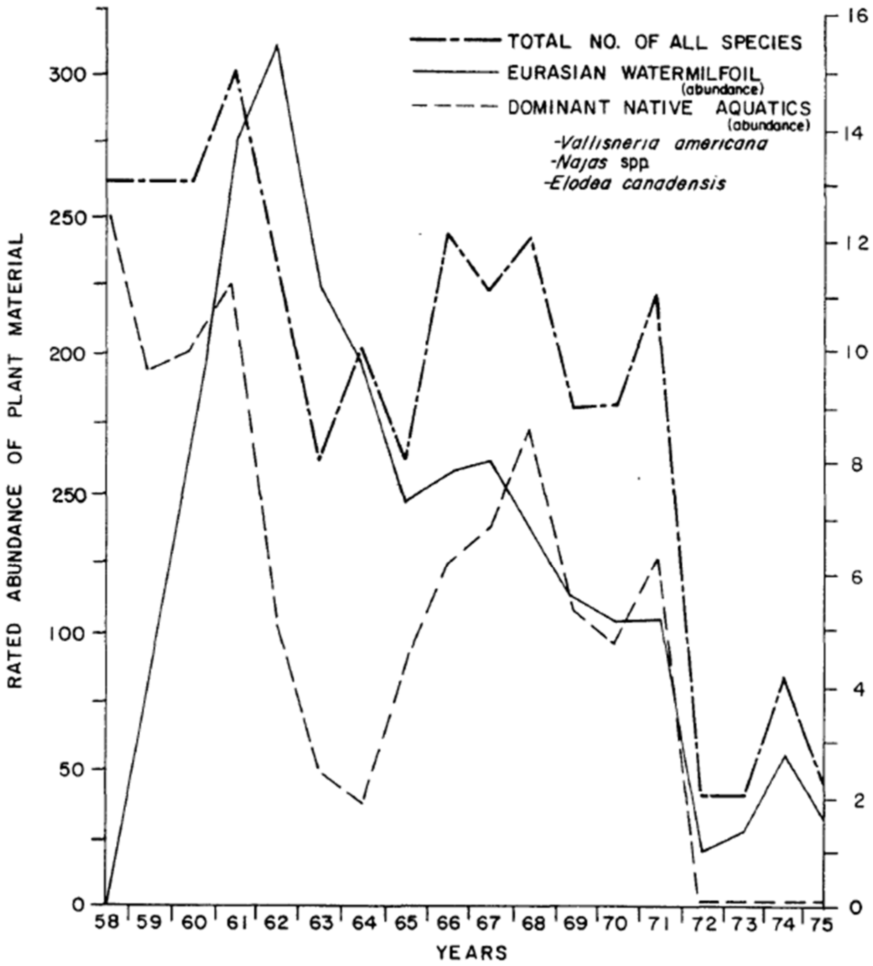
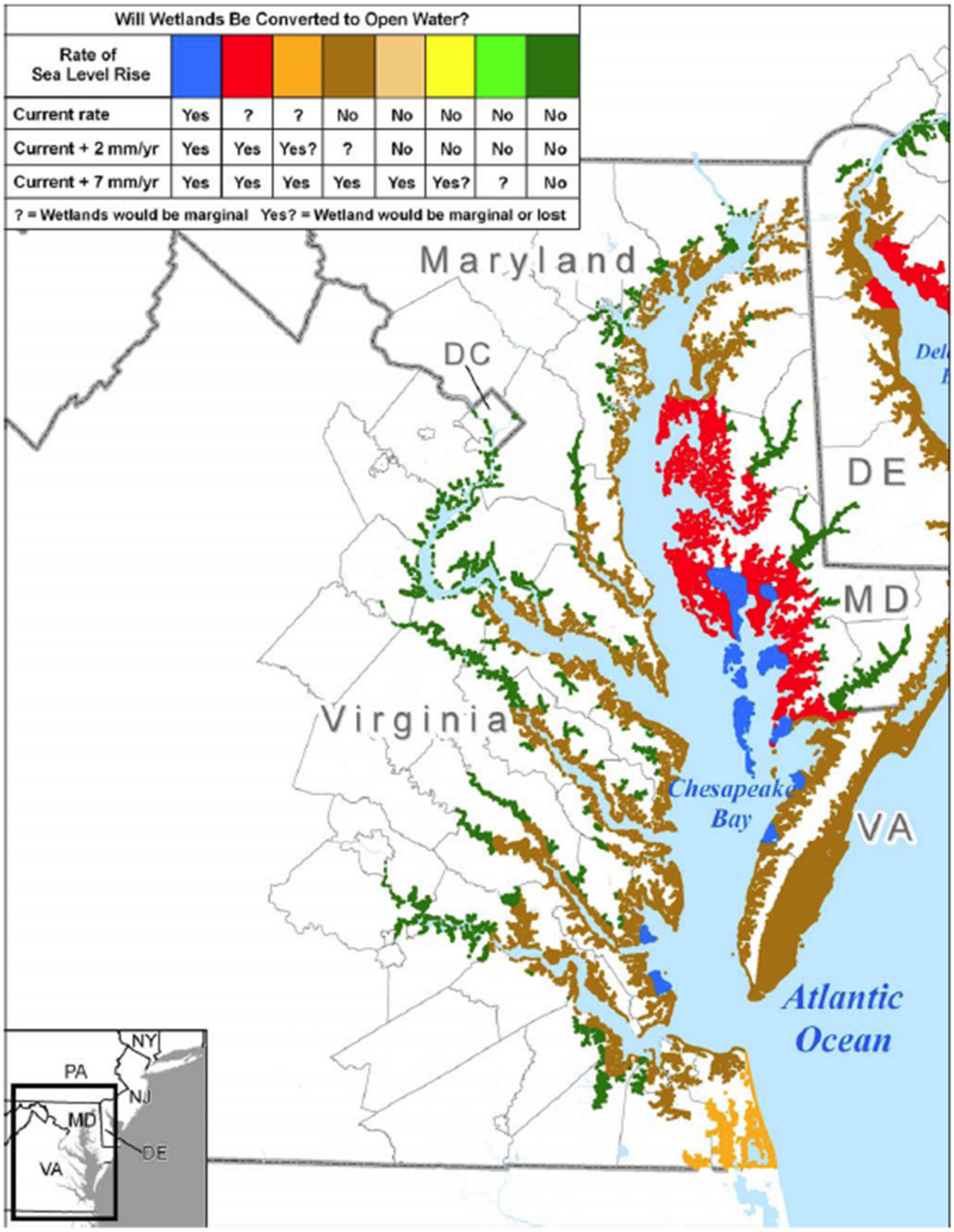


Figure 4. Population fluctuations of watermilfoil compared to the dominant native species and total number of species found on the Susquehanna Flats from 1958-1975 (figure adapted from Bayley et al. 1978).

Table B.2.3-1
Chesapeake Bay Wetlands
Three Sea Level Rise Scenarios
(Reed et al 2008)



Will Wetlands Be Converted to Open Water?

Rate of Sea Level Rise	🟦	🟥	🟧	🟫	🟫	🟨	🟩	🟩
Current rate	Yes	?	?	No	No	No	No	No
Current + 2 mm/yr	Yes	Yes	Yes?	?	No	No	No	No
Current + 7 mm/yr	Yes	Yes	Yes	Yes	Yes	Yes?	?	No

? = Wetlands would be marginal   Yes? = Wetland would be marginal or lost

Figure 2.1.12. Wetland Response Map for the Chesapeake Bay Region. Note that the Lower Maryland Eastern Shore Region is considered separately. Source: Titus et al. (Section 2.2).

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APPENDIX A - RELICENSING FIELD STUDIES

A.1Shoreline Erosion and Sediment Deposition

Field studies were conducted by Exelon in 2006 and 2007 to characterize bank stability, shoreline erosion, and nearshore sedimentation along Conowingo Pond margins and islands (including the gorge reach), the river below the dam to the mouth of Deer Creek, and tributaries (Muddy Creek, Broad Creek, Conowingo Creek, Peters Creek, Fishing Creek, Octoraro Creek, Deer Creek). Inventoried tributaries were surveyed as much as 2,000 feet upstream of the mouth. The findings of these studies are summarized in this section.

A.1.1 Shoreline Types

Shorelines consist of a discontinuous distribution of the following types:

- Bedrock outcrops;
- Weathered bedrock (fractured and fragmented);
- Alluvium (material transported and deposited by running water);
- Colluvium (material mass transported by gravity); and
- Disturbed/Artificial

Bedrock outcrops occur as exposures along the river and island shorelines and mid-stream (inundated or exposed). Bedrock may be bare, covered with alluvium, and/or with colluvium at the toe-of-slope. Weathered bedrock consists of fragmented rock of varying sizes (boulders to gravel). Vegetation may be present and rooted in rock fractures or unconsolidated sediment. Distinguishing properties such as stratification in alluvium, bank failure by mass wasting (e.g., slumps, fallen trees by undercutting), and soil profile development are evident. Disturbed/artificial shorelines consist of retaining walls, docks, armored shores (e.g., riprap, gabions), canal towpath berm, rail embankment fill, laid rock (purpose unknown), industrial structures (e.g., Peach Bottom Atomic Power Station and the Muddy Run Project), and manicured lawns to the water’s edge.

A.1.2 Erosion Features

A reconnaissance level shoreline erosion inventory was conducted for the Project area. Observations were visually conducted from a boat, with two exceptions. A few quiescent sites along gorge islands permitted upland access to evaluate safety and a separate trip was made to verify on land what appeared by boat to be a pending encroachment onto a working railway track.

Evidence of shoreline erosion is ubiquitous along unconsolidated shorelines. Typical features are bank undercutting, fallen trees, mass wasting, terraces, and scarps. In general, two zones of erosion (not always present at a single location) are recognizable in Conowingo Pond. A lower zone was visible within 1 to 3 feet of the water elevation at the time of the survey (within the range of Project water level fluctuation in the pool) and a higher zone extended 10 to 15 feet above the water elevation at the time of the survey (above the range of pool fluctuation).

The Norfolk Southern railroad embankment dominates the eastern shoreline of Conowingo Pond. Exposed vertical banks reached about 20 feet above the water level at the time of survey. The abandoned Susquehanna and Tidewater Canal towpath berm dominates the western shoreline below the Pennsylvania Fish and Boat Commission boat launch opposite the Muddy Run powerhouse. For the most part, the erosion consists of nominal undercutting, but greater erosion (e.g., 5 to 6 feet vertical bank) was noted below the Peach Bottom Atomic Power Station. In summary, erosion is ongoing along 'soft' shorelines that consist predominantly of unconsolidated sediment. Where shorelines are 'hard' (i.e, predominantly bedrock, retaining wall, rip-rap) there is little to no erosion.

The observed erosion along Conowingo Pond is predominantly due to natural processes - wind generated waves, river flow, surface runoff, and mass wasting. Boat wakes are likely another contributing factor at the summer recreation level of the Pond, and ice effects may be important during colder winters.

Shoreline erosion is a natural condition of riverine systems and high degrees of erosion may not be judged to be an issue of concern. Ranking of shoreline erosion was based on encroachment onto a resource of value. Since the shoreline inventory was conducted prior to any natural or cultural resource inventories, the chosen resource for ranking was infrastructure. Shorelines experiencing a relatively high degree of erosion without posing a physical threat to existing infrastructure were therefore ranked as moderate.

Shorelines can be categorized and mapped by the predominance of erosion properties as follows:

- Low to Moderate Erosion: Predominantly unconsolidated material; includes natural shoreline (alluvium or colluvium) or disturbed/artificial shoreline (e.g., canal towpath berm, rail embankment); existing infrastructure not adversely affected.
- Residential: Predominantly disturbed/artificial shorelines clearly associated with residential use; includes hard and soft shorelines.
- Minimum to None: Predominantly bedrock outcrops or non-residential disturbed/artificial hard shorelines. Bedrock may be bare, covered with alluvium, and/or with colluvium at toe-of-slope; bedrock may be weathered. Non-residential hard shorelines include industrial and engineered structures not clearly associated with residential use.

The shoreline erosion inventory of the Conowingo Project area is illustrated in Figure A.1.2-1.

A.1.3 Depositional Features

Some shorelines are not erosional but are actively accreting, that is, gradually extending into and up out of the pond by sedimentation. Sediment originating outside of the Conowingo Project system, as well as some of the sediment eroding from Project area banks, are transported and deposited as alluvium elsewhere in the system. Large expanses of alluvium are deposited as accretionary features at or near the downstream ends of existing islands and at/near tributary mouths.

Accretionary features are stabilized by vegetation when optimal conditions of inundation and sediment stability are reached. Once established, vegetation initiates a cycle of sediment trapping, stabilization and accretion. Different degrees of stabilization and vertical accretion have been reached in Conowingo Pond, ranging from littoral areas with or without submerged aquatic vegetation (SAV) to wetlands with emergent vegetation. This process is particularly prominent at Mt. Johnson Island, Peters Creek, and Fishing Creek. Depositional features in these areas are described in greater detail below. Alluvial accretionary features also are found below the Norman Wood Bridge, e.g., at an unnamed island below Piney Island.

Sediment deposition along shorelines is also manifested by gently sloping deposits at the water's edge. These deposits include sediment at the mouths of minor streams entering the river (e.g., Muddy Run), sediment associated with stormwater runoff that drains riparian areas, and sediment deposited by receding floodwaters.

The sediment composition of accretionary littoral zone substrates examined in these field studies is consistent with the findings of the USGS and MGS (Hainly et al. 1995; Hill et al. 2006). The USGS and MGS studies identified a major property of bottom sediments in Conowingo Pond below Hennery Island to be significant anthracite coal content associated with sands.

Mt. Johnson Island

Accretionary sediment deposition is evident on the downstream side of Mt. Johnson Island from aerial photographs (Figure A.1.3-1). Bathymetric contours were acquired from the 2010 survey conducted for RSP 3.12 (Water Level Management). Two shoals are separated by a narrow channel. Flow is stronger in the channel than on the shoals.

Near the water's edge at the upper limits of the littoral zone, along the south shore of the island, the substrate consists of bedrock and boulders of weathered bedrock. The shoal substrate consists of sand and silt[17] (Table A.1.3-1). The sands are predominantly sub-angular to well-rounded quartz (coarse-to-fine) with varying amounts of coal. Sand-sized grains of coal are angular and can be abundant. Biotite flakes and coal are found in sands and silts.

Peters Creek

Sediment deposition at the mouth of Peters Creek also is evident on aerial photographs (Figure A.1.3-2). The substrate consists of a sub-angular to rounded medium sand and silt or “jelly-like” mud (Table A.1.3-2). The sand is predominantly quartz with varying amounts of coarse sand-sized angular coal grains. Biotite flakes are present in the sand. The organic rich silt sample had a minor amount of coal.

Several hundred feet upstream of the mouth there is another form of accretion is taking place. A laterally and vertically accreting point bar has developed on the inside bend of the channel opposite Peach Bottom Marina. A wetland has become established on this point bar deposit.

Fishing Creek

Sediment deposition at the mouth of Fishing Creek also is evident on aerial photographs (Figure A.1.3-3). The substrate ranges from pebbles and cobbles at the shallowest area to sand and silt elsewhere (Table A.1.3-3). Silts contained some sand (quartz and coal). One sample was medium-to-coarse grained coal sand.

A.2 Aquatic Vegetation and Sedimentary Conditions

As noted previously, there is an interactive feedback relationship between sediment accretion and vegetation. This mechanism is described in greater detail in this section as it relates to sedimentary processes. RSP 3.12 (Water Level Management - Littoral Zone and Water Level Fluctuation) investigated the relation of aquatic vegetation and sediment with respect to littoral habitat (see separate report).

A.2.1 Bedrock Gorge Area

For a distance of about 7,000 feet a large extent of riverbed is exposed below the Holtwood Dam spillway, between Piney Island and the York County shoreline. This area is comprised of intermittently

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[17] Sediment classified in accordance with the Udden-Wentworth scale (see Appendix C).

exposed bedrock with shallow pools at low water levels (Figure A.2.1-1). Field work conducted in 2006 and 2007 noted a change in habitat character about 3,500 feet below the spillway. This correlates with a hydrologic change manifested by a line of rapids on USGS topographic maps and breaking water on aerial photographs (Figure A.2.1-2).

The upstream section appears to be a higher energy flow regime. Vegetation grows in cracks and crevasses on the protected downstream side of rocks. The pools here are smaller and more isolated (10 to 100 square feet) while the downstream section has larger more contiguous areas of open water (1,000 to 10,000 square feet) that are wider and deeper. Upstream vegetation is generally shorter and less abundant than that downstream. As the energy conditions diminish downstream, the vegetation becomes more prominent, growing on most available rock surfaces, upstream and downstream. The downstream area corresponds to the riverbed emergent marsh of PPL studies (PPL and Kleinschmidt 2006).

Pioneer vegetation, primarily water willow (*Justicia Americana*) and purple loosestrife (*Lythrum salicaria*), become established in silt deposited by receding waters in crevasses on bare rock and in the silt matrix of predominantly weathered bedrock and gravel/cobble substrates (Figure A.2.1-3). Dense root mats with trapped sediment ultimately develop and may be stripped from the rock by moving water. The root mats are important for the development of more complex vegetation zones because, as they continue to trap sediment, they become thicker and provide a foundation for soil development.

Vegetative zones correlating with elevation and inundation are evident. The water willow and purple loosestrife zone (lower elevation with longer periods of inundation) transitions to grasses, sedges and rushes (Figure A.2.1-4). The width of these zones is a function of slope (i.e., narrow zones with steep slopes). An element of protection against erosion is afforded to the vegetation growing at higher elevations.

A.2.2 Conowingo Pond Below Hennery Island

Wetland distribution in Conowingo Pond below Hennery Island is constrained by sedimentary and hydrogeomorphic (HGM) regimes reflecting different geomorphic settings, water sources and hydrodynamics. These differences, in turn, influence how these wetlands function (Smith et al. 1995). Geomorphic setting refers to topographic position in the landscape; water source refers to the location of water just prior to entry to the wetland; and hydrodynamics refers to the energy of moving water and flow direction.

The wetlands fall within the HGM class of riverine wetland (Brinson et al. 1995). The geomorphic setting is floodplain or riparian corridor; the dominant water source is overbank flow from a channel or subsurface hydraulic connections between stream channel and wetlands; and the dominant flow is unidirectional and horizontal. Overland flow from adjacent uplands and tributary inflow may be additional sources of water for the wetlands. The role of sediment movement within this HGM context is unique for each type.

Figure A.2.2-1 illustrates the distribution of the three major HGM classes identified in Conowingo Pond below Hennery Island: pond margin, tributary margin, and pond/tributary observed during a 2008 presence/absence wetlands survey. The 2010 survey conducted for the Water Level Management Study reaffirmed this classification. Each of these designations refers to the major driver of wetland properties during typical, non-storm conditions. That is, pond margin wetlands are influenced primarily by the Susquehanna River; tributary margin wetlands are influenced primarily by the tributary; and pond/tributary wetlands are strongly influenced by both river and tributary.

Wetlands associated with tributary mouths may be placed in any one of the three categories. For example, Wetlands 18 and 19, located at the heads of Hopkins and Policemans Coves, respectively, where tributary streams empty to the Pond, are more strongly influenced by Pond processes and are termed pond margin wetlands. In contrast, Wetlands 22, 23, and 25, located near the confluence of tributaries and the Pond, are more strongly influenced by tributary stream processes and are termed tributary margin wetlands. Wetlands 6 and 24 are positioned such that both tributary and Pond hydrology exercise a strong influence on the wetlands identified.

At Fishing Creek water willow is established on the cobble/pebble bar opposite the stream mouth. Waves were seen breaking on the cobble/pebble bar which may be an incipient island (Figure A.2.2-2). Snags promote vertical accretion by trapping sediment. As the water willow becomes established, more sediment is trapped and the bar stabilizes and continues to aggrade horizontally and vertically.

A.2.3 Downstream EAV/SAV Study

Substrate grain size was characterized below Conowingo Dam as part of RSP 3.17 (Downstream EAV/SAV Study) (see separate report). Figure A.2.3-1 illustrates the distribution of bedrock and dominant sediment grain sizes in the Project area below the dam. Bedrock predominates with limited extents of sediment ranging from predominantly medium sand to predominantly boulder. River flow strength visibly dissipates as it enters a deeper channel below Smith Falls. Above the falls, flow is confined and strengthened by outcropping bedrock. Flow rates are elevated under low flow condition where narrow channels are formed by bedrock as well as under higher flows when outcrops are submerged but concentrate most of the flow within narrow channels.

The outcrops begin below Bird Island (just below Rowland Island) extending to Roberts Island, with greater concentrations within the first mile downstream of Bird Island. Below Roberts Island and Smith Falls the river gradient decreases while substrate transitions to broad areas dominated by sand and silt. The presence of cobble and bedrock are still apparent mainly concentrating along the island perimeters and river margins.

As discussed earlier in Section 3.1.1, the Project reach below the dam prior to its construction was likely similar to how it is today. A natural barrier existed at the site of the dam (Hectors Falls) and flow was strong enough to be a navigation hazard and inhibit sediment deposition until the mouth of the river below Smith Falls.

APPENDIX B - ADDITIONAL RELEVANT LITERATURE

B.1 Sedimentary Processes Downstream of Dams

The interactions of the variable flow regime and variable sediment-transport capacity of released waters on existing substrate and sources of sediment supply are basic concepts influencing sedimentary processes downstream of hydroelectric dams. At Conowingo Dam, site-specific factors also include local bed level control by bedrock and an armor layer and tributary input. These are discussed in detail below.

B.1.1 Sediment-Transport Capacity of Dam Releases

Fine-grained sediment (silts and clays) are generally transported in suspension in the water column, supported by turbulence, while coarse grains travel as bedload close to or at the channel bottom (Ritter et al 2002). Particles may, at any given time, be part of the bedload or suspended load, depending on discharge fluctuations. Hydroelectric facilities differentially modify the supply and transport of coarse and fine sediment that pass a dam (Potyondy and Andrews 1999). At one extreme are run-of-the-river facilities that allow passage of all sediment. At the other extreme are impounding structures that trap bedload with all or part of the suspended load deposited in the reservoir or in upstream backwaters (Kondolf 1997). Water releases from these dams have the kinetic energy (sediment-transport capacity) to move sediment but carry little sediment (i.e., they are “hungry waters”). The river system response to hungry waters is to reduce the excess sediment-transport capacity, if possible, by erosion (bank erosion, bed scouring, and/or bed armoring) (Clarke et al 2008). In addition to reduced sediment loads, released waters carry sediment of reduced grain size (Brandt 2000). A reduction in peak flows downstream may lessen the overall impact of sediment-starved waters by allowing fine sediment to accumulate (Kondolf 1997). Similarly, tributary input that reduces the sediment-transport capacity of the main channel may promote the deposition of suspended sediments (Petts 1980).

B.1.2 Local Bed Level Controls – Bedrock and Armor Layer

Downstream channel adjustments in slope, cross-sectional shape, plan form, and bed form are variable, depending on how the channel boundary (bed and bank) responds to the sediment-transport capacity and sediment load of releases from the reservoir. Interactions of the channel perimeter and flow are largely dependent on the erosion potential of the flow and erodibility of bed and bank. The presence of bedrock is a constraining variable.

Grant et al (2003) identified three factors that influence the capacity of a channel downstream of a dam to adjust: 1) transportability of the bed sediment, indexed by its grain size relative to shear stresses exerted by the flow across the full spectrum of discharge regime; 2) erodibility of the bed and banks, as influenced by cohesiveness and/or prevalence of bedrock; and 3) opportunity for lateral mobility within the confines of overall width and topography of the valley floor. The downstream effects of a dam are related to the change in frequency of sediment-transporting flows and the ratio of sediment supply below and above the dam. River response to these variables can be strongly influenced by the broader geologic setting, such as bedrock. This is the case with the Project area.

It has been observed (RSP 3.17) that the configurations of bedrock outcrops within the channel downstream of the dam confine and strengthen flow. Under lower flow conditions, outcrops form narrow flow channels allowing water to pass between outcrops at elevated flow rates. During higher flow conditions, these outcrops become inundated, altering the flow dynamic while still concentrating a majority of the flow within the channels created by the outcrops. Generally, these outcrops are present beginning below Bird Island (just below Rowland Island) extending to Roberts Island, with greater concentrations within the first mile downstream of Bird Island. Below Roberts Island and Smith Falls the hydraulic gradient of the river decreases and substrate transitions to broad areas dominated by sand and silt. The presence of cobble and bedrock are still apparent mainly concentrating along the island perimeters and river margins.

Along the continuum of potential river responses, the actual adjustments that occur reflect constraints of the channel (Petts 1980). Constraints include resistance to erosion (predominant grain-size of the bed, bedrock outcrops, adhesion of bank sediments, vegetation) and existing channel dimensions (cross-sectional area and shape, slope) which can locally affect flow velocity. In the downstream reach of the Susquehanna River below Conowingo Dam, the major channel constraint is the presence of bedrock, as noted above.

Williams and Wolman (1984) investigated 21 dams on alluvial rivers throughout the United States. All exhibited a lowering of mean bed level immediately downstream of the dam unless constrained by very coarse material or bedrock. Local bed level controls, such as the emergence of bedrock or development of an armored layer (discussed below) interrupts channel erosion even though flow releases have the capacity to entrain sediment.

In the long-term, as finer sediments are selectively winnowed and transported downstream by hungry tailwaters, coarse lag deposits of large gravels, cobbles, or boulders may produce a bed with surface sediment coarser than the subsurface sediment (armor layer) (Nestler et al 1986; Bunte and Abt 2001). Once an armor layer has developed, the finer sediment below is protected from erosion until the armored surface is rearranged or removed by strong flow events (Gordon et al 1992). Bedrock may be exposed if it is near the surface.

Armored layers devoid of fine sediment were not observed below the dam during the field work for RSP 3.17. While unconsolidated substrates are limited in distribution below Conowingo Dam, they are also poorly sorted. That is, coarse substrates of a predominant grain size fraction (i.e., cobble and boulder substrates) will have sand and silt as a matrix or in crevices.

The effect of the microflow regime of boulders and bedrock outcrops may be an important factor affecting benthos downstream of Conowingo Dam. The turbulence generated by flow around isolated roughness elements (individual boulders) impact the distribution of macroinvertebrates (Bouckaert and Davis 1998). When present, a large roughness element dominates the flow of the immediate surroundings within an overall complex natural stream flow pattern.

B.1.3 Sediment Supply and Tributary Input

Location of a dam with respect to sediment sources influences dam impacts on downstream sediment regime (Reiser et al 1989). The potential for hungry waters is greater when a dam is located below major sediment sources. In contrast, hydrologic alteration of hydroelectric dams located above major sources of sediment will likely create deposition problems when sediment input exceeds the sediment-transport capacity of flows.

The sediment supply of tributaries must also be considered. Major tributaries of the downstream reach of the Conowingo project are Octoraro Creek and Deer Creek. Flood tidal flow and storm surges from Chesapeake Bay may also supply sediment to some areas of the downstream project reach. While a dam interrupts natural sediment transport along the main stem, the input of downstream tributary sediment can alter the process-response relationships of regulated flow and altered sediment loads in the main stem (Petts 1980). Relevant factors include the location of tributary inflow, amount and size of tributary sediment, and the desyncronization of tributary inflow with the main stem (Potyondy and Andrews 1999). The contribution of sediment from tributaries to an armored reach below a dam complicates estimates of sediment transport rates based on main stem bed grain sizes (Wilcock et al 2009). For example, sand and fine gravel supplied by tributaries below a dam with an armored bed of cobble and coarse gravel may be transported by dam releases. However, a transport rate formula applied to the grain size of the bed would produce an estimate of negligible transport when there is actually substantial bed transport because of the tributary input.

B.2 Storm Events and Sediment Pulses

The impact of major disturbance events, such as hurricanes and tropical storms, on habitat and ecosystem services[18] cannot be generalized. There is no doubt that the initial effect of sediment transport (removal and/or burial of organisms and habitat) by extreme flows and elevated sediment supplies can be great. However, the resilience of aquatic biota (fauna and flora) to recover from these natural events is also great. Thus, to evaluate the impact of sediment pulses from the Susquehanna River to Chesapeake Bay, it is relevant to consider how estuarine ecosystems initially respond to extreme episodic storm events as well as recover from them.

The ecological impact of Tropical Storm Agnes (Agnes) on Chesapeake Bay, a storm with a recurrence interval greater about 500 years was due to many factors of which sedimentation is just one. To assess potential consequences to Chesapeake Bay by extreme reservoir scouring during a major storm, one should review the documented sedimentological impact of Susquehanna River discharge to the Bay during Agnes and other large storm events (see Section 3.3.2). Additionally, such an assessment must also be made within the context of relative sea level rise and the ability to forecast the ecological effects of extreme events.

B.2.1 Estuarine Ecosystem Response: Initial Impacts and Recovery

The type and severity of the ecological damage from hurricanes is a function of unique combinations of a variety of factors, such as storm category, landfall location, trajectory after landfall, rainfall, land use (Mallin and Corbett 2006). The properties of hurricanes and tropical storms that have affected Chesapeake Bay are quite variable (Table B.2.1-1). As such, it would be expected that storm-related impacts and ecological recovery would also be varied.

The most direct and observable impacts of sediment pulses to Chesapeake Bay are increases in water column turbidity and sedimentation. The Chesapeake Bay Program Scientific and Technical Advisory Committee reported on the impact of Susquehanna River sediment to Chesapeake Bay (STAC 2000). This report highlights the susceptibility of SAV and benthic organisms to sediment influx. Impacts to SAV growth are due to light attenuation and sediment adhering to leaf surfaces. Sediment-associated increases in nutrients also promote the growth of epiphytes and phytoplankton which may also attenuate light. Impacts vary with species due to differences in leaf architecture. For example, low salinity species with spreading canopies are affected more by sediment adherence than high salinity species with narrow strap-like leaves. Timing of sediment input also influences ecological response. During colder months

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[18] Daily et al (1997) use the term 'ecosystem services' to refer to a wide range of conditions and processes through which natural ecosystems, and the species that are part of them, help sustain and fulfill human life.

there will be little impact of sediment on SAV. This is because freshwater and low salinity species have no standing crop and high salinity species have reduced light requirements due to low metabolic rates. Benthic invertebrates expend energy burrowing out of freshly deposited sediment or filtering suspended sediment, their recruitment can be impaired, and mortality rates increase with increasing depths of burial.

There is no doubt that the extreme event of Tropical Storm Agnes devastated the SAV populations of Chesapeake Bay. Aquatic biologists have observed, however, that the recovery of Bay SAV communities from Agnes has been much slower than recoveries from extensive damages suffered from other large storm events (e.g., 1933 (August), Hurricane Hazel (October 1954), Tropical Storms Connie and Diane (August 1955)) which recovered in 2 to 3 years (Bayley et al 1978; Stevenson and Confer 1978; Stevenson et al 1979; Orth and Moore 1982; Kemp et al 1983). The slower recovery after Agnes has been attributed, in part, to the overprint of declining water quality by human-induced actions rather than to an inability to recover from the events (Bayley et al 1978; Stevenson and Confer 1978; Stevenson et al 1979).

Declines in diversity and density of SAV, and fluctuations in species composition, are documented in upper Chesapeake Bay, including Susquehanna Flats, from the late 1950s to the mid-1980s (Bayley et al 1978; Stevenson and Confer 1978; Orth and Moore 1982; Kemp et al 1983) (Figure B.2.1-1). Within the context of an overall decline in Bay SAV from the mid-60s to 1983, punctuated by Agnes, Kemp et al (1983) examined potential reasons for the decline bay-wide and at Susquehanna Flats. They concluded nutrient enrichment and turbidity are the key factors while storm events may have accelerated the existing record of decline and played more of a secondary role. Management of SAV resources was viewed from the standpoint of relative importance and controllability. That is, reducing suspended sediment input to the Bay from runoff is something controllable and should be continued. The logic in that is substantiated by the rapid increase in SAV at Susquehanna Flats since the late 1990s (Orth et al 2010). Total bed area more than doubled 1984 to 2006 and there is a highly negative correlation of SAV abundance with nitrogen loads and light availability (as measured by Secchi depths and total suspended solids). Nutrient reduction is viewed as the priority strategy for SAV.

Large localized impacts of storm events may not be a strong factor in bay-wide or region-wide SAV patterns (Orth et al 2010). For example, Hurricane Isabel (September 2003) locally affected SAV directly exposed to winds in the lower Bay, but was not identified as a strong driver in the overall SAV abundance of the Bay.

Timing is also a very important factor on the effect of extreme storm events on SAV in Chesapeake Bay (Wang and Linker 2005). The Chesapeake Bay Estuarine Water Quality Model was used to compare simulations of 100-year storm events occurring in different seasons - spring, summer, and autumn. The study found that the severity of extreme-storm damage to SAV from sediment and nutrient loading depends on storm timing relative to the growing season. Significant damage was found to occur in months of high SAV shoot biomass, but there is no significant damage if the storm occurs in the winter or other times outside the growing season. Included in the model simulations was Hurricane Juan (November 1985). Wang and Linker (2005) note that their model results are consistent with observations that the January 1996 storm had little effect on SAV beyond the event itself, while, in comparison, Tropical Storm Agnes (June 1972) had a great impact.

The critical factor influencing the ability of benthic organisms to survive sedimentation events is sediment overburden stress (Nichols et al 1978; Hinchey et al 2006). This metric relates burial thickness and sediment bulk density. It is considered a better measure of the force exerted by burial than depth alone and incorporates two sediment properties that influence ease of movement for organisms - void ratio and compaction. Laboratory and field studies indicate the response of estuarine benthos to normal and extreme sediment burial events is variable.

Laboratory experiments conducted on infaunal and epifaunal estuarine species indicate variable responses to sediment overburden stress as a function of life position, motility, and tolerance to anoxic conditions (Hinchey et al 2006). Some species exhibited adaptations that may allow them to survive deposition events of the magnitude common in estuaries.

Benthos response to sediment pulses is variable. Sediment cores in upper Chesapeake Bay indicate the sediment pulse layer from Agnes consisted of silts and clays with minor fine sand (see next sub-section below). Field and laboratory experiments of benthic invertebrate responses to burial by silt/clay mixtures indicate that impacts vary as a function of time of burial, depth of burial, type of sediment, temperature and species (Nichols et al 1978; Maurer et al 1986). *In situ* experiments in the Buzzards Bay, Massachusetts estuary suggest there is a critical value of overburden stress above which organisms cannot initiate vertical escape (Nichols et al 1978). In laboratory experiments, Maurer et al (1986) found that responses to 36 to 40 cm of sediment burial were species-specific. The degree of vertical migration and mortality of test organisms showed reversed trends in sandy and silt-clay sediments.

Studies conducted to assess impacts of pulses of sedimentation from the discharge of dredged material on estuarine benthic communities provide insight to behavior after storm-event burial. Schaffner (2010) evaluated community-level responses of soft sediment macrobenthos to two large-scale dredged material disposal disturbance events in lower Chesapeake Bay. Community metrics included species richness, abundance, biomass, and community composition. Reference stations represented regional ambient communities. Minimal effects were discerned with disposal sediment thicknesses ≤ 15 cm. Following the cessation of disposal it took 1.5 years or less for the community metrics to reach reference station levels for disposal thicknesses greater than 15 cm.

B.2.2 Extreme Events and Ecological Forecasting

In an attempt to systematically evaluate the hurricane/tropical storm impacts to Chesapeake Bay, Stevenson and Kearney (2005) developed a classification system that considers three main forcing functions for estuarine impacts – precipitation, wind speed, and storm surge. Precipitation potentially leads to massive runoff in the upper reaches of an estuary; winds generate waves that cause subtidal and shoreline erosion and disrupt estuarine circulation; and storm surge may introduce oceanic organisms, erode marsh edges, and introduce saline waters to non-saline uplands. Twenty-seven different combinations of driver impacts were identified to have affected Chesapeake Bay in the 20th century. Hurricane type clearly influences local ecological response. Additionally, rising sea level is identified as a condition that will affect future impacts of large storms in Chesapeake Bay (see next sub-section)

The ability to forecast the impacts of extreme ecological stress can be a highly valuable tool for resource managers but is very difficult to accurately achieve (Litaker and Tester 2003; Valette-Silver and Scavia 2003). The difficulty in predicting and/or preventing ecological consequences of a future Agnes-type storm is highlighted by the multiple permutations of process and response variables discussed in this Section.

B.2.3 Impact of Sea Level Rise to Chesapeake Bay

The inclusion of global climate change, the concomitant rise in relative sea level, and increased frequency of major storms in Chesapeake Bay as part of future management strategies has been the focus of numerous watershed and state-specific syntheses and assessments. These reports include: *Climate Change and the Chesapeake Bay* (Pyke et al 2008); *A Sustainable Chesapeake: Better Models for Conservation* (Burke and Dunn 2010); and *Global Warming and the Free State: Comprehensive Assessment of Climate Change Impacts in Maryland* (Boesch 2008).

Changes in sea level are due to global changes in the absolute level of the sea (from changes in the shape of ocean basins or the volume of ocean water) and localized changes in land elevation (from subsidence or uplift). The sea level observed at a location is a combination of both mechanisms and is called "relative" sea level. Relative sea level along the mid-Atlantic coast is rising at present and is expected to continue to rise, perhaps at accelerated rates, with future climatic change and global warming. Sediment input from storm events is an important mechanism by which Chesapeake Bay wetlands will be sustained with the prospect of relative sea level rise (RSLR).

For coastal wetlands not to be drowned by RSLR, they must keep pace with it; that is, the wetlands must maintain their intertidal position by vertical accretion at a rate equal to the rise in sea level or by migrating inland (Scavia et al 2002; Wood et al 2002; Cahoon et al 2009). Vertical accretion is a combination of in place accumulation of organic material (peat) by primary productivity and inorganic mineral sediment. Inorganic and organic sediment supply is particularly important for areas where landward migration is limited by steep slopes, coastal development, and shore protection measures such as berms, levees, and bulkheads. If a wetland cannot keep pace with RSLR, it will gradually become submerged and eventually convert to a mudflat or open water.

RSLR has already contributed to the loss of Chesapeake Bay wetlands at the Blackwater National Wildlife Refuge in Maryland (over 50 percent during the 20th century) and elsewhere in the Bay (Stevenson et al 2000). A problem identified at Blackwater is the net loss of sediment by tides; it is possibly only during hurricane events that sediments are deposited during tidal inundation. In the long-term, intertidal wetlands in the upper Bay and tributaries, with high sediment loads, will fair better than those in the lower Bay where large areas are deteriorating due to insufficient sediment supply (Wood et al 2002). Net vertical accretion varies across geomorphic settings (Reed et al 2008; Cahoon et al 2009). Primary environmental drivers influencing accretion are sediment supply from storms and sediment supply from river flow under non-storm conditions.

SLAMM Version 5.0 (Sea Level Affecting Marshes Model) was applied by The National Wildlife Federation to simulate tidal marsh area and habitat responses to sea level rise in Chesapeake Bay (Glick et al 2008). Survival of many of the marshes in the Susquehanna River/Northern Chesapeake Bay area under certain scenarios is attributable to significant influx of sediment from the Susquehanna River enabling them to keep pace with sea level rise.

The USEPA conducted a study to assess the degree to which wetlands in Chesapeake Bay can keep pace with RSLR under three scenarios – current rates (approximately 3 millimeters (mm) per year); 5 mm per year, and 10 mm per year (Boesch 2008; Reed 2008; Calhoon et al 2009) (Figure B.2.3-1). The tidal freshwater marshes at the Susquehanna River mouth and nearest to Susquehanna Flats are predicted to keep pace with RSLR under each scenario. However, the tidal freshwater marshes along smaller streams with less of a sediment load opposite the Susquehanna River (Northeast, Elk, and Sassafras Rivers) and the brackish marshes along bay margins below the Susquehanna River are predicted to keep pace under current rates, but are marginal (maintained under optimal conditions) or potentially lost under the accelerated rates.

APPENDIX C - UDDEN WENTWORTH GRAIN SIZE CLASSIFICATION

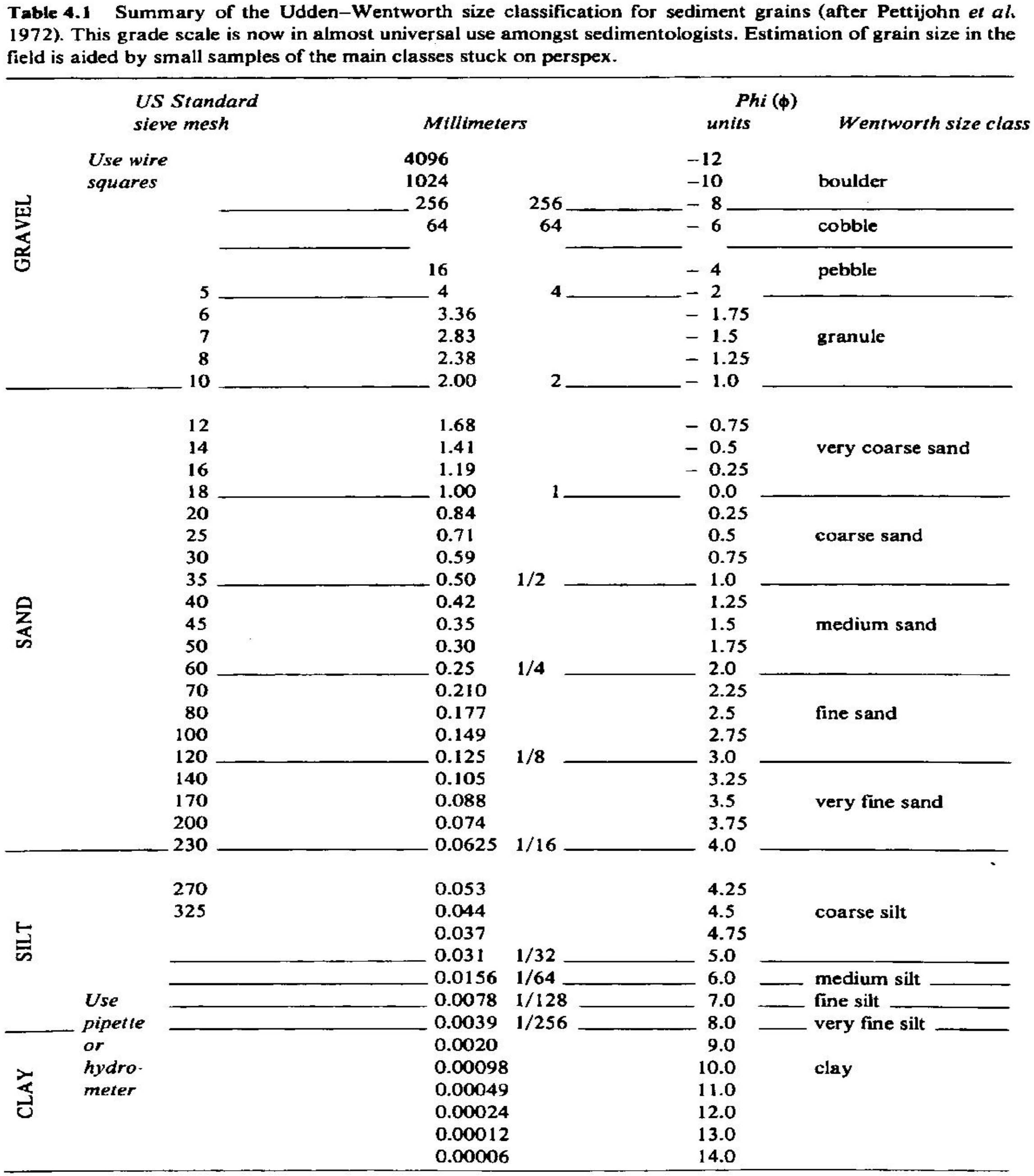
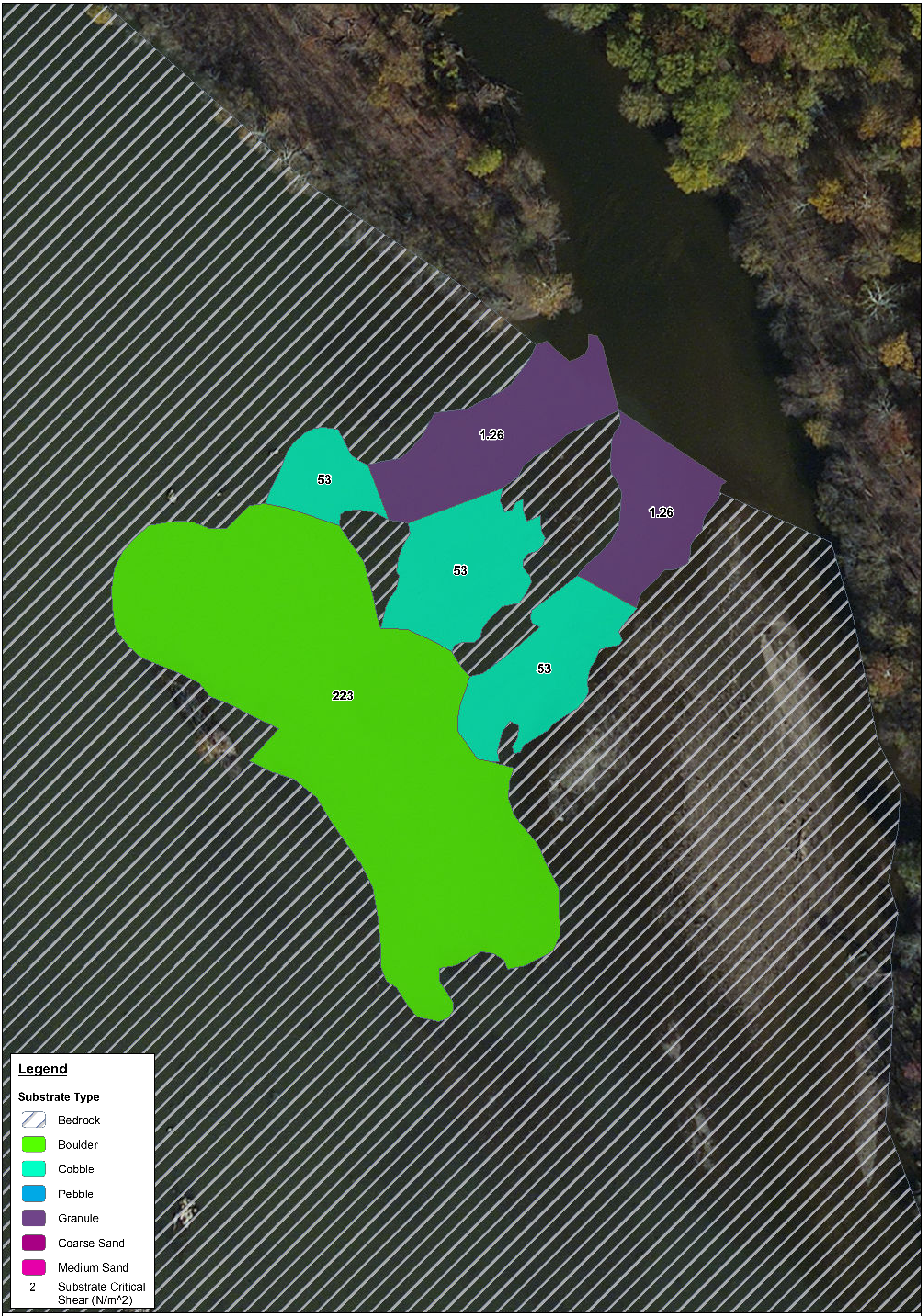


Table 4.1 Summary of the Udden–Wentworth size classification for sediment grains (after Pettijohn *et al.* 1972). This grade scale is now in almost universal use amongst sedimentologists. Estimation of grain size in the field is aided by small samples of the main classes stuck on perspex.

	US Standard sieve mesh	*Millimeters*		*Phi (ϕ) units*	*Wentworth size class*
GRAVEL	*Use wire squares*	4096		−12	
		1024		−10	boulder
		256	256	−8	
		64	64	−6	cobble
		16		−4	pebble
	5	4	4	−2	
	6	3.36		−1.75	
	7	2.83		−1.5	granule
	8	2.38		−1.25	
	10	2.00	2	−1.0	
SAND	12	1.68		−0.75	
	14	1.41		−0.5	very coarse sand
	16	1.19		−0.25	
	18	1.00	1	0.0	
	20	0.84		0.25	
	25	0.71		0.5	coarse sand
	30	0.59		0.75	
	35	0.50	1/2	1.0	
	40	0.42		1.25	
	45	0.35		1.5	medium sand
	50	0.30		1.75	
	60	0.25	1/4	2.0	
	70	0.210		2.25	
	80	0.177		2.5	fine sand
	100	0.149		2.75	
	120	0.125	1/8	3.0	
	140	0.105		3.25	
	170	0.088		3.5	very fine sand
	200	0.074		3.75	
	230	0.0625	1/16	4.0	
SILT	270	0.053		4.25	
	325	0.044		4.5	coarse silt
		0.037		4.75	
		0.031	1/32	5.0	
		0.0156	1/64	6.0	medium silt
	Use pipette or hydrometer	0.0078	1/128	7.0	fine silt
		0.0039	1/256	8.0	very fine silt
CLAY		0.0020		9.0	
		0.00098		10.0	clay
		0.00049		11.0	
		0.00024		12.0	
		0.00012		13.0	
		0.00006		14.0	

From Leeder, M.R. 1982. Sedimentology: Process and Products.

APPENDIX D - DOWNSTREAM SUBSTRATES, VEGETATION AND SHEAR STRESS



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N

0 50 100 200 Feet

Shear Stress Key Areas
Substrate Map
Key Area 1

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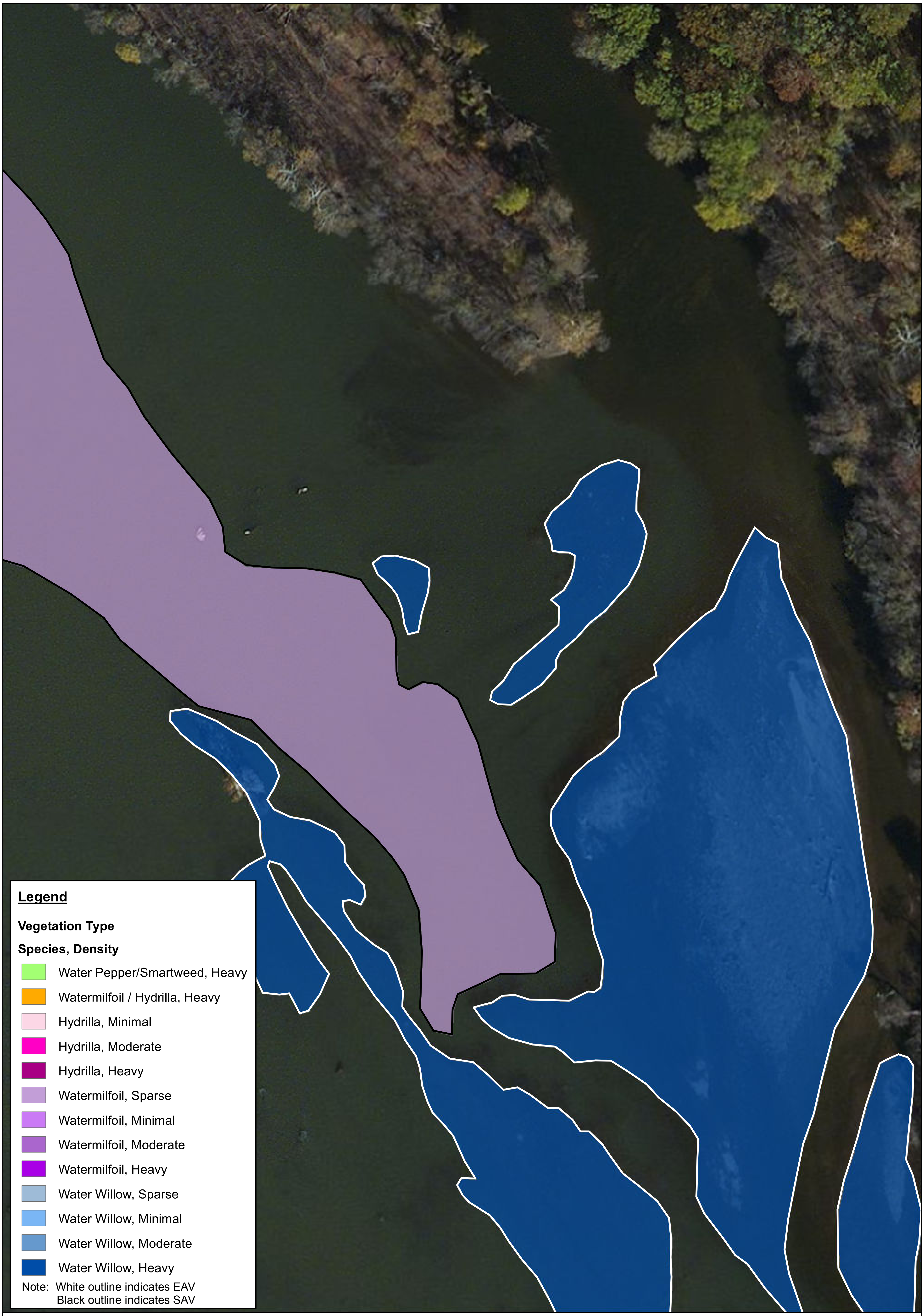

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Shear Stress Key Areas
Vegetation Map
Key Area 1

Source: Bing Maps™ Imagery
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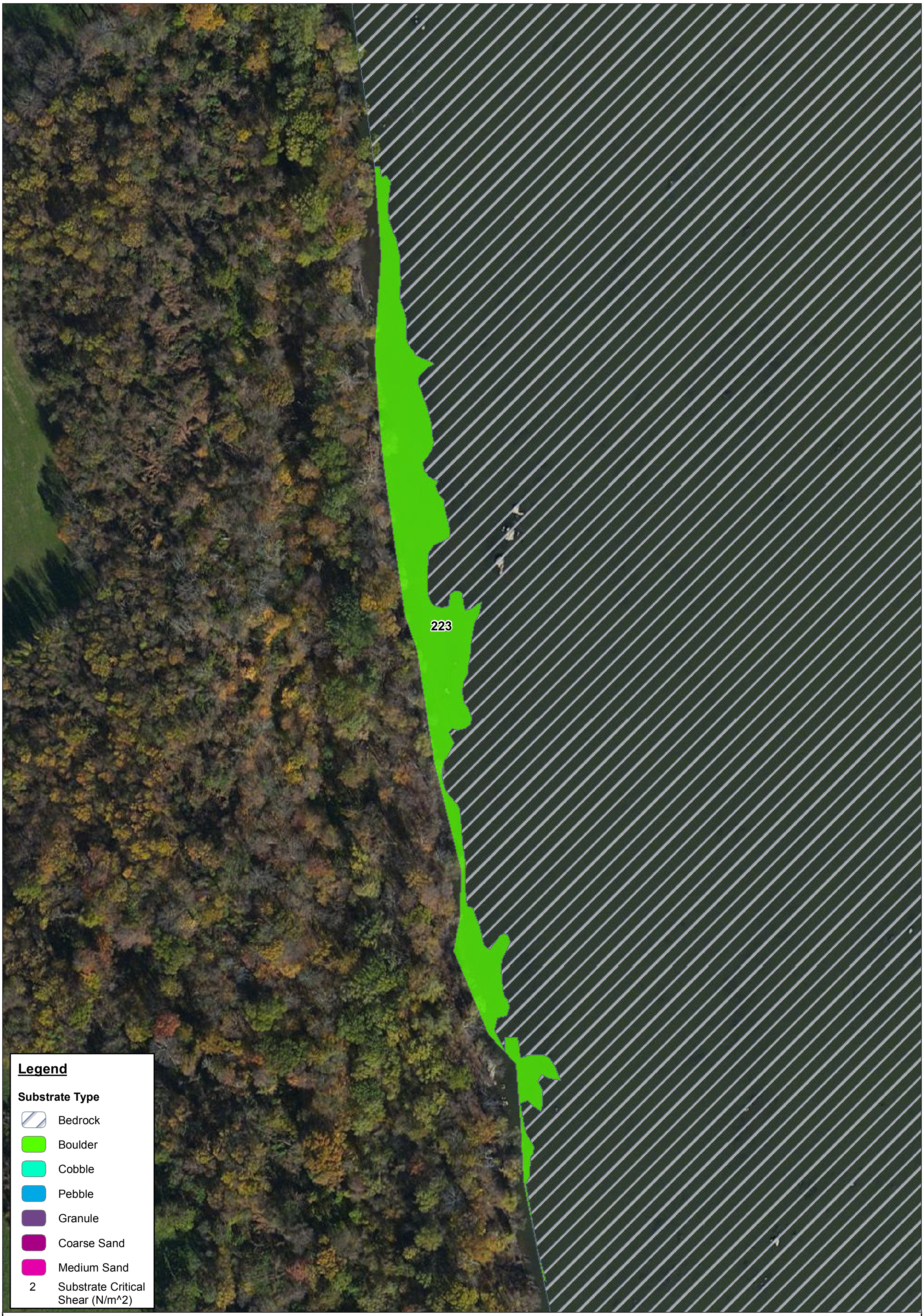

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Shear Stress Key Areas
Substrate Map
Key Area 2

Source: Bing Maps™ Imagery
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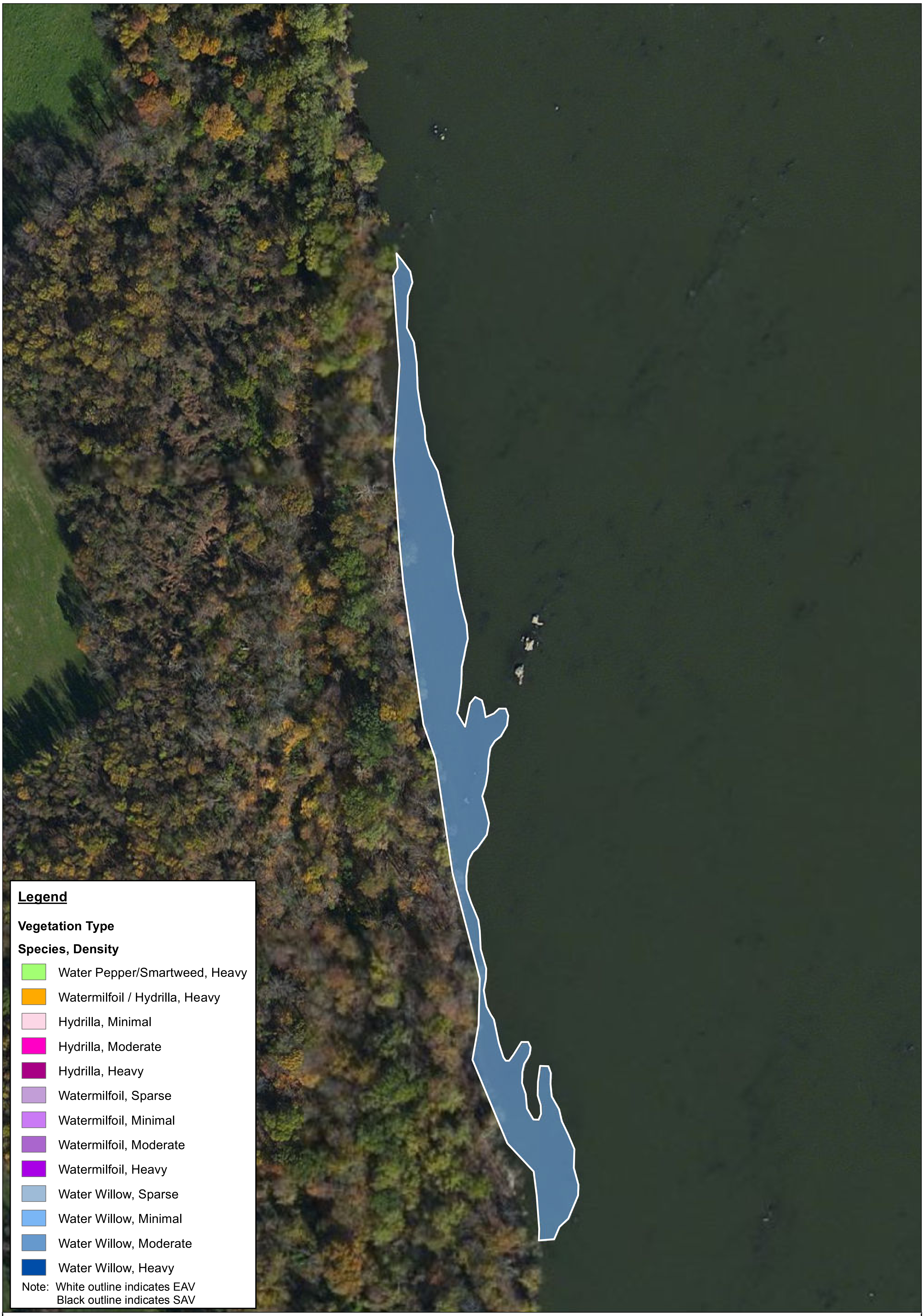

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Shear Stress Key Areas
Vegetation Map
Key Area 2

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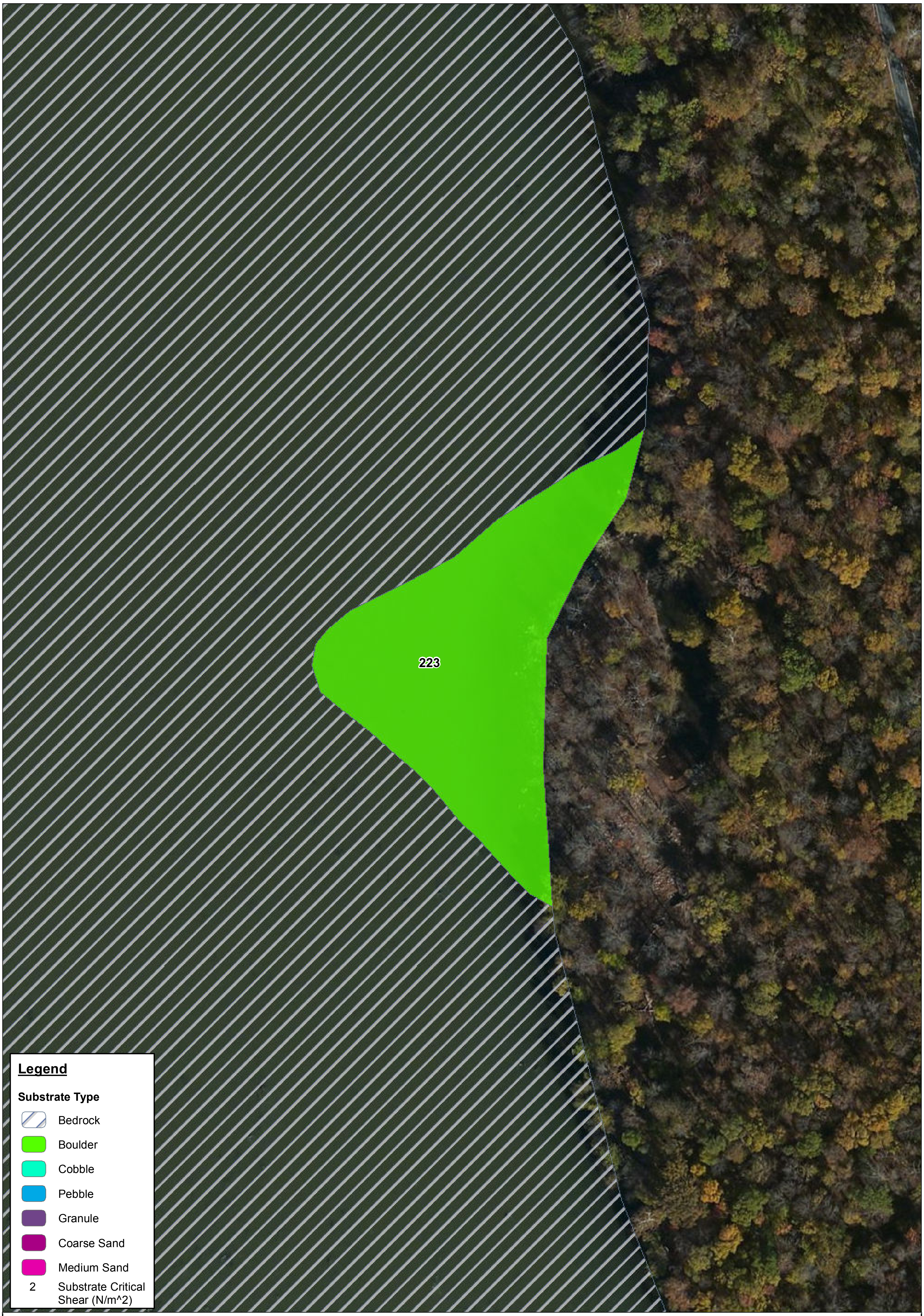

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Feet

Shear Stress Key Areas
Substrate Map
Key Area 3

Source: Bing Maps™ Imagery
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Legend

Vegetation Type

Species, Density

- 🟩 Water Pepper/Smartweed, Heavy
- 🟧 Watermilfoil / Hydrilla, Heavy
- ▨ Hydrilla, Minimal
- 🟪 Hydrilla, Moderate
- 🟪 Hydrilla, Heavy
- 🟪 Watermilfoil, Sparse
- 🟪 Watermilfoil, Minimal
- 🟪 Watermilfoil, Moderate
- 🟪 Watermilfoil, Heavy
- 🟦 Water Willow, Sparse
- 🟦 Water Willow, Minimal
- 🟦 Water Willow, Moderate
- 🟦 Water Willow, Heavy

Note: White outline indicates EAV
Black outline indicates SAV

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Shear Stress Key Areas
Vegetation Map
Key Area 3

Source: Bing Maps™ Imagery
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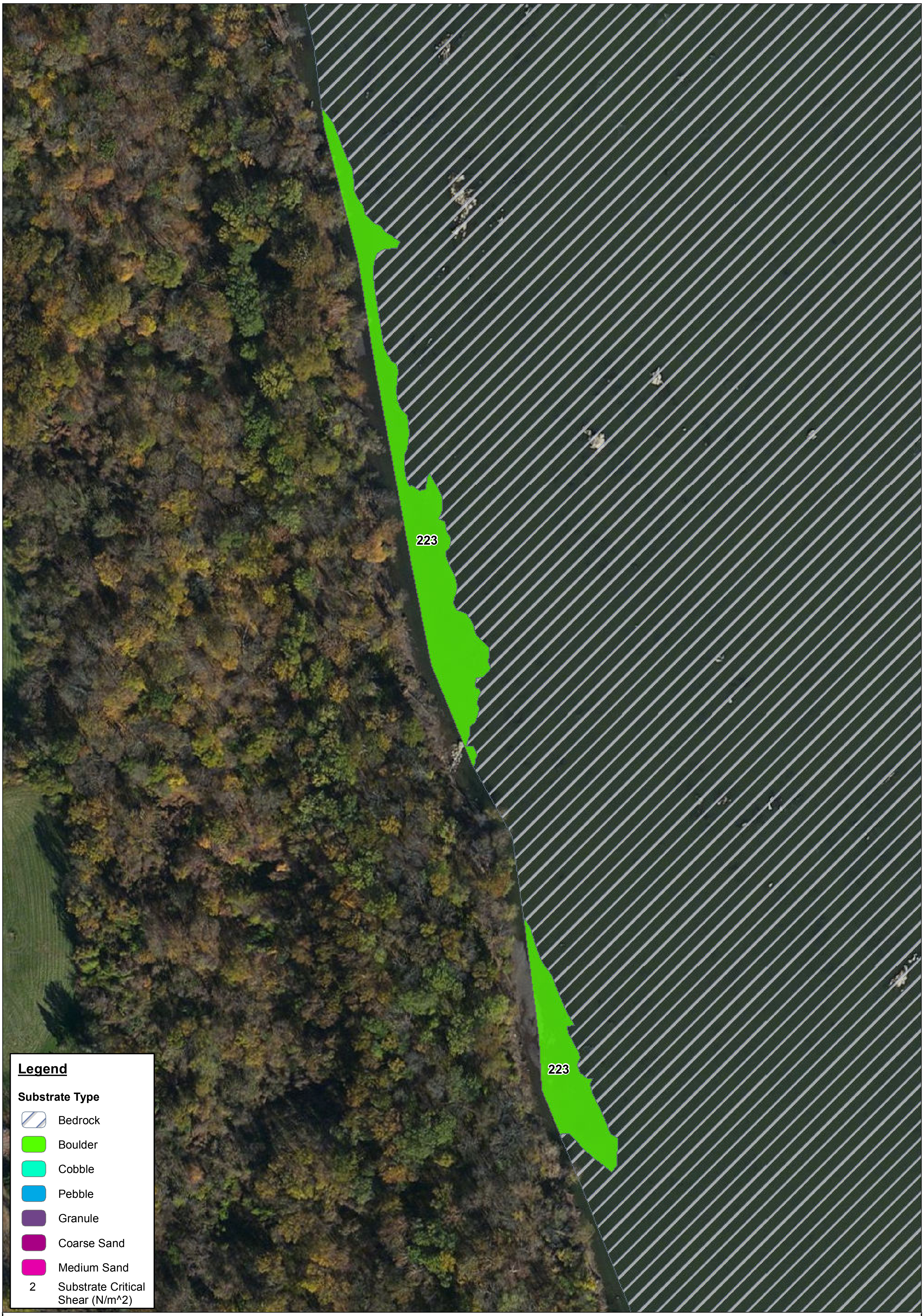

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Shear Stress Key Areas
Substrate Map
Key Area 4

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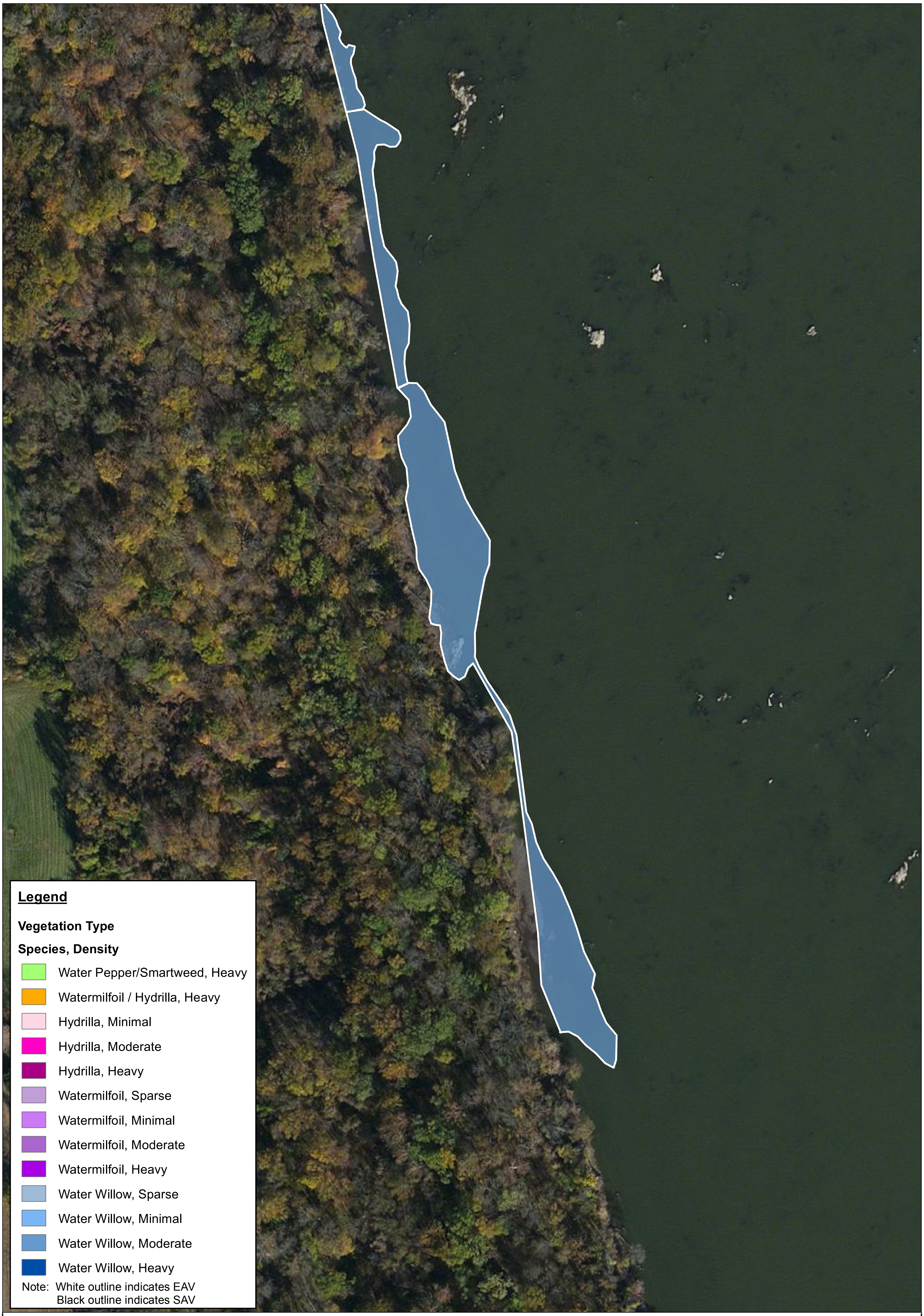

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Vegetation Type

Species, Density

- 🟩 Water Pepper/Smartweed, Heavy
- 🟧 Watermilfoil / Hydrilla, Heavy
- ■ Hydrilla, Minimal
- ■ Hydrilla, Moderate
- ■ Hydrilla, Heavy
- ■ Watermilfoil, Sparse
- ■ Watermilfoil, Minimal
- ■ Watermilfoil, Moderate
- 🟪 Watermilfoil, Heavy
- ■ Water Willow, Sparse
- ■ Water Willow, Minimal
- ■ Water Willow, Moderate
- 🟦 Water Willow, Heavy

Note: White outline indicates EAV
Black outline indicates SAV

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Shear Stress Key Areas
Vegetation Map
Key Area 4

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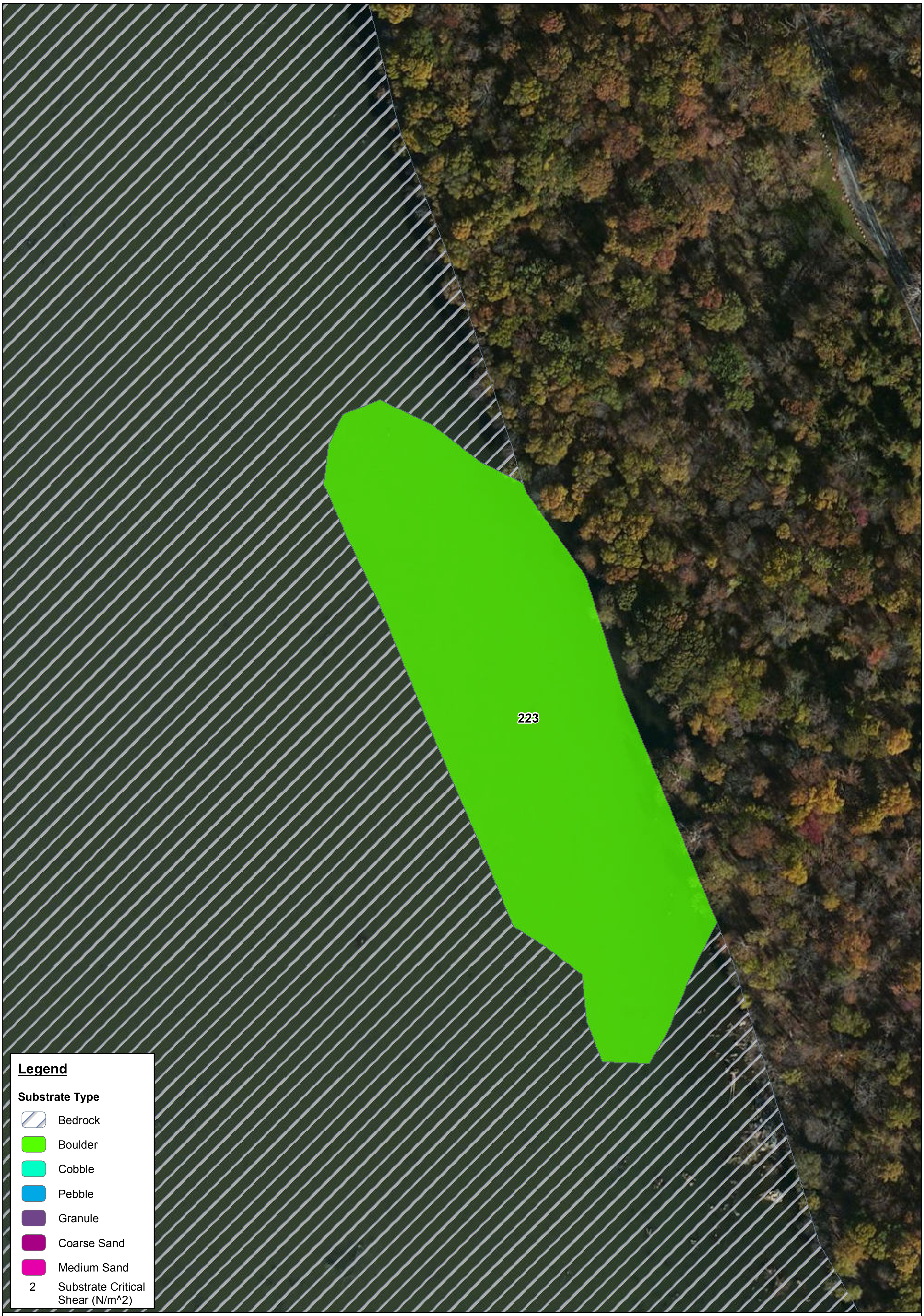

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Shear Stress Key Areas
Substrate Map
Key Area 5

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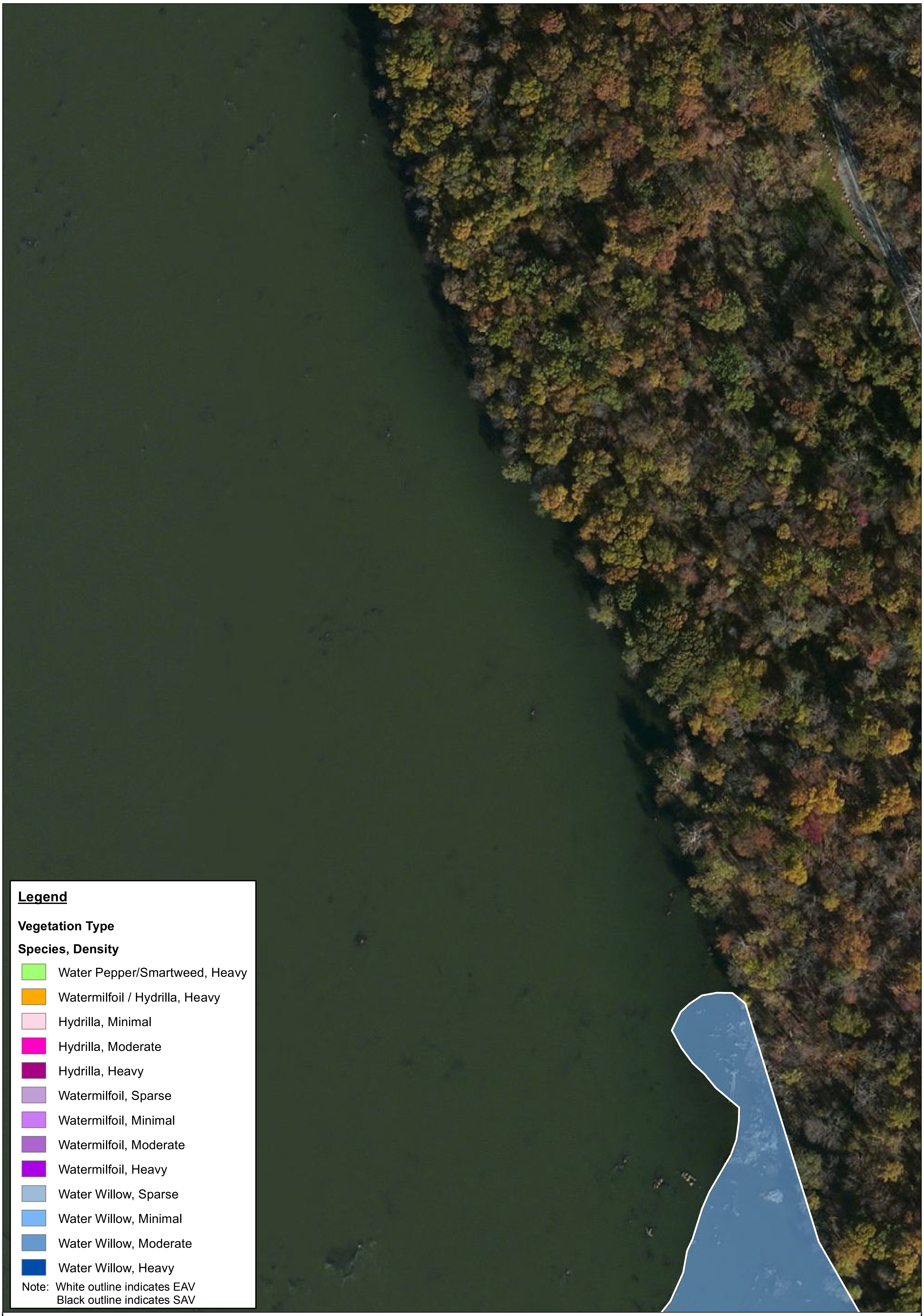

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Shear Stress Key Areas
Vegetation Map
Key Area 5

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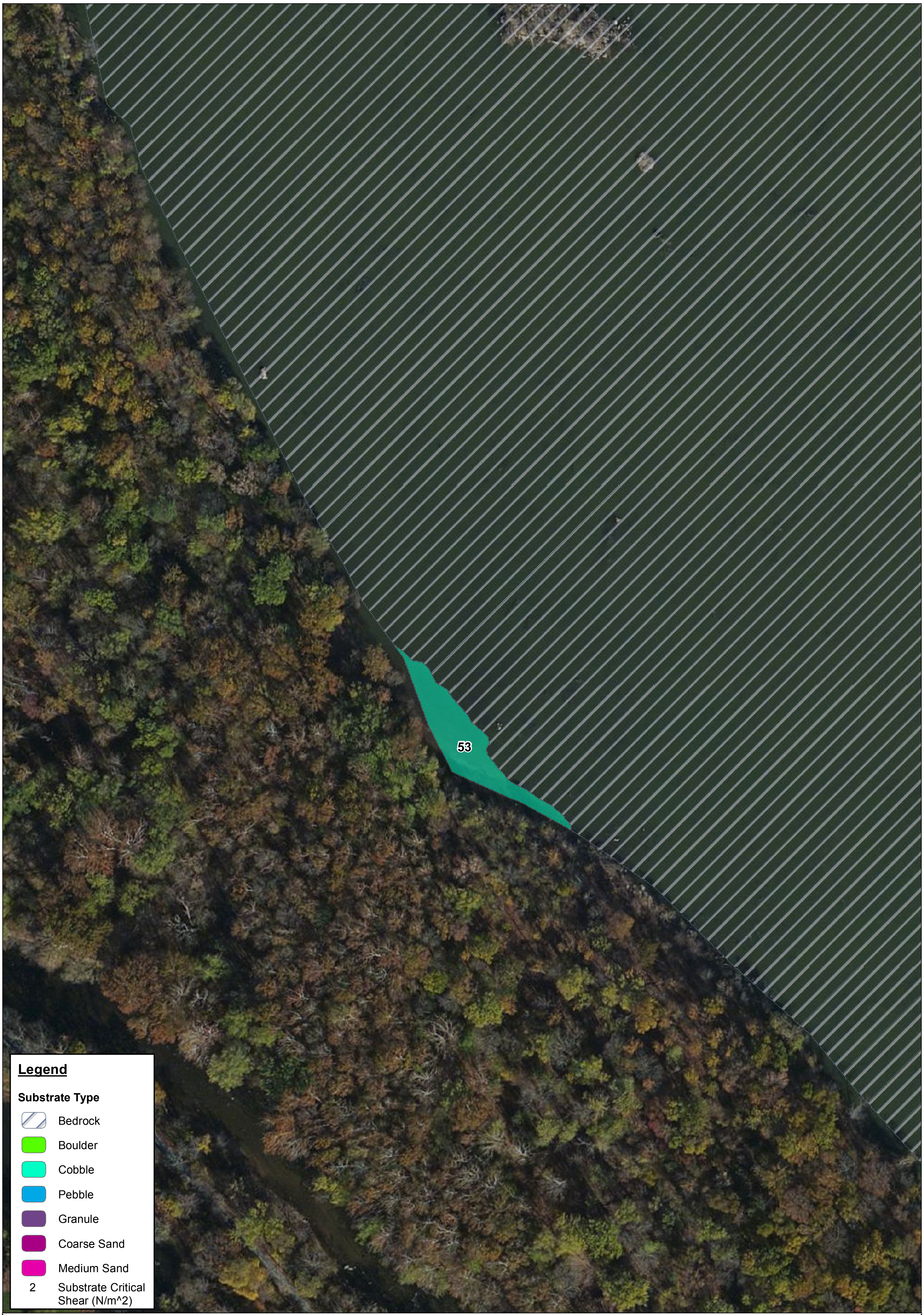

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Shear Stress Key Areas
Substrate Map
Key Area 6

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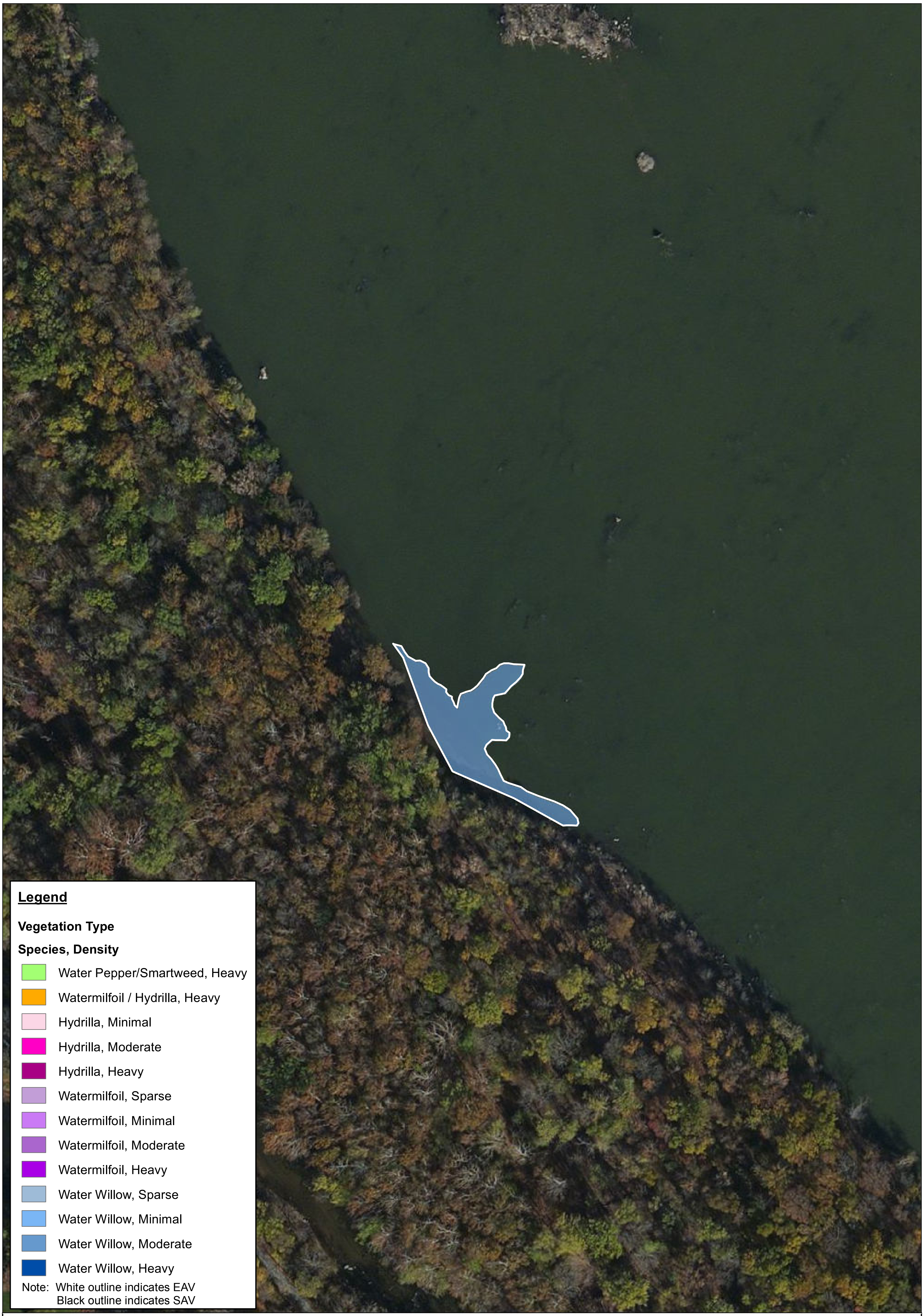

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0 75 150 300
Feet

Shear Stress Key Areas
Vegetation Map
Key Area 6

Source: Bing Maps™ Imagery
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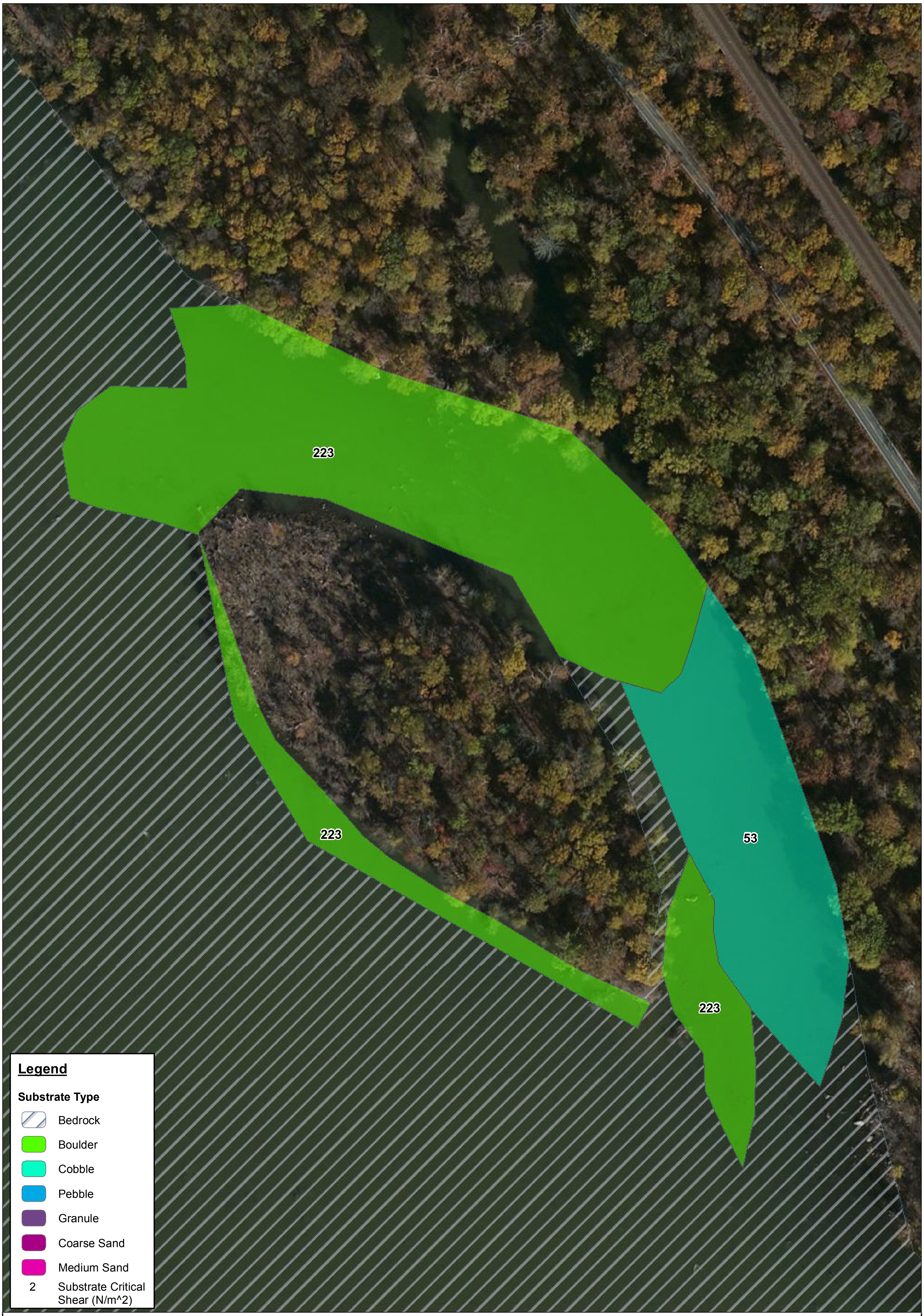

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0 75 150 300 Feet

Shear Stress Key Areas
Substrate Map
Key Area 7

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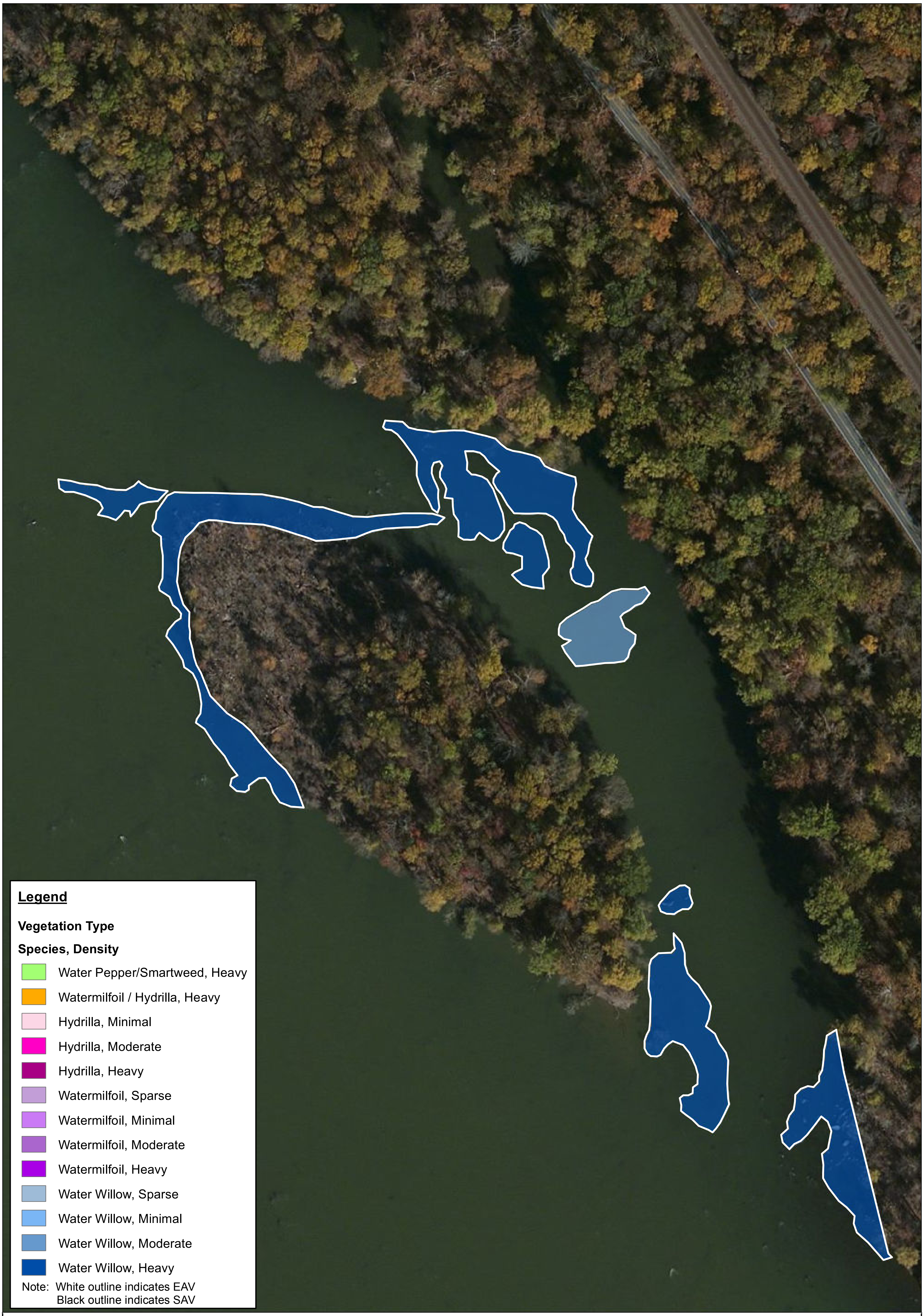

Legend

Vegetation Type

Species, Density

- 🟩 Water Pepper/Smartweed, Heavy
- 🟧 Watermilfoil / Hydrilla, Heavy
- 🟪 Hydrilla, Minimal
- 🟪 Hydrilla, Moderate
- 🟪 Hydrilla, Heavy
- 🟪 Watermilfoil, Sparse
- 🟪 Watermilfoil, Minimal
- 🟪 Watermilfoil, Moderate
- 🟪 Watermilfoil, Heavy
- 🟦 Water Willow, Sparse
- 🟦 Water Willow, Minimal
- 🟦 Water Willow, Moderate
- 🟦 Water Willow, Heavy

Note: White outline indicates EAV
Black outline indicates SAV

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Shear Stress Key Areas
Vegetation Map
Key Area 7

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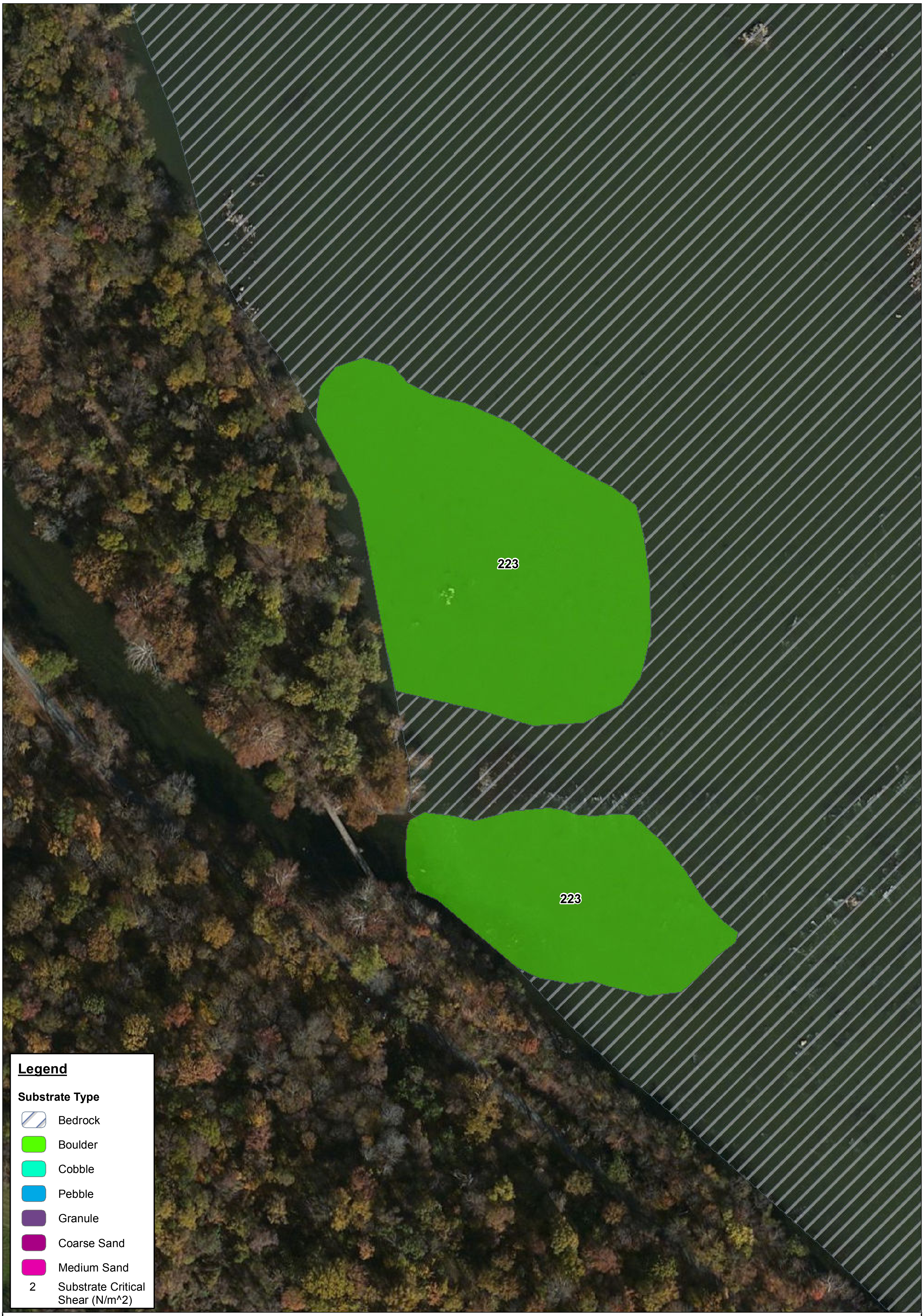

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0 75 150 300 Feet

Shear Stress Key Areas
Substrate Map
Key Area 8

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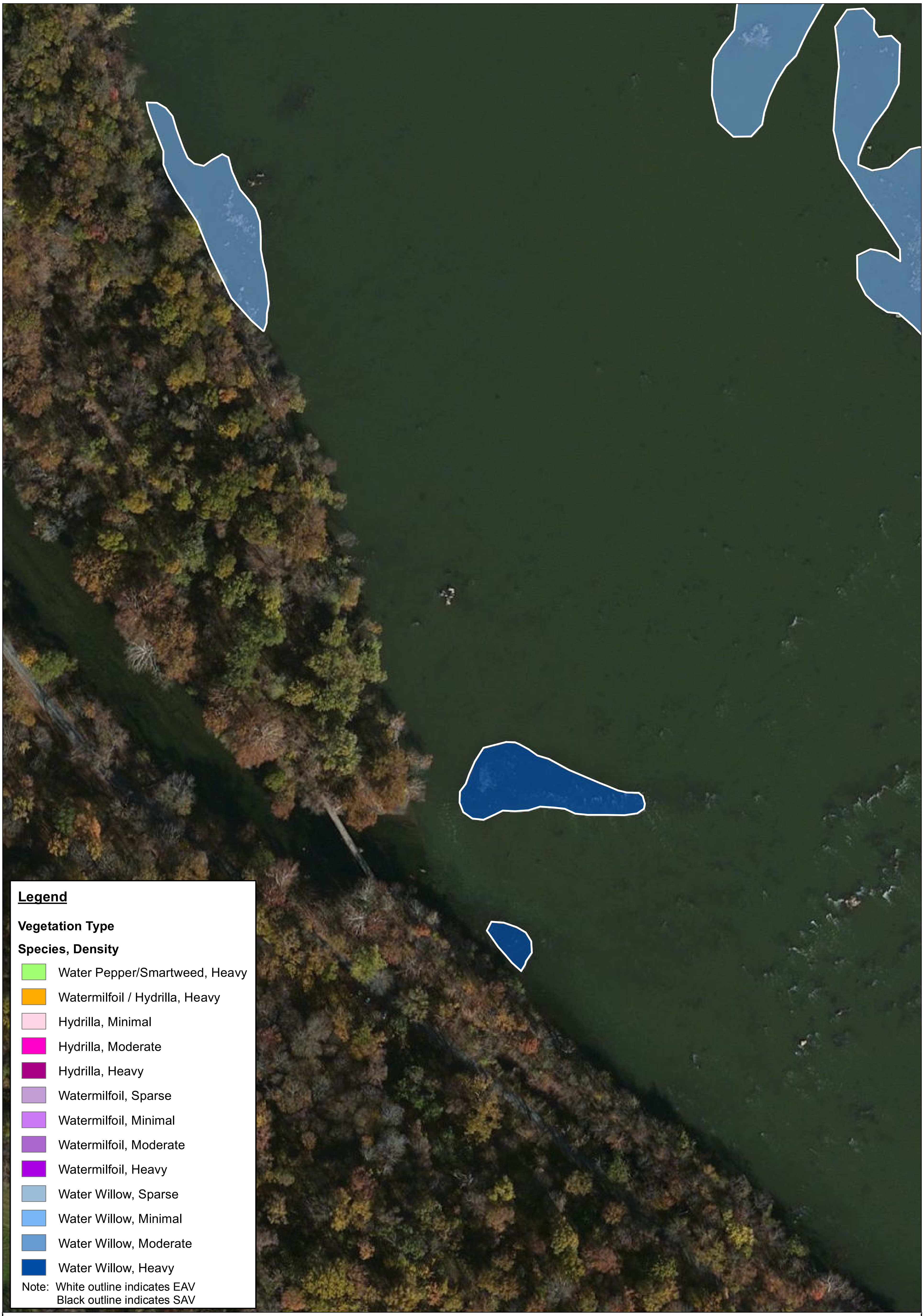

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Shear Stress Key Areas
Vegetation Map
Key Area 8

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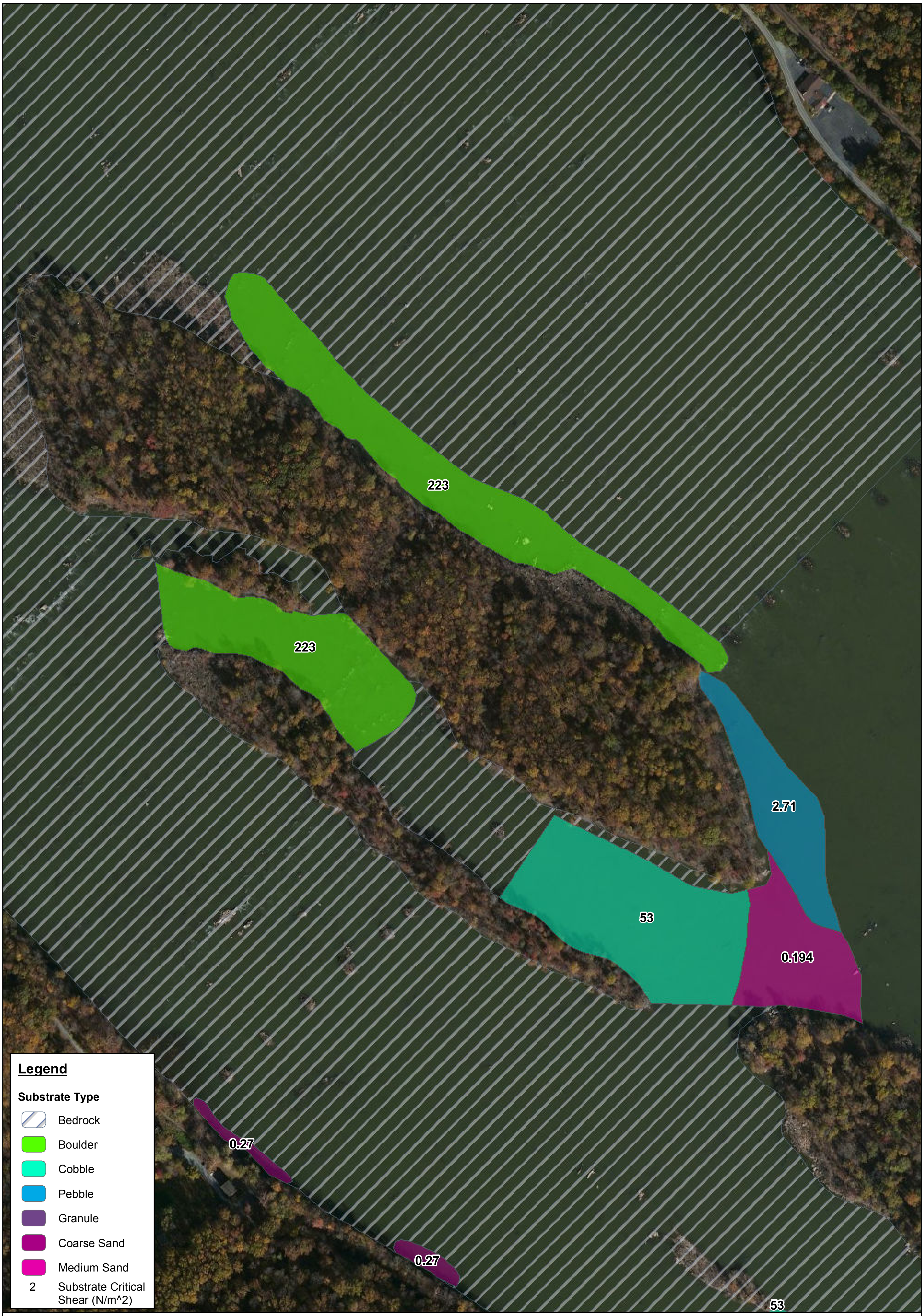

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SEDIMENT INTRODUCTION AND TRANSPORT STUDY (RSP 3.15)
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PROJECT NO. 405
1:4,200

0 175 350 700
Feet

Shear Stress Key Areas
Substrate Map
Key Area 9

Source: Bing Maps™ Imagery
URS Custom Data

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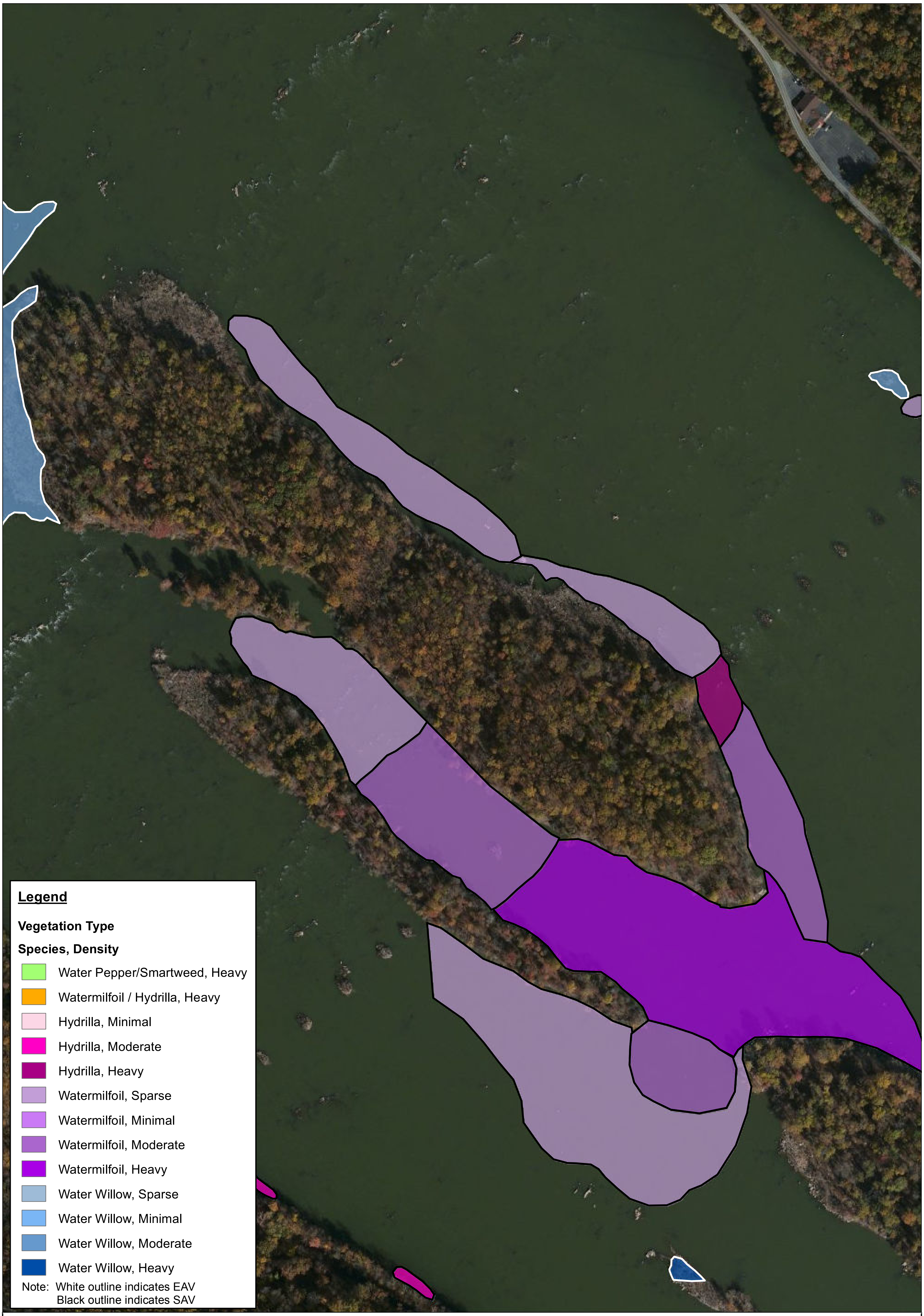

EXELON GENERATION COMPANY, LLC

SEDIMENT INTRODUCTION AND TRANSPORT STUDY (RSP 3.15)
CONOWINGO HYDROELECTRIC PROJECT
PROJECT NO. 405
1:4,200

0 175 350 700
Feet

N

Shear Stress Key Areas
Vegetation Map
Key Area 9

Source: Bing Maps™ Imagery
URS Custom Data

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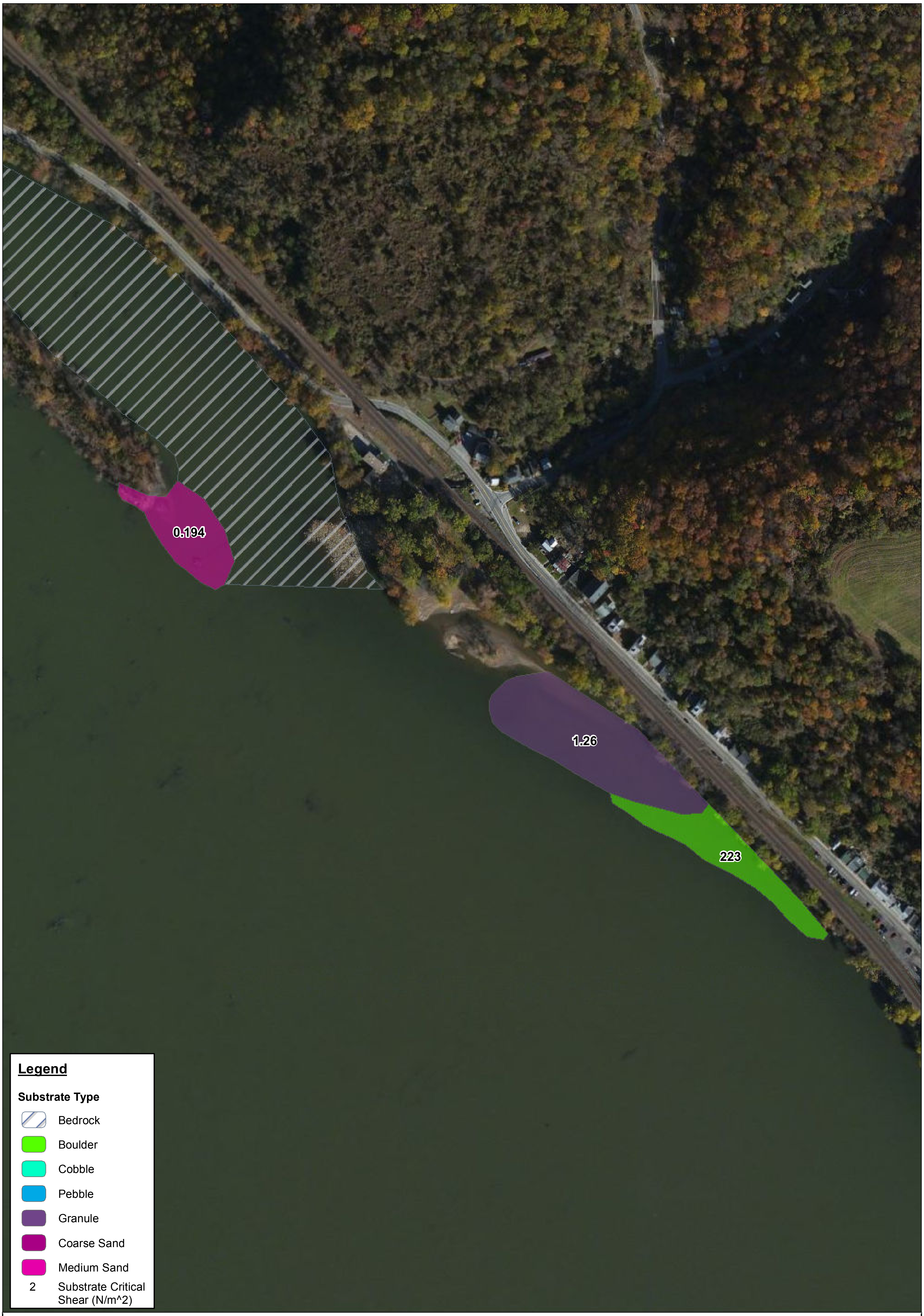

Exelon.

EXELON GENERATION COMPANY, LLC

SEDIMENT INTRODUCTION AND TRANSPORT STUDY (RSP 3.15)
CONOWINGO HYDROELECTRIC PROJECT
PROJECT NO. 405
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N

0 125 250 500 Feet

Shear Stress Key Areas
Substrate Map
Key Area 10

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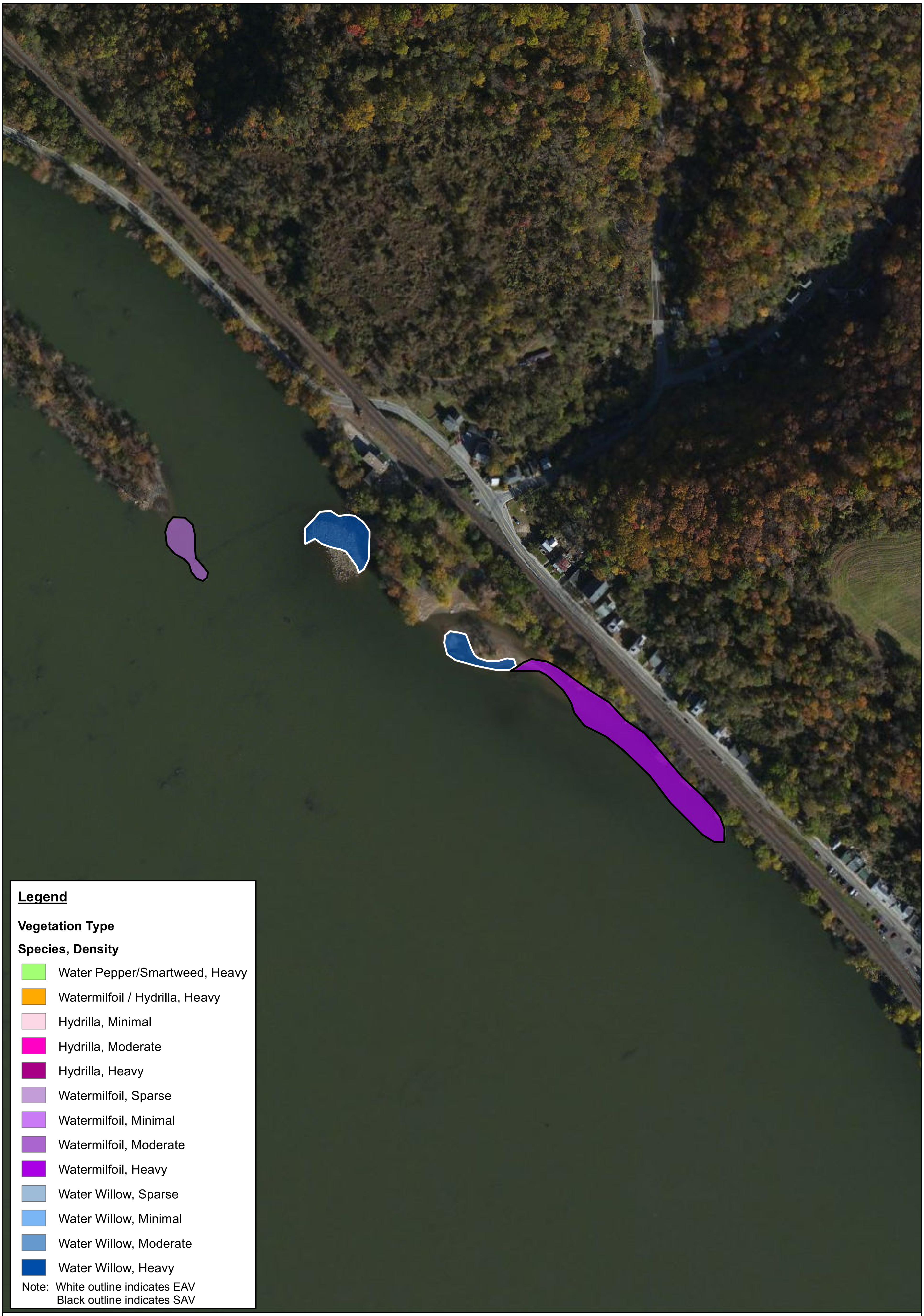

EXELON GENERATION COMPANY, LLC

SEDIMENT INTRODUCTION AND TRANSPORT STUDY (RSP 3.15)
CONOWINGO HYDROELECTRIC PROJECT
PROJECT NO. 405
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N

0 125 250 500 Feet

Shear Stress Key Areas
Vegetation Map
Key Area 10

Source: Bing Maps™ Imagery
URS Custom Data

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EXELON GENERATION COMPANY, LLC

Exelon.

SEDIMENT INTRODUCTION AND TRANSPORT STUDY (RSP 3.15)
CONOWINGO HYDROELECTRIC PROJECT
PROJECT NO. 405
1:1,800

Shear Stress Key Areas
Substrate Map
Key Area 11

N

0 125 250 500 Feet

Source: Bing Maps™ Imagery
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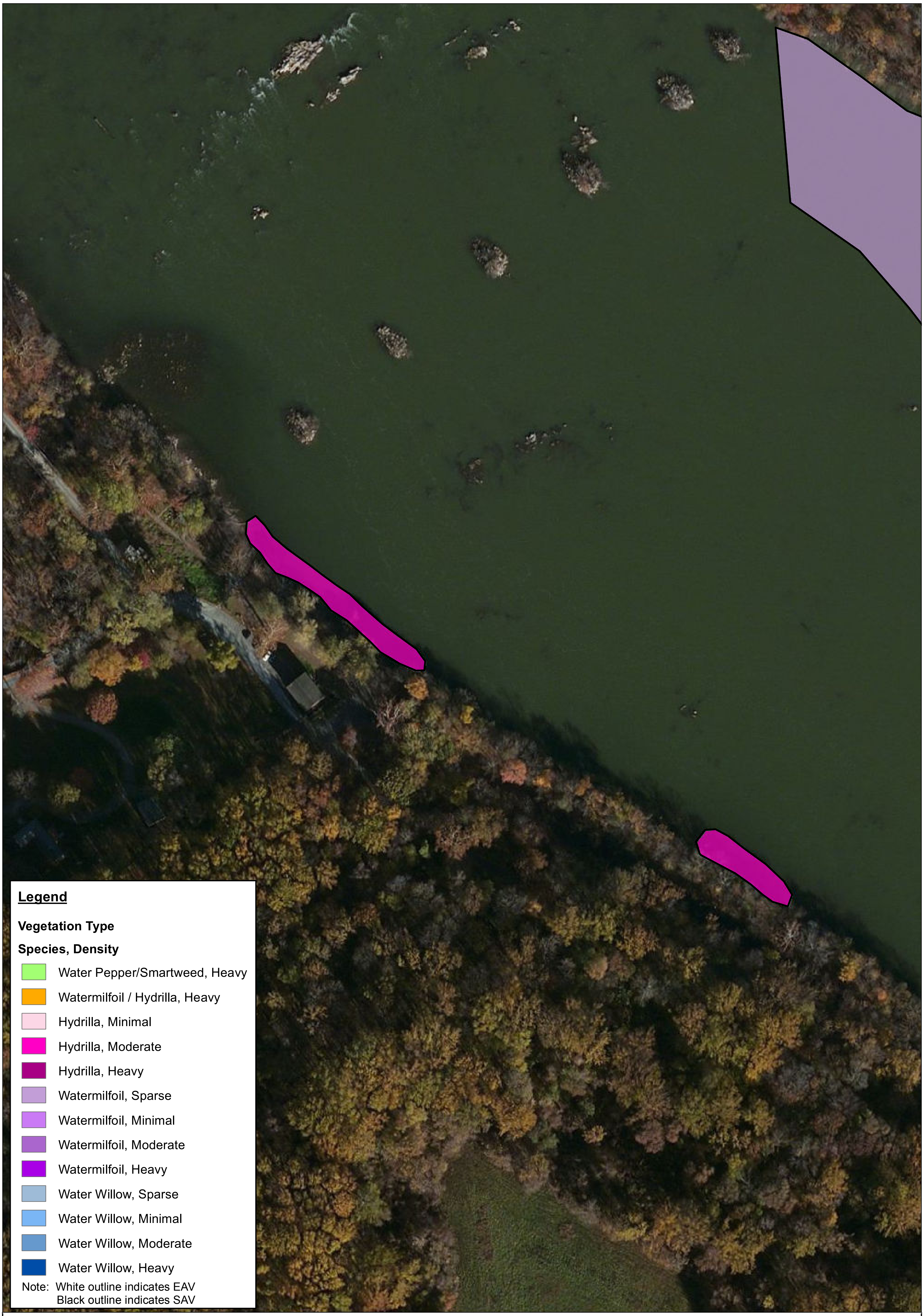

EXELON GENERATION COMPANY, LLC

Exelon.

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SEDIMENT INTRODUCTION AND TRANSPORT STUDY (RSP 3.15)
CONOWINGO HYDROELECTRIC PROJECT
PROJECT NO. 405
1:1,800

Shear Stress Key Areas
Vegetation Map
Key Area 11

0 **175** **350** **700** **Feet**

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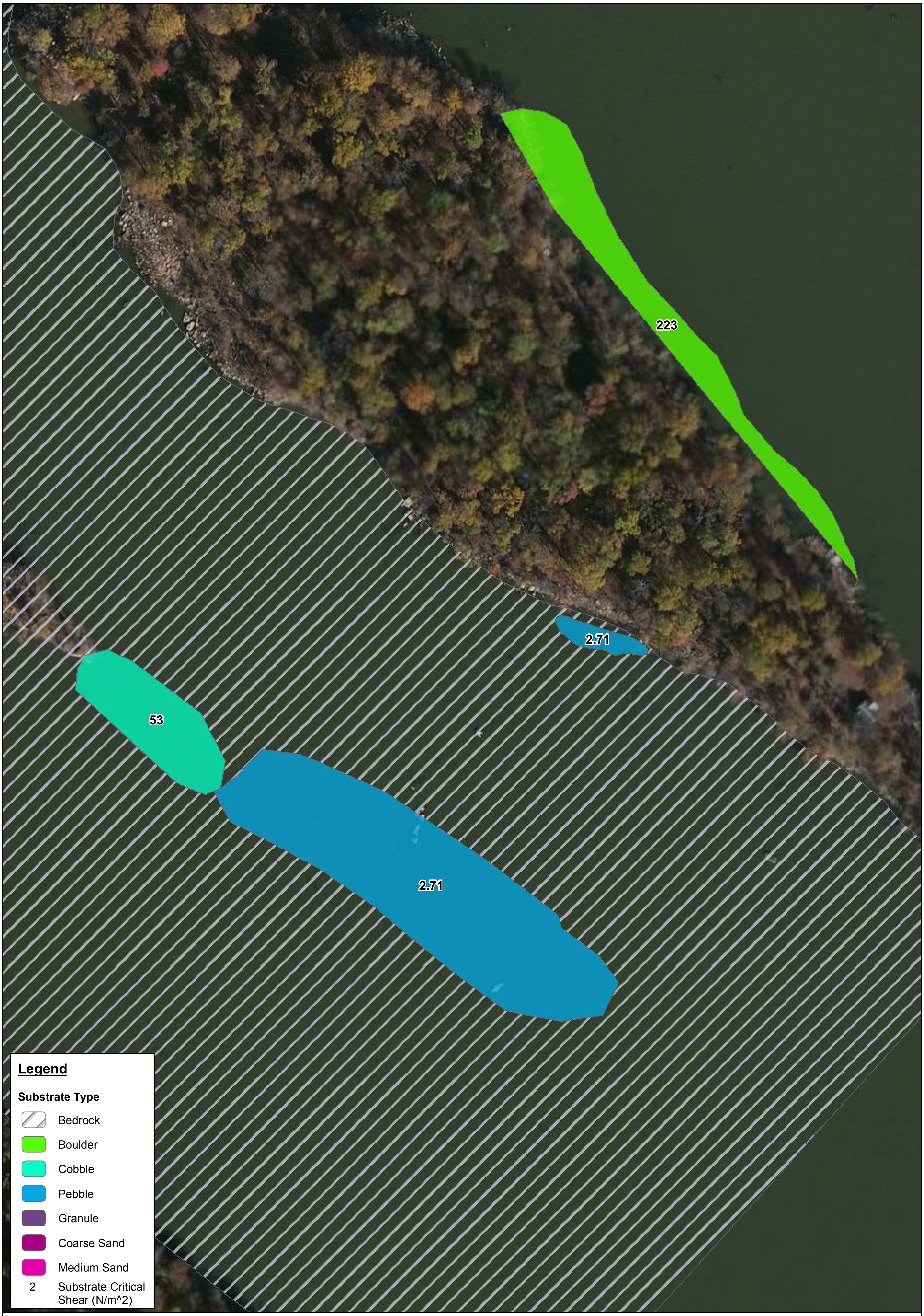

EXELON GENERATION COMPANY, LLC

SEDIMENT INTRODUCTION AND TRANSPORT STUDY (RSP 3.15)
CONOWINGO HYDROELECTRIC PROJECT
PROJECT NO. 405
1:1,800

0 75 150 300 Feet

N

Shear Stress Key Areas
Substrate Map
Key Area 12

Source: Bing Maps™ Imagery
URS Custom Data

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EXELON GENERATION COMPANY, LLC

SEDIMENT INTRODUCTION AND TRANSPORT STUDY (RSP 3.15)
CONOWINGO HYDROELECTRIC PROJECT
PROJECT NO. 405
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N

0 75 150 300 Feet

Shear Stress Key Areas
Vegetation Map
Key Area 12

Source: Bing Maps™ Imagery
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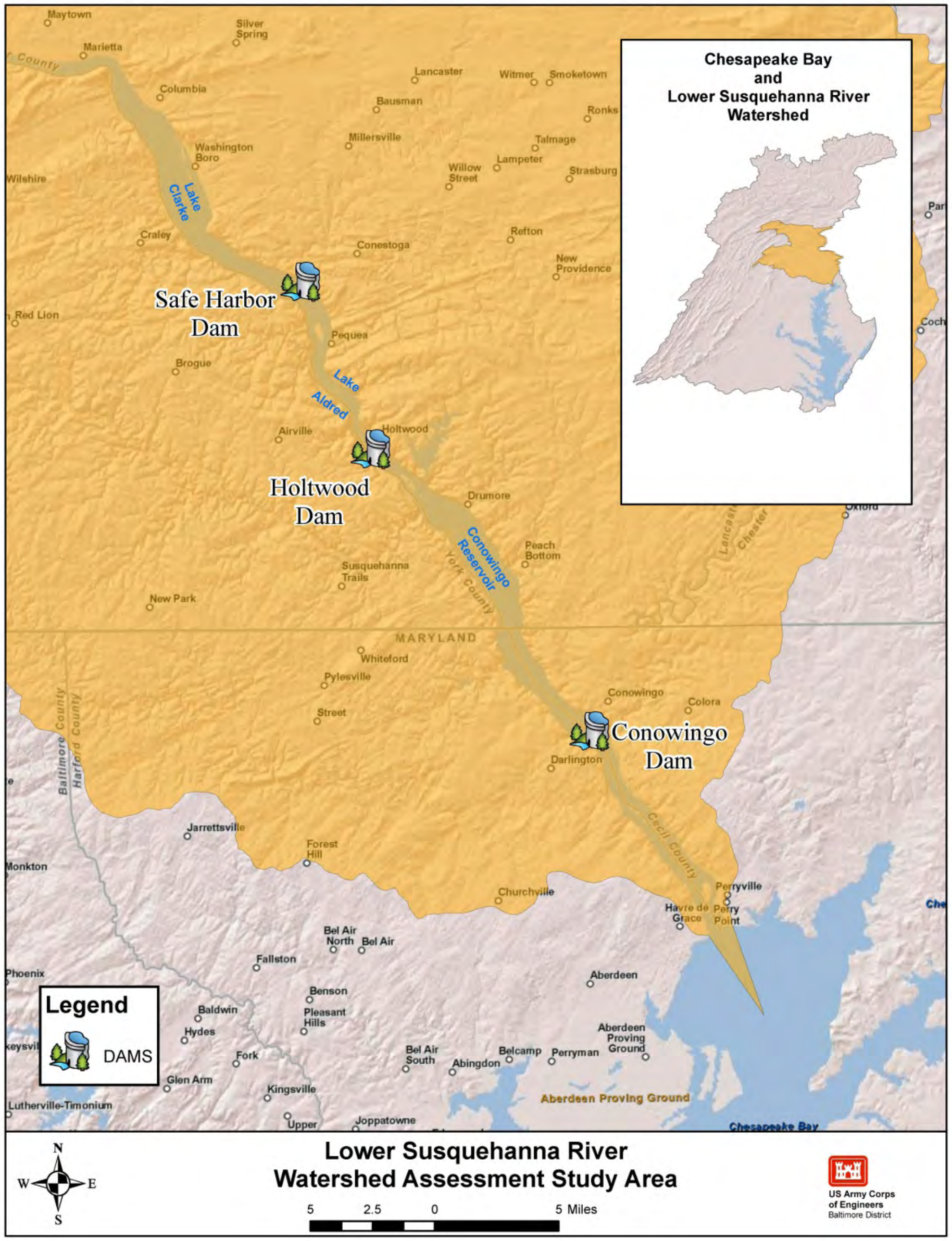
APPENDIX E – LOWER SUSQUEHANNA RIVER WATERSHED ASSESSMENT UPDATE (JULY 2012)

Lower Susquehanna River Watershed Assessment

Update

Name
Agency
Date



Lower Susquehanna River Watershed Assessment Study Area

Assessment Initiation

- ✓ Funding from Congress to “restart” study – May ‘09
- ✓ Sediment Task Force Reconvened – Oct. ’09
- ✓ Scoping Kick-off meeting – June ‘10
- ✓ Scoping completed – April ‘11.
- ✓ Executed Project Management Plan/Cost-Sharing Agreement – September ‘11
- ✓ Federal funding of $250K secured – September ‘11
- ✓ Team Kick-off meeting – November ‘11

Assessment Partners

USGS
science for a changing world

SRBC

MDE

MARYLAND
DEPARTMENT OF
NATURAL RESOURCES

U.S. ARMY
ENGINEER RESEARCH AND DEVELOPMENT CENTER
ERDC

The Nature Conservancy
Protecting nature. Preserving life.™

- Each agency will be providing funding and/or conducting specific tasks for the assessment.

Assessment Components

- **River Basin Assessment (Sec 729 of WRDA ‘86)**
- **Cost: $1.4 million**
- **Legal Cost-sharing sponsor: MDE**
- **75 Federal/25 Non-Federal Cost Share**
- **3 Years**

Assessment Components

- **Identification of sediment management strategies (Dredging? Innovative Re-use? By-passing? Alter Reservoir Operations? Other?).**

- **Use of models to link incoming sediment and associated nutrient projections to in-reservoir processes at the hydroelectric dams.**

- **Use of models to forecast effects of sediment management strategies to living resources in Chesapeake Bay.**

- **Integration of the MD, PA, NY Watershed Implementation Plans (WIPs).**

- **Concept-level designs and costs.**

- **Will *not* lead directly to construction.**

Lower Susquehanna River Watershed Assessment

Mission

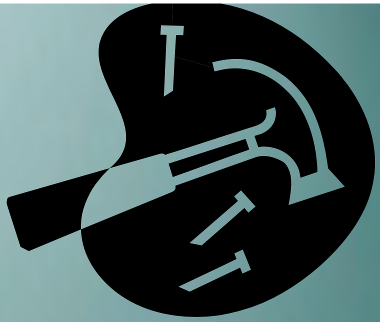
To comprehensively forecast and evaluate sediment and associated nutrient loads to the system of hydroelectric dams located on the Susquehanna River above the Chesapeake Bay and consider structural and non-structural strategies to manage these loads to protect water quality and aquatic life in the Chesapeake Bay.

Lower Susquehanna River Watershed Assessment

Goals & Objectives

1. Evaluate strategies to manage sediment and associated nutrient delivery to the Chesapeake Bay.
    - ➢ Strategies will incorporate input from Maryland, New York, and Pennsylvania TMDL WIPs.
    - ➢ Strategies will incorporate evaluations of sediment storage capacity at the four hydroelectric dams on the Lower Susquehanna River.
    - ➢ Strategies will evaluate types of sediment delivered and associated effects on the Chesapeake Bay.
2. Evaluate strategies to manage sediment and associated nutrients available for transport during high flow storm events to reduce impacts to the Chesapeake Bay.
3. Determine the effects to the Chesapeake Bay from the loss of sediment and nutrient storage from behind the hydroelectric dams on the Lower Susquehanna River.

Modeling Tools



1. CBP Partnership-Watershed Model
   - Sediment and nutrient loads from the watershed at key locations into the reservoirs.
2. HEC-RAS 1D Model
   - Hydrologic conditions and sediment transport into Conowingo Reservoir (from upper 2 reservoirs)
3. 2D Adaptive Hydraulics Model (ADH)
   - Erosion/deposition within Conowingo Reservoir
   - Sediment transport out of Conowingo reservoir
   - Response of reservoir and flats to various scenarios.
4. CBP Partnership - Chesapeake Bay Model
   - Impact of sediments and nutrients on light attenuation, SAV, chlorophyll, and DO

Assessment Analysis Approach

1.) 2D/3D effects desktop analysis plus building initial model mesh

2D ADH model

ERDC-$45K

2.)Sediment and nutrient loads from Lower Susquehanna Watershed into reservoirs

CBP Partnership Watershed Model

EPA

3.) Sediment loads divided into grain size fractions and routed through Lake Clark and Aldred

1D HEC-RAS model

USGS-$80K

4.) Sediment load by grain size routed through Conowingo Reservoir, Dam, and the Susquehanna Flats

2D ADH model

ERDC-$270K

5.) Run selected modeling scenarios

ERDC/USGS /EPA

6.) Change in total sediment load by grain size passing Conowingo and Susquehanna flats

2D ADH model

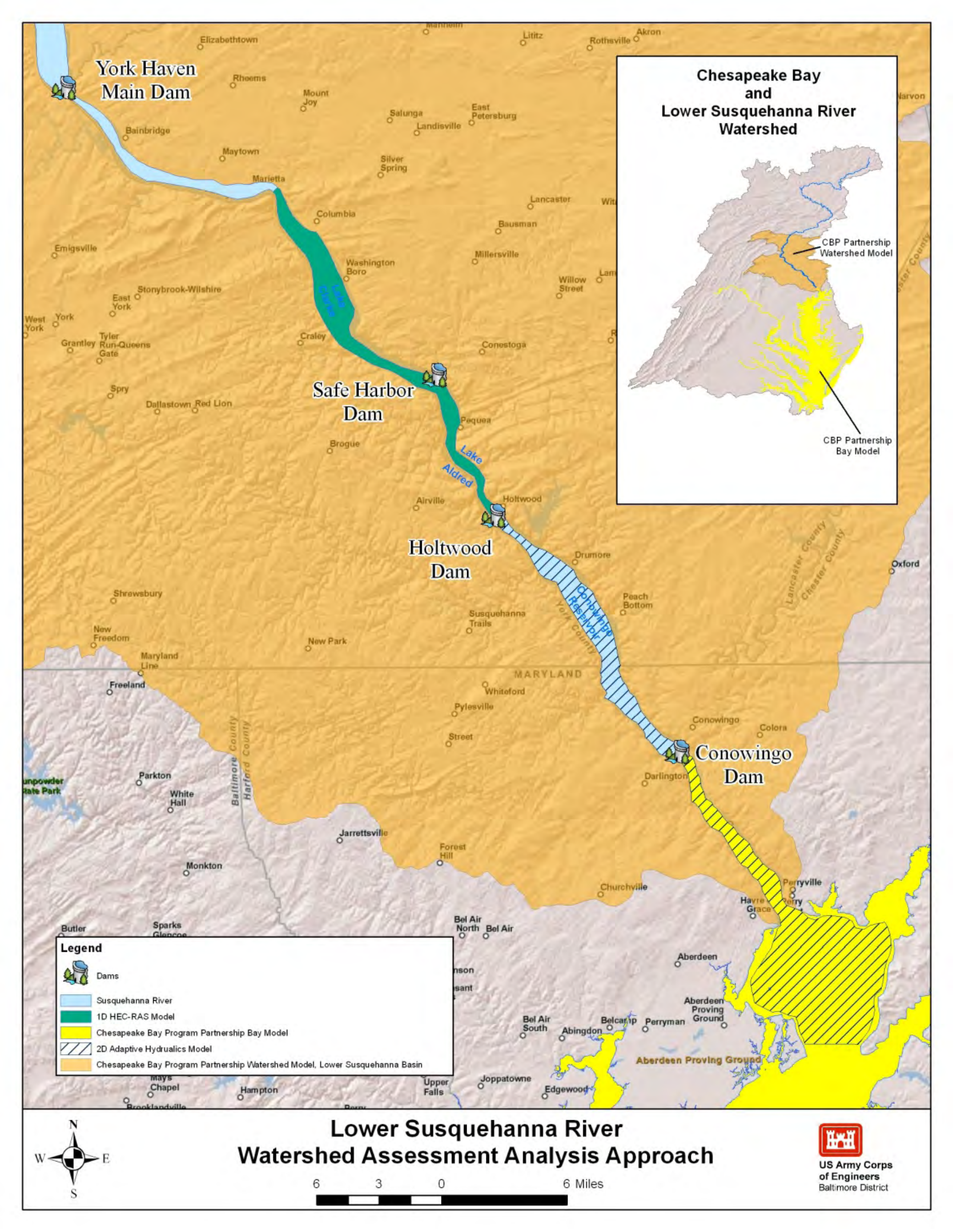
ERDC-(Costs included in Step 4)

7.) Impacts of altered sediment and associated nutrient loads on Bay

CBP Partnership Bay Model

$235.1K

Lower Susquehanna River Watershed Assessment Analysis Approach



Prospective Modeling Scenarios

1. **Base Condition –**

   WQ/sediment accumulation rate under existing conditions.

2. **Watershed Management –**

   WQ/sediment accumulation rate after implementation of TMDL's.

3. **What Happens when the Reservoir Fills –**

   Impact on WQ/sediment accumulation rate to the Bay (assume TMDL's are being met).

4. **Effect of Scouring during Winter/Spring Runoff –**

   WQ/sediment accumulation rate with scouring of the bottom of a full reservoir (utilize Jan '96 event).

5. **Effect of Scouring from a Tropical Storm –**

   Same as Scenario 4 except event will occur in summer (substitute the Jan '96 event).

6. **Reservoir Bypass –**

   Impacts on WQ/sediment accumulation rates with a system bypassing sediment from behind Conowingo to below the dam.

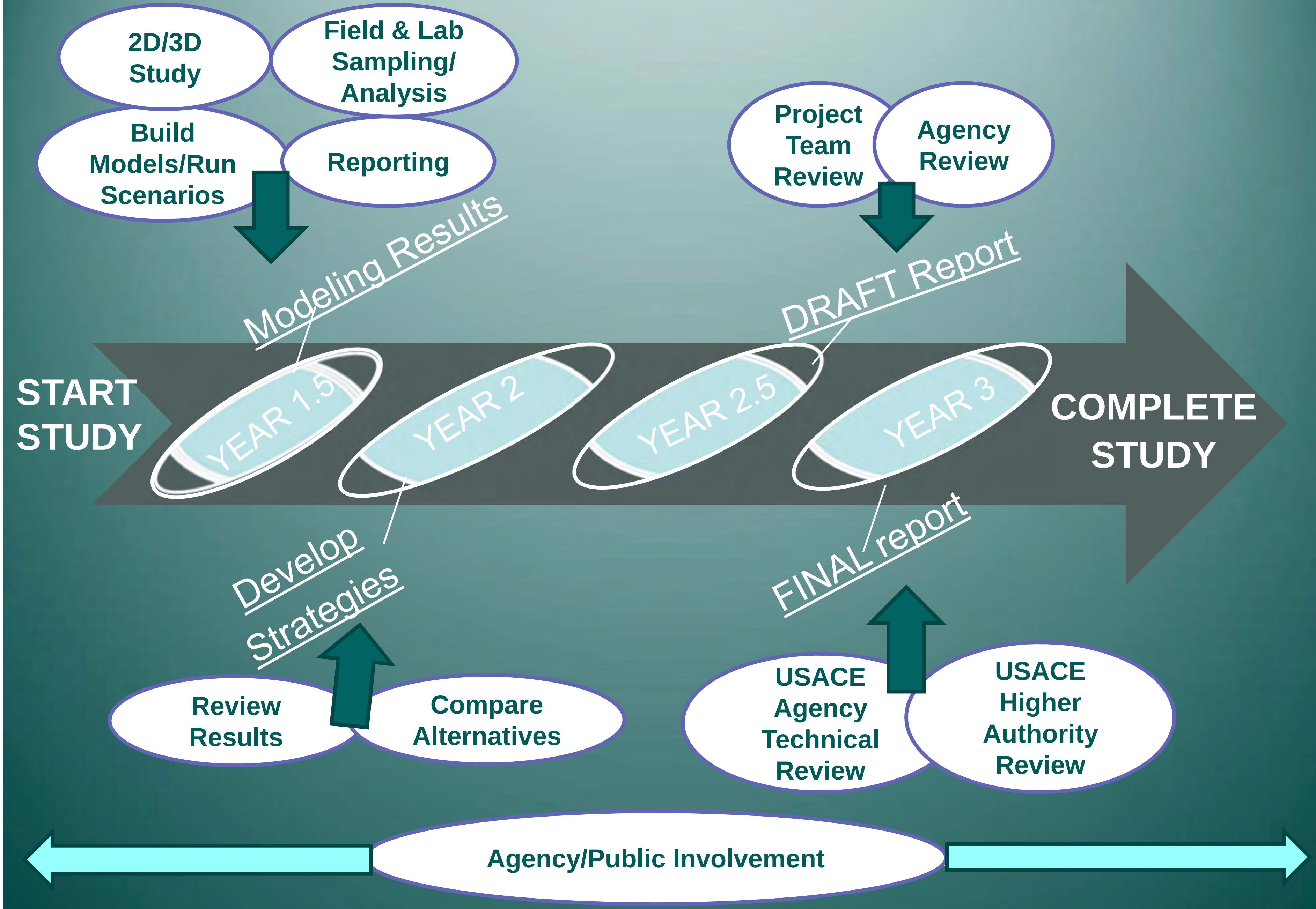
7. **Reservoir Strategic Dredging –**

   WQ/sediment accumulation rate impacts from dredging fines in potentially any reservoir.

8. **Modify Dam Operations –**

   Effects of altering the flow and/or the way the Conowingo is currently operated..

Assessment Timeline



2D/3D Study

Field & Lab Sampling/ Analysis

Build Models/Run Scenarios

Reporting

Modeling Results

Project Team Review

Agency Review

DRAFT Report

START STUDY

YEAR 1.5

YEAR 2

YEAR 2.5

YEAR 3

COMPLETE STUDY

Develop Strategies

FINAL report

Review Results

Compare Alternatives

USACE Agency Technical Review

USACE Higher Authority Review

Agency/Public Involvement

Activities

Conowingo Reservoir: Is 2D Modeling Adequate or Are 3D Effects Potentially Significant?

- ►<u>2D ADH model Assumption</u>: System is well mixed therefore 2D model is appropriate for all conditions that deliver significant sediment.
- ►<u>When are 3D Effects Important?</u>
  - Low river discharge into reservoir
  - Flow velocity is low; turbulence and mixing at a minimum
  - High water residence time in reservoir

Desktop Analysis of 3D Effects

- **Purpose:** Evaluate if 2D ADH model can adequately simulate long-term sedimentation processes in Conowingo Reservoir or will 3D effects significantly impact 2D simulations.
- **Approach:** Evaluate sediment availability to reservoir when 3D impacts may be significant
  1. Conduct a desktop analysis of sediment transport/hydrologic conditions. Utilize existing data:
     a) Residence time curve (Exelon hydrologic data)
     b) Flow (USGS historical data)
     c) Sediment rating curve (1D HEC-RAS model)
  2. Assume that flows greater than 30,000 cubic feet per second (cfs) have a very low retention time (5 days or less); therefore, there is sufficient mixing at these low flows (i.e., no 3D effects).
  3. Based on analysis, determine if a 2D model is appropriate to simulating sediment transport in Conowingo Reservoir.

Desktop Analysis of 3D Effects

Results

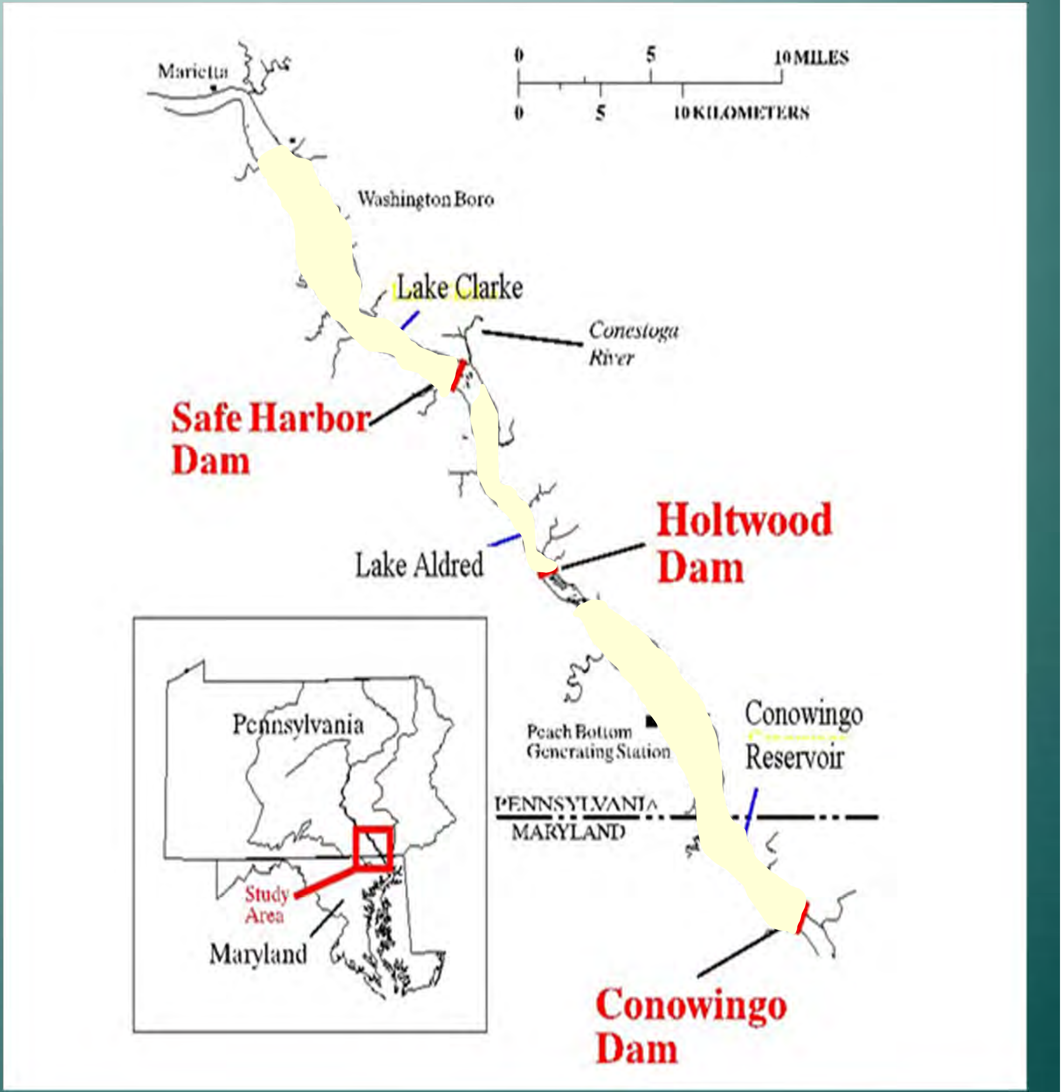
- Of ~4.28 million tons of annual sediment inflow, ~.22 million occurs during flows of 30,000 cfs or less (5%).
- Reservoir is exposed to only 5% of total yearly load during low flow conditions
- This means 3D effects occur, but are negligible.
- <u>A 2D model is appropriate for simulating sediment transport in Conowingo Reservoir.</u>

2D ADH Model Development – ERDC lead

- One model for Conowingo Reservoir and one model for the flats
- Includes:
  - 2008 bathymetric surveys
  - Routines for power plant operations and flood gates
  - SAV effects (impacts how sediment is transported in the flats) included

1D HEC-RAS Model Development – USGS Lead

- Marietta gage - Conowingo Reservoir
- LIDAR data
- Bathymetry (’96 and ‘08)
- Flood insurance data from FEMA used to fill in where bathymetry data was not available
- 4 sediment transport curves (ranking flow with sediment concentration values)
- Operational – Sept. 2012



Chesapeake Bay Environmental Model Package ERDC Lead

Data Search

- CBEMP requires information on physical properties and composition of solids flowing over Conowingo Dam.
- Search of relevant data conducted
  - Solids size distribution
  - C, N, P species and concentrations
  - Metals
- Findings:
  - As flow over Conowingo increases, composition of transported materials resembles reservoir bed material
  - Existing data is sufficient to characterize transported material for modeling.

SEDFlume Data and Analysis

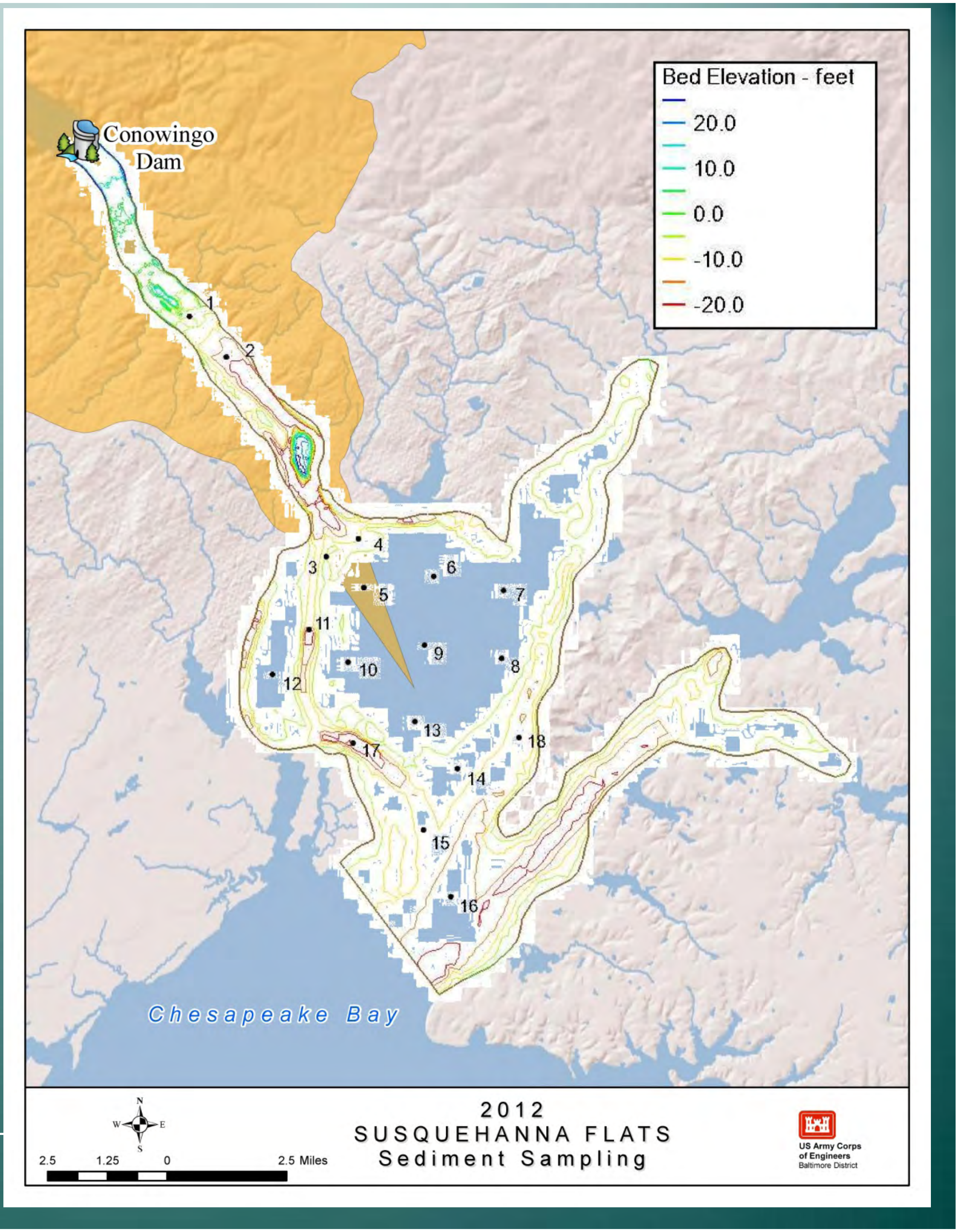
- 15 sediment cores were collected in April 2012 in Conowingo Reservoir and run through SEDflume
- Analysis will determine erodability of sediments.
- Equations for critical shear stress

Suspended Sediment Sampling

- USGS collected suspended sediments at Conowingo dam during several 2010 high flow events (March/October/December 2010) and during Tropical Storm Lee (September 2011).
  - Supplemental to regular monitoring
  - Suspended-sediment chemistry
  - Grain-size analysis
- Data provides
  - C, N, P particle size distribution; will help determine what grain size each is associated with.
  - Measures of Particulate P with Fe and Mn to determine if P is organic or associated with Fe and Mn (i.e. inorganic).
- Data here: http://waterdata.usgs.gov/nwis

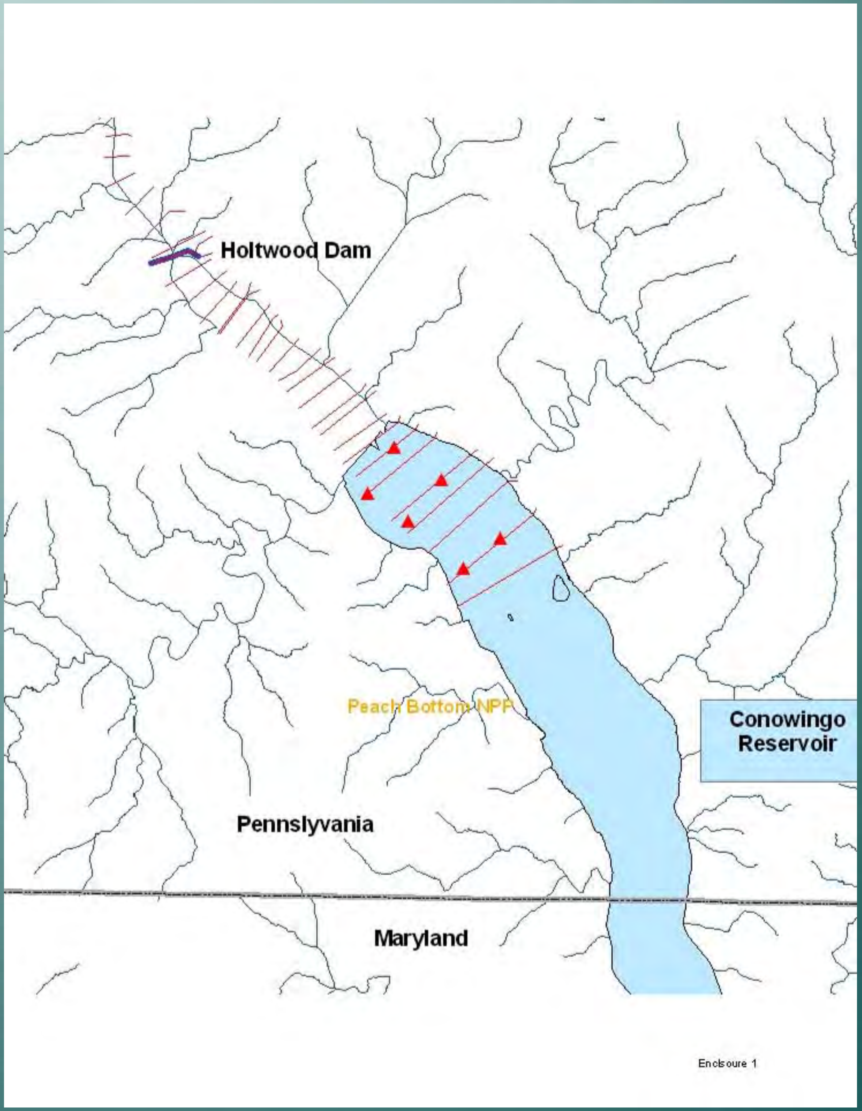
Susquehanna Flats Sediment Sampling

- MGS collected surficial grab samples in May 2012
- Grain-size analysis
- Data will refine 2D ADH model



Conowingo Reservoir Sediment Sampling

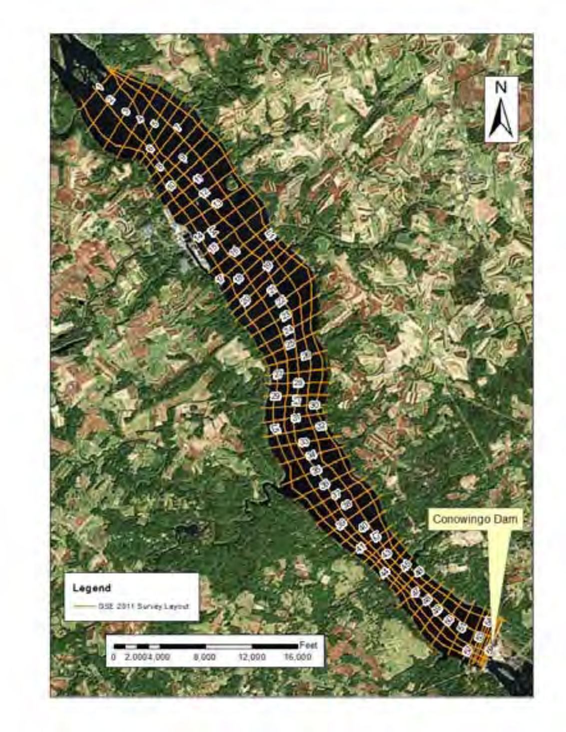
- USGS collected grab surface sample sediment in June 2012
- 96-99% sand in upper reservoir



Exelon Conowingo Bathymetry Surveys

- 3,434 acre-ft (~5.07 million tons) of sediment accumulated from ’08-’11
- Average of 1.69 million tons of deposition annually.
- Remaining sediment storage capacity: ~21,800 acre-ft (assume 142,000 acre-ft is steady-state volume.

Historic Coverage



2011 Coverage

Stakeholder Outreach

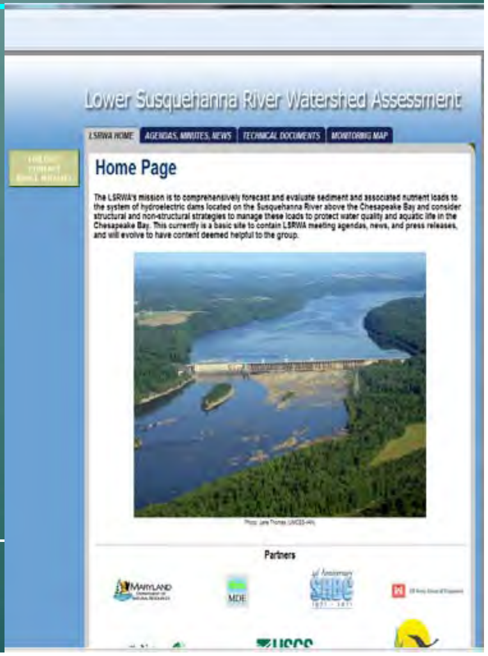
- ✓ Study Initiation Notice Feb 2012
- ✓ Agency Coordination Letters Feb 2012
- ✓ Facebook Page:

http://www.facebook.com/pages/Lower-Susquehanna-River-Watershed-Assessment/359608094092593

- ✓ LSRWA Website:

http://mddnr.chesapeakebay.net/LSRWA/index.cfm

- ✓ Stakeholder Involvement Plan
- ✓ Quarterly Email updates
- ✓ Provide updates at other Chesapeake Bay Meetings



Home Page

The LSRWA's mission is to comprehensively forecast and evaluate sediment and associated nutrient loads to the system of hydroelectric dams located on the Susquehanna River above the Chesapeake Bay and consider structural and non-structural strategies to manage these loads to protect water quality and aquatic life in the Chesapeake Bay. This currently is a basic site to contain LSRWA meeting agendas, news, and press releases, and will evolve to have content deemed helpful to the group.

Schedule of Upcoming Activities *

Complete Initial HEC-RAS Hydraulic Model	Ongoing-Sept 2012
Sediment Characterization (SEDFlume)	Mar-Sept 2012
Literature Search	July-Sept 2012
Hydrodynamics Model Runs	April-Sept 2012
Modeling of Baseline Condition	October 2012
Alternative Identification and Site Evaluation	Oct-Dec 2012
Modeling of Alternatives	Jan-Mar 2013
Sediment Management Strategy Development	Summer 2013

* The schedule for activities after September 2012 is contingent upon receiving adequate Federal funding in FY13.

APPENDIX F – 2011 CONOWINGO POND BATHYMETRIC SURVEY

GOMEZ AND SULLIVAN
Engineers, P.C.

Memo

To: Conowingo Relicensing Stakeholders

From: Gomez and Sullivan

Date: 8/3/2012

Re: Conowingo Pond Bathymetric Survey Analysis

Introduction

In September 2011, the Susquehanna River basin received heavy precipitation from Tropical Storm Lee[1]. Following the storm, the USGS estimated that Conowingo Dam's daily average flow peaked at 708,000 cfs with an instantaneous peak of 767,000 cfs (Personal Communication, Mike Langland [USGS], February 2012) – the Conowingo USGS gage's third highest recorded flow since it was established in October 1967. Given the opportunity to investigate how Conowingo Pond's sediment levels may have been affected by a major flood, Exelon decided to conduct a bathymetric survey of Conowingo Pond, with the following objectives:

1) Compare the 2011 results to the 2008 USGS bathymetry survey to determine whether Conowingo Pond experienced net deposition or scour.
2) Establish a physical "baseline" benchmark.
3) Provide the results for use as an input data set for the Lower Susquehanna River Watershed Assessment's Conowingo Pond modeling efforts.

This memo describes the background and analysis related to the bathymetric survey that Gomez and Sullivan conducted during the week of October 24, 2011.

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[1] Tropical Storm Irene preceded Tropical Storm Lee, and was responsible for the Susquehanna River's high base flow immediately prior to Tropical Storm Lee's arrival. This memo refers to the cumulative event as Tropical Storm Lee.

Methodology

Gomez and Sullivan collected bathymetric data at previously surveyed USGS transect locations, as well as at several additional transect locations in Conowingo Pond during the week of October 24, 2011 (Figure 1 and Figure 2). Data were collected from a 19-foot-long pontoon boat with a front-mounted echo-sounder and a real time kinematic global positioning system (RTK-GPS) placed directly above the echo-sounder.

The RTK-GPS utilized was a Sokkia GRX1 base and rover. A 35 W Pacific Crest repeater radio was used to extend the base-rover link distance to approximately 5 miles. When the GPS unit is in RTK mode, it has a horizontal accuracy of approximately ± 0.033 ft + 0.005 ft per mile from the base station. When in differential GPS (DGPS) mode, the unit has a horizontal accuracy of approximately ± 1.6 ft. GSE cross-sections 1 through 52 and all longitudinal profiles were collected in RTK mode. GSE cross-sections 53 through 59 were collected in DGPS mode. All position data were streamed to the bathymetric unit at a 10 Hz frequency (10 samples per second), where the position and timestamp were stored.

The bathymetric unit used was a Sontek RiverSurveyor M9. The RiverSurveyor M9 uses a vertical hydroacoustic beam to measure water depths between approximately 0.65 ft and 260 ft, with an approximately 0.003 ft resolution. The unit specifications state a depth accuracy of ±1% (e.g., ±0.5 ft at a 50-ft water depth), which was verified in the field during the survey through the use of a flat metal surface attached to a pre-measured rope length lowered into the water (Table 1). The RiverSurveyor also recorded water column velocities and a second water depth measurement through the use of eight angled hydroacoustic beams, only four of which are used at one time. The average water depth recorded by the velocity beams served as a secondary depth measurement to verify the primary (vertical beam) depth measurement. Water velocity and water depth measurements were continuously recorded in one-second intervals[2] throughout the entire study. The RiverSurveyor M9 recorded all data internally and also outputted to a USB-linked tablet computer for real-time data monitoring. Real-time data streamed to the tablet computer were redundantly saved on the tablet to prevent data loss.

Measured depth data were combined with water surface elevations (WSE) to calculate bed elevations, such that Bed Elevation = Water Surface Elevation – Water Depth[3]. WSEs were recorded at three locations along Conowingo Pond: Conowingo Dam, Peach Bottom Atomic Power Station (Peach Bottom), and Muddy Run. Though the surveyed portion of Conowingo Pond is primarily a backwater-type area from Conowingo Dam, a small but perceptible WSE gradient, typically less than

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[2] The unit measured bottom depths several times per second, and then recorded the average of all valid measurements made during the one-second interval.

[3] The bathymetry unit was placed approximately 8 inches (0.67 ft) deep in the water. The exact distance was measured and input into the RiverSurveyor's software every day prior to surveying. The RiverSurveyor's software automatically accounts for this in recorded depths.

0.25 ft, is measurable between Conowingo and Peach Bottom. To account for this WSE difference, the WSE gradient between Conowingo Dam and Peach Bottom was used to determine the WSE throughout Conowingo Pond. Muddy Run WSEs were not used because that area of Conowingo Pond is heavily influenced by Holtwood and Muddy Run operations. Thus, we determined that extrapolating the WSE gradient between Conowingo Dam and Peach Bottom to the most upstream cross-section (just downstream of Hennery Island) was the most appropriate WSE estimation method.

Several steps were taken to get Conowingo Pond's WSE gradient. First, WSEs at Conowingo (30-min interval) and Peach Bottom (~2.5-min interval) were interpolated over time to create a 1-min time series for both stations. Next, a WSE gradient (WSE change per river mile) was calculated between the two stations, for each 1-min interval. Then, for each depth measurement point, the linear distance upstream of Conowingo Dam was calculated, and the measurement point's time stamp (rounded to the nearest minute) was matched with a corresponding Conowingo Pond WSE gradient by matching 1-minute time stamps. The WSE at each measurement point was then calculated by multiplying the point's distance upstream of Conowingo Dam by the timestamp-matched WSE gradient. WSEs were then subtracted by the water depths to calculate bed elevations.

The Quality Assurance/Quality Control (QAQC) version of the 2008 Conowingo Pond bathymetry data set was provided by the USGS to Exelon. Data collection and analysis methodology for the 2008 data set are described in Langland (2009). The data set consists of spatially-georeferenced (latitude/longitude) depths from Conowingo Pond's normal water surface elevation of 109.2 ft NGVD 1929[4]. These data were used to compute bed elevation changes relative to historic bed elevations from fall 2008.

Our analysis followed the methodology described in Langland (2009), except that an additional method for calculating transects' average water depths from Normal Pool (109.2 ft NGVD 1929) was used. Langland (2009) calculated water volumes using the mid-point method, such that water volume equaled cross-sectional effective length multiplied by width between adjacent cross-sections multiplied by the cross-sectional average depth. The cross-section *width* was determined by calculating the distance between the first and last point of each cross-section. The cross-section *effective length* was calculated as half the distance to the next upstream cross-section plus half the distance to the next downstream cross-section. Langland (2009) calculated transects' *average depths* by taking the average of all points collected in each cross-section, normalized to Conowingo Pond's normal pool elevation, such that $D_{avg} = \frac{\sum_{i=1}^{n} d_i}{n}$, where D_{avg} is a transects' average depth, n is the number of points in a transect, and d_i is the depth from Normal Pool at point i. Our alternative method

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[4] The Langland (2009) data set was collected with reference to Conowingo Datum water surface elevations. All water depth data provided to Exelon were converted to bed elevation data in NGVD 1929. Conowingo Datum elevations are 0.7 ft below NGVD 1929 elevations, such that elevation 108.5 ft in Conowingo Datum equals elevation 109.2 ft in NGVD 1929.

was similar, except that it weighted depths by the distance, such that $D_{avg} = \frac{\sum_{i=1}^{n} d_i * w_i}{\sum_{i=1}^{n} w_i}$, where D_{avg} is a transects' average depth, n is the number of points in a transect, d_i is the depth from Normal Pool at point i, and w_i is the space between adjacent points in the same transect. Then, the total water volume was calculated for each cross-section as: $V_{water} = L_{eff} * W * D_{avg}$, where V_{water} is the cross-section's water volume, L_{eff} is the cross-section's effective length, W is the cross-section's width and D_{avg} is the cross-section's average depth.

Since the raw QAQC data available for the USGS 2008 survey had been adjusted for QAQC reasons during the initial steps of this analysis, cross-sectional average depths were re-calculated for this analysis, rather than using the volumes reported in Langland (2009). The cross-sectional widths and lengths were not changed from the Langland (2009) values, since those parameters have not appreciably changed since 2008. The Langland (2009) and recalculated total water volumes matched closely. When compared, Langland (2009) reported a total water volume of 162,398 acre-ft (the report had rounded to the nearest 1,000 acre-ft), while we computed a total 2008 water volume of 162,604 acre-ft using our recalculated unweighted average depths. Thus, the two calculations matched within 206 acre-ft.

As was done in Langland (2009), net sediment deposition was calculated as the change in water volumes between 2008 and 2011, such that any decrease in water volume was attributed to an equal increase in sediment volume (net deposition) and any increase in water volume was attributed to an equal decrease in sediment volume (net scour[5]). A normalized dry density of 67.8 lb/ft^3 was used to calculate sediment weight from sediment volumes. Sediment weights were reported in tons, where 1 ton equals 2,000 pounds. Once the individual cross-section sediment changes were computed, an aggregated Conowingo Pond water volume and sediment change was calculated as the sum of all cross-sections' net volume and sediment volume/weight change.

Results

The data were compiled and combined with other near-shore elevation data to create an updated Conowingo Pond bed elevation map (Figure 3). Bed elevations from the 2008 and 2011 surveys were compared at all 26 historic USGS cross-sections (Appendix A: Historic Cross-Section Comparison). All 59 transects collected in 2011 are shown in Appendix B: 2011 Cross-Section Plots.

The results showed that there were three distinguishable sections within Conowingo Pond. The upper Pond (USGS XC 1 – USGS XC 10) was shallow, with average channel depths of 17 feet or less[6]. The

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[5] In the context of a particular cross-section, "scour" refers to a net sediment removal between 2008 and 2011, only implying that the sediment has moved out of that particular cross-section. In the context of the entire Conowingo Pond, "net scour" refers to the Pond's overall sediment flux across all cross-sections, meaning that the total amount of sediment in Conowingo Pond has changed.

[6] The depths and changes in depths cited in this section refer to the weighted average depth calculations.

upper Pond generally had small amounts of net scour (< 1 ft avg.) between the 2008 and 2011 survey, such as in USGS XC 6 (Figure 4). The middle of the Pond (USGS XC 11 – USGS XC 18) was moderately shallow, with average channel depths between 14 and 22 feet. The middle Pond experienced small to negligible amounts of net deposition, with average bed elevations rising between 0.0 and 0.6 ft. Though the middle Pond experienced little net change, there were local areas of scour and deposition that were roughly balanced, such as in USGS XC 16 (Figure 5). The lower end of the Pond (USGS XC 19 – USGS XC 26) had increasingly deeper cross-sections, with average depths ranging from just over 21 feet to nearly 50 feet. The lower Pond transects had relatively large amounts of net deposition, with between 1 and 3.5 feet of average bed elevation increase between the 2008 and 2011 surveys. The only exception to this in the Lower Pond was at USGS XC 21, which only experienced a 0.38 ft average bed elevation increase between the 2008 and 2011 survey[7].

Deposition and scour occurred in predicable locations. Deposition was generally most noticeable along the river's edges or shallower areas. Conversely, there was typically little to no deposition (or occasionally scour) near the river's thalweg (the deepest point in the transect, or area where the majority of the flow travels through). This pattern emerged in the middle pond, and became more apparent in farther downstream transects (Figure 6).

Aggregated cross-section data were plotted in longitudinal profiles to compare 2008 and 2011 average bed elevations (Figure 7 and Figure 8) and changes in average bed elevation (Figure 9 and Figure 10), using both average depth methodologies. The profiles support the hypothesis that the upper and middle pond are in dynamic equilibrium. It also confirms that the lower pond is still experiencing substantial deposition, with the amount of deposition increasing closer to Conowingo Dam.

The sediment volume change for each cross-section was calculated using the weighted and unweighted water volume methodologies. Water volume and sediment results for each cross-section are shown for the unweighted methodology in Table 2 and for the weighted methodology in Table 3. Between 2008 and 2011, the net Conowingo Pond water volume decrease was between 2,940 acre-ft (using the unweighted methodology) and 3,434 acre-ft (using the weighted methodology). This corresponds to a sediment volume [weight] increase between 2,940 acre-ft [4.34 million tons] and 3,434 acre-ft [5.07 million tons] from fall 2008 to October 2011. Averaged over the approximately 3 years between the 2008 and 2011 survey, the data show a Conowingo Pond sediment deposition rate of approximately 980 acre-ft per year to 1,145 acre-ft per year, or 1.45 million tons per year to 1.69 million tons per year for the 2008-2011 period.

Using data from Langland (2009), an analysis was done comparing the pond's estimated remaining sediment capacity over time. Conowingo Pond's remaining sediment capacity calculated by subtracting the Pond's total water volume by Langland (2009)'s Conowingo Pond steady state water

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[7] The cross-section plot of USGS XC 21 shows several "spikes" in the 2008 data set that were not picked up in the 2011 survey. These spikes raised the 2008 average cross-section depth, explaining why USGS XC 21 appeared to experience less deposition than the surrounding cross-sections. These spikes may be due to logs, debris, or localized bedrock features.

volume estimation of 142,000 acre-ft. Figure 11a and Figure 11b show the plot of remaining sediment capacity over time next to a similar plot originally shown in Academy of Natural Sciences (1994). An exponential trendline was fitted to Figure 11b to show a similar line as the Academy of Natural Sciences (1994) figure. A sensitivity analysis for several steady-state water volumes showed that the trendline's general shape was maintained for a wide range of steady state volumes. A second sensitivity analysis showed that the trendline's general shape was insensitive to removing any of the individual points from the best-fit plot, including the 2011 results.

Discussion

A comparison of the 2008 and 2011 data sets provide great insight into the sediment transport processes occurring in Conowingo Pond. But, while these two surveys were taken within a relatively short period of time, these comparisons are not the same as a before and after comparison isolating a single event. Historic data have shown there is a considerable amount of deposition that occurs in Conowingo Pond on an annual basis, as the average Conowingo Pond sediment inflow between 1996 and 2008 was approximately 1.5 million tons/year, with a long-term (1959–2008) average deposition of approximately 2 million tons per year (Langland 2009). These historic deposition rates are comparable to the 2008-2011 deposition rates calculated in this study 1.45 to 1.69 million tons per year).

When viewing the individual cross-section plots, it is apparent that the magnitude and location of riverbed changes varied longitudinally along the Pond. In the upper and middle Pond (USGS XC 1 to USGS XC 18) there is little net change between 2008 and 2011, though some cross-sections experienced channel "shifting" or redistribution, such that the deposition and scour areas were roughly equal. This indicates that a large portion of the Pond is likely in "dynamic equilibrium". This is consistent with other USGS findings, which had concluded that the Pond has been in equilibrium at or above USGS XC 16 since 1959. It also shows that the proportion of the Pond in equilibrium is increasing. Beginning around USGS XC 19, three phenomena are apparent:

1) Within each cross-section, the amount of deposition begins to clearly outweigh the amount of scour, resulting in net deposition. The longitudinal profile comparison (Figure 7) further supports the first observation, generally showing between 1 and 3.5 feet of deposition averaged across the cross-section at USGS XC 19 and farther downstream.

2) The cross-sections generally experienced some scour along the river's thalweg or main channel, accompanied by larger amounts of deposition along the banks. Deposition was only observed along one bank when the thalweg was located adjacent to one of the river banks (e.g., USGS XC 20-23). The disparity was most obvious in the farthest downstream cross-sections (Figure 6). It is logical that local scour would occur at a cross-section's thalweg, as one would expect re-suspension to occur where the highest flows, and thus velocities, are found. It is not clear from this data set where the scoured sediment was transported to (e.g., downstream cross-sections, out of the Pond). It would be reasonable to assume that at least

some of the sediment scoured from the farthest downstream comparable cross-section (USGS XC 26) passed over the Conowingo Dam spillway.

3) Between 2008 and 2011, the river thalweg appeared to shift towards the center of the dam, where the spillway is located. This was likely a result of flows following Tropical Storm Lee, during which the Conowingo powerhouse was shut down to protect the turbines. As a result, all flow was passed through the Conowingo spillway, which had a large number of its crest gates (42 of 50) opened at one point.

While 2011 cross-section data were collected closer to the dam than at USGS XC 2008, no previous data sets exist in these areas. Thus, no scour/deposition comparison could be completed for Conowingo Pond downstream of USGS XC 26 at this time. These cross-sections may serve as a reference point for future surveys.

The Academy of Natural Sciences (1994) figure shows equilibrium as a condition where net deposition never permanently stops, though it does occur at reduced rates, and stored sediment never permanently remains at the non-flood steady-state level. It shows that storm events mobilize and remove previously deposited sediment, pushing the system back below a non-flood steady state condition, starting the net deposition cycle again.

The comparison in Figure 11 between the Academy of Natural Sciences (1994) figure and Conowingo Pond's estimated remaining sediment capacity shows a clear trend of Conowingo Pond filling over time in a manner consistent with the Academy of Natural Sciences (1994) figure. It shows that Conowingo Pond, on the whole, is on the rising limb of the curve, but is at a point where the rate of net deposition is reduced and net scour may begin to influence the reservoir's position above or below the long-term mean. The trendline's insensitivity to steady state water volume estimates and removal of individual data points further support this statement. It is unclear at this point whether Conowingo Pond has reached its long-term mean sediment storage level.

In summary, the Academy of Natural Sciences (1994) figure shows that 1) a reservoir's long-term equilibrium sediment volume is less than its true steady-state volume, due to periodic scouring events; and 2) as a reservoir approaches its steady state capacity, it fills increasingly slower, such that a true steady-state volume is rarely, if ever, reached. The Conowingo Pond data show that Conowingo Pond has experienced diminishing sedimentation over time, as the Pond approaches a non-flood steady state capacity. It also shows a scour event (1996), though no immediate pre-storm bathymetric sample was available to show the actual pre and post-storm sediment volumes. The similarity between the Conowingo Pond data and the Academy of Natural Sciences (1994) figure show that Academy of Natural Sciences's (1994) figure likely serves as a good template for predicting Conowingo Pond's future behavior.

Conclusions

Several important points were addressed through analysis of the 2011 bathymetric survey.

First, the survey results support the previous USGS hypothesis that the upper and middle portions of Conowingo Pond have reached dynamic equilibrium, where long term sediment inflow approximately equals long term sediment outflow. It also appears that the zone of dynamic equilibrium has expanded farther downstream than in previous surveys, perhaps extending to USGS XC 18, which is approximately 3.7 miles upstream of Conowingo Dam.

Secondly, 2008-2011 cross-section comparisons indicate that there was local scour (re-suspension) in portions of the Pond's lower cross-sections. The amount of deposition, however, generally exceeded the amount of scour. It was not clear where the re-suspended sediment was transported to.

Thirdly, given that the deposition prior to Tropical Storm Lee is unknown, the flood's sediment profile impacts cannot be directly assessed. Using two different methods, we calculated that the Conowingo Pond water volume decreased (due to a sediment volume increase) between 2,940 acre-ft and 3,434 acre-ft from 2008 to 2011, or between 980 acre-ft per year and 1,145 acre-ft per year. This corresponds to a total sediment deposition of 4.34 million tons to 5.07 million tons, or a rate of 1.45 million tons per year to 1.69 million tons per year, which matches historic deposition rates well.

Finally, the Conowingo Pond data compare well to a typical reservoir sedimentation profile over time. This was true in sensitivity analyses testing various steady state water volumes and excluding individual data points throughout the fitted curve. Thus, it appears the Academy of Natural Sciences (1994) curve likely serves as a reasonable template for how Conowingo Pond will continue to accumulate and scour over time. It is unclear at this point whether Conowingo Pond has reached its long-term mean sediment storage levels as shown in the Academy of Natural Sciences (1994) figure.

References

Langland, M.J., 2009. Bathymetry and Sediment-storage Capacity Change in Three Reservoirs on the Lower Susquehanna River, 1996-2008. United States Geological Survey Scientific Investigations Report 2009-5110. 21p.

Langland, M.J. and R.A. Hainly, 1997. Changes in Bottom-Surface Elevations in Three Reservoir on the Lower Susquehanna River, Pennsylvania and Maryland, Following the January 1996 Flood – Implications for Nutrient and Sediment Loads to Chesapeake Bay. United States Geological Survey Water-Resources Investigations Report 97-4138. 34p with plates.

Academy of Natural Sciences. Issues Regarding Estimated Impacts of the Lower Susquehanna River Reservoir System on Sediment and Nutrient Discharge to Chesapeake Bay. The Academy of Natural Sciences of Philadelphia, Division of Environmental Research. Report No. 94-20. 6 September, 1994.

Table 1: Observed versus measured water depths, from the bathymetric unit verification.

Observed Depth (ft)	Bathymetric Unit Measured Depth (ft)	Difference (ft)	Difference (%)
7.0	6.99	-0.01	-0.14
12.0	11.91	-0.09	-0.75
17.0	17.03	0.03	0.17
22.0	22.09	0.09	0.41
27.0	26.89	-0.11	-0.41

Table 2: Conowingo Pond cross-section sediment calculations, using unweighted average depths. Red numbers in parentheses are negative.

USGS Cross-Section Number	Distance US of Dam (ft)	Effective Length (ft)	Cross-Section Width (ft)	Unweighted Average Depth at Normal Pool [109.2 ft NGVD 1929] (ft)			Water Volume at Normal Pool (acre-ft)			Sediment Accumulation (acre-ft)	Sediment Accumulation (tons)
				2008	2011	Difference	2008	2011	2008-2011		
1	60,000	2,200	4,880	12.20	12.51	0.31	3,084	3,006	77	77	114,340
2	57,700	2,250	6,400	14.37	14.15	(0.22)	4,678	4,751	(72)	(72)	(106,770)
3	56,600	2,350	6,200	15.21	15.53	0.32	5,194	5,088	106	106	156,012
4	54,800	2,150	6,310	16.42	16.19	(0.24)	5,041	5,115	(74)	(74)	(108,849)
5	52,900	1,800	5,900	15.64	15.49	(0.15)	3,777	3,813	(36)	(36)	(52,948)
6	49,800	2,600	6,810	14.87	14.95	0.07	6,075	6,046	30	30	44,137
7	47,010	2,775	6,350	14.96	17.04	2.08	6,895	6,053	842	842	1,243,557
8	44,250	2,430	6,900	15.09	14.14	(0.95)	5,442	5,808	(365)	(365)	(539,555)
9	42,150	2,130	6,540	16.20	15.88	(0.32)	5,080	5,182	(102)	(102)	(150,747)
10	39,990	1,400	7,000	15.26	15.09	(0.17)	3,394	3,432	(38)	(38)	(55,922)
11	37,500	1,900	7,710	12.93	14.53	1.60	4,885	4,347	538	538	794,504
12	35,800	3,420	6,510	15.94	16.17	0.23	8,263	8,146	116	116	171,981
13	33,150	3,175	4,700	20.13	20.32	0.19	6,961	6,896	65	65	96,682
14	29,450	3,150	4,710	20.68	21.09	0.41	7,183	7,043	140	140	206,816
15	26,850	2,530	5,050	20.92	20.70	(0.21)	6,073	6,135	(62)	(62)	(92,147)
16	24,400	2,570	5,300	19.24	19.49	0.26	6,095	6,015	81	81	118,977
17	21,700	2,550	6,180	20.45	20.74	0.29	7,503	7,399	104	104	153,158
18	19,300	2,525	5,000	21.74	21.73	(0.01)	6,299	6,302	(4)	(4)	(5,276)
19	16,650	2,625	5,240	21.64	21.93	0.29	6,926	6,833	93	93	137,103
20	14,050	2,187	3,560	28.66	29.28	0.62	5,233	5,122	111	111	163,832
21	12,275	2,085	3,350	30.28	28.62	(1.66)	4,589	4,856	(267)	(267)	(394,202)
22	9,880	2,162	3,380	30.50	31.15	0.65	5,226	5,116	110	110	161,778
23	7,950	2,175	3,520	32.96	34.06	1.09	5,986	5,793	192	192	284,131
24	5,530	2,400	4,450	37.78	40.50	2.71	9,929	9,263	665	665	982,556
25	3,150	1,915	4,610	45.28	47.23	1.96	9,572	9,176	396	396	585,159
26	1,700	2,425	4,750	48.89	50.00	1.11	13,222	12,929	293	293	432,539
Total	-	-	-	-	-	-	**162,604**	**159,664**	**2,940**	**2,476**	**4,340,848**

Table 3: Conowingo Pond cross-section sediment calculations, using weighted average depths. Red numbers in parentheses are negative.

USGS Cross-Section Number	Distance US of Dam (ft)	Effective Length (ft)	Cross-Section Width (ft)	Weighted Average Depth at Normal Pool [109.2 ft NGVD 1929] (ft)			Water Volume at Normal Pool (acre-ft)			Sediment Accumulation (acre-ft)	Sediment Accumulation (tons)
				2008	2011	Difference	2008	2011	2008-2011		
1	60,000	2,200	4,880	12.60	12.54	0.06	3,106	3,090	16	16	23,337
2	57,700	2,250	6,400	14.26	14.42	(0.16)	4,715	4,769	(53)	(53)	(78,452)
3	56,600	2,350	6,200	15.96	15.98	(0.02)	5,339	5,345	(5)	(5)	(7,591)
4	54,800	2,150	6,310	16.66	16.96	(0.31)	5,188	5,284	(95)	(95)	(140,737)
5	52,900	1,800	5,900	15.65	15.66	(0.01)	3,817	3,819	(2)	(2)	(3,007)
6	49,800	2,600	6,810	15.09	15.40	(0.30)	6,135	6,259	(124)	(124)	(183,005)
7	47,010	2,775	6,350	16.49	16.80	(0.30)	6,671	6,794	(123)	(123)	(181,706)
8	44,250	2,430	6,900	14.82	15.78	(0.96)	5,704	6,074	(370)	(370)	(545,906)
9	42,150	2,130	6,540	16.37	16.61	(0.25)	5,234	5,313	(79)	(79)	(116,491)
10	39,990	1,400	7,000	15.31	16.05	(0.74)	3,444	3,611	(167)	(167)	(246,907)
11	37,500	1,900	7,710	15.01	14.48	0.52	5,047	4,871	176	176	259,516
12	35,800	3,420	6,510	16.43	16.24	0.19	8,398	8,303	96	96	141,080
13	33,150	3,175	4,700	20.87	20.57	0.30	7,150	7,047	102	102	151,068
14	29,450	3,150	4,710	20.86	20.86	0.00	7,106	7,104	2	2	2,347
15	26,850	2,530	5,050	21.64	21.36	0.28	6,347	6,264	83	83	123,021
16	24,400	2,570	5,300	20.27	19.72	0.55	6,338	6,166	172	172	253,873
17	21,700	2,550	6,180	20.87	20.62	0.25	7,550	7,460	90	90	133,167
18	19,300	2,525	5,000	22.04	21.77	0.28	6,388	6,308	80	80	117,718
19	16,650	2,625	5,240	22.62	21.63	0.99	7,143	6,829	314	314	463,741
20	14,050	2,187	3,560	30.16	28.60	1.56	5,391	5,112	279	279	411,278
21	12,275	2,085	3,350	31.13	30.73	0.40	4,992	4,927	64	64	94,812
22	9,880	2,162	3,380	33.43	31.79	1.64	5,608	5,333	274	274	405,053
23	7,950	2,175	3,520	35.94	33.58	2.36	6,317	5,903	414	414	611,712
24	5,530	2,400	4,450	41.64	38.61	3.04	10,210	9,465	745	745	1,100,243
25	3,150	1,915	4,610	49.07	45.61	3.46	9,946	9,244	702	702	1,036,292
26	1,700	2,425	4,750	52.75	49.56	3.19	13,949	13,105	844	844	1,246,207
Total	-	-	-	-	-	-	**167,234**	**163,800**	**3,434**	**3,434**	**5,070,661**

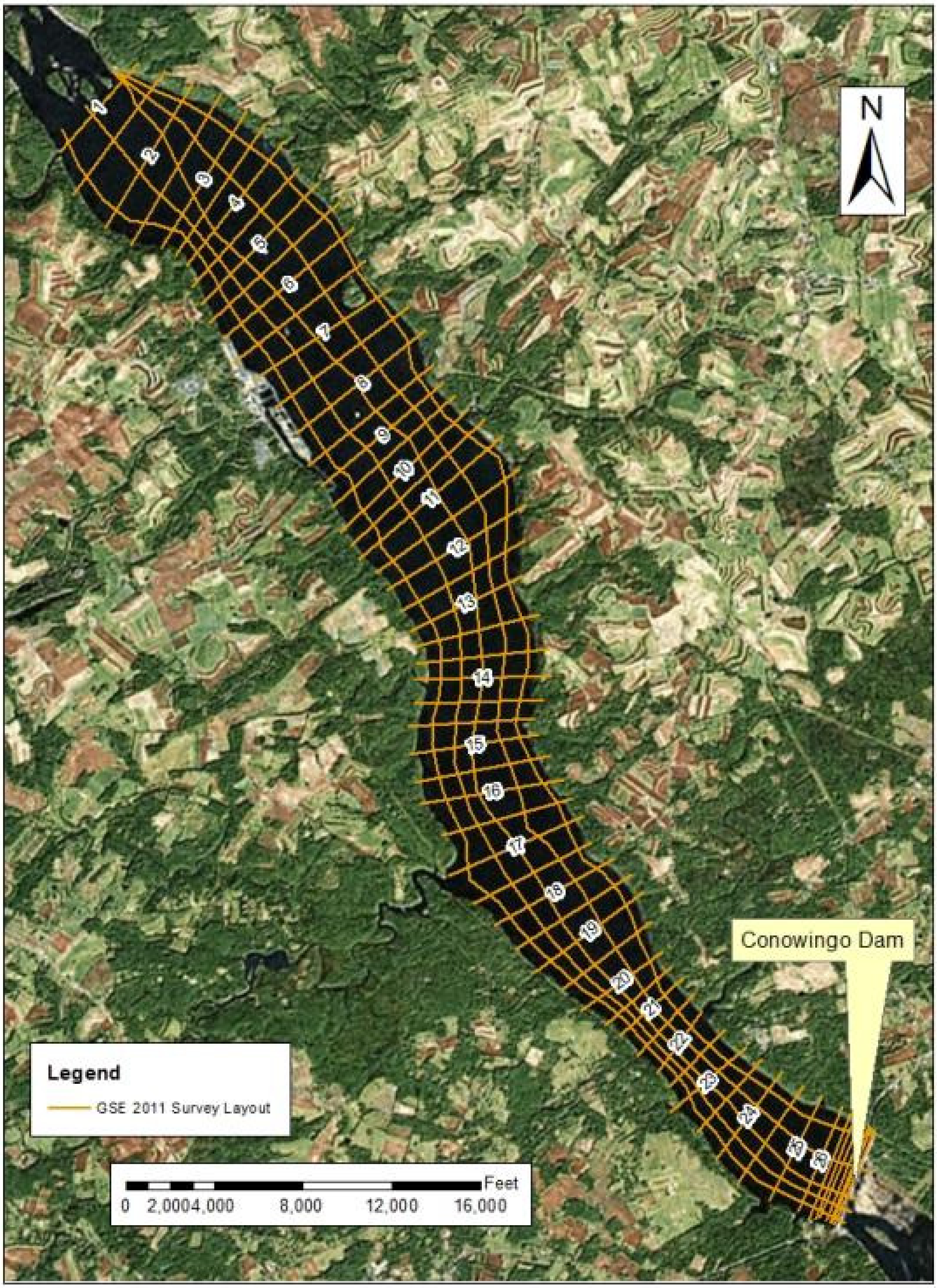


Figure 1: GSE 2011 data collection transects. Numbers shown are USGS 2008 XC numbers.

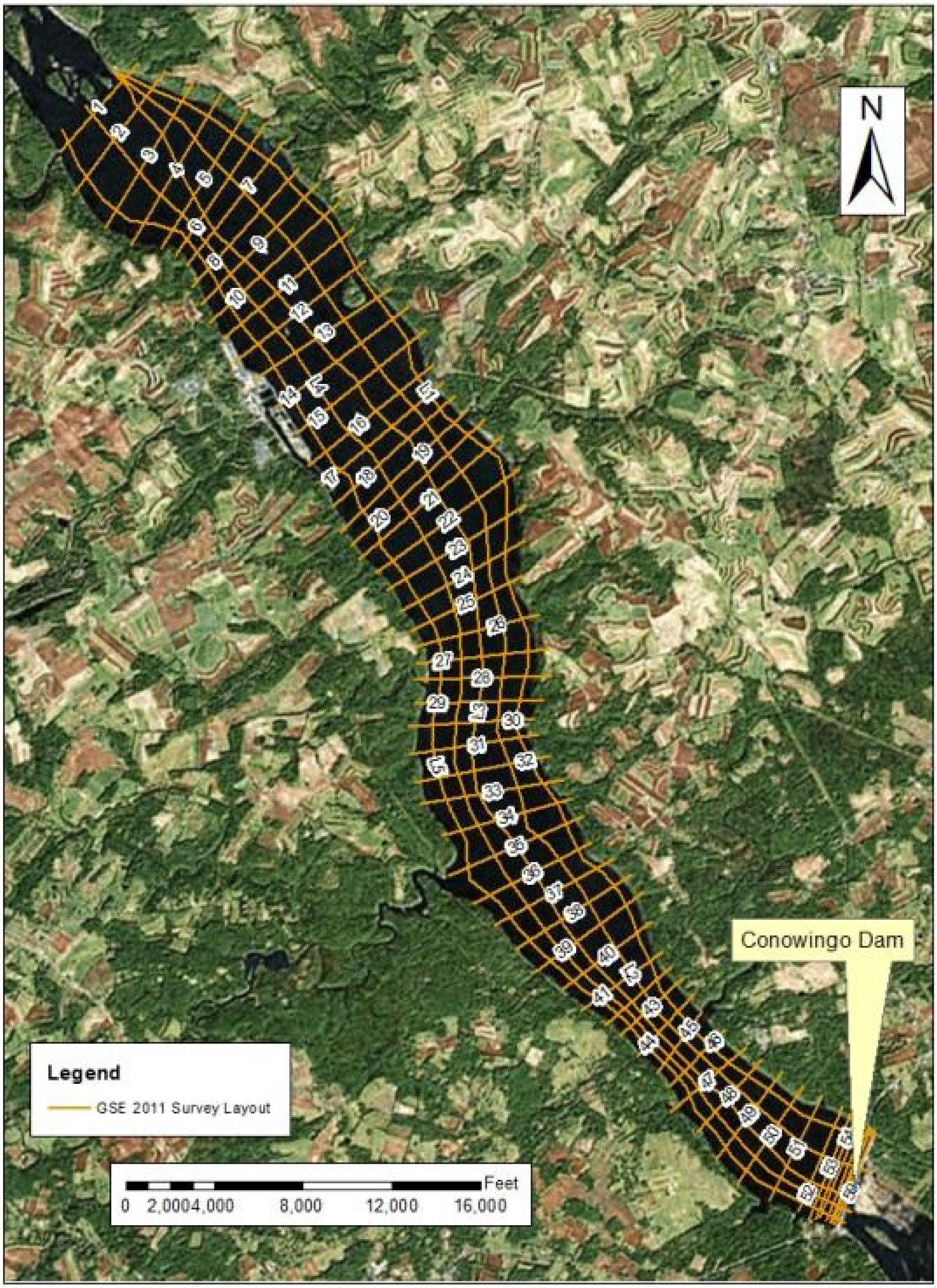


Figure 2: GSE 2011 data collection transects, with GSE 2011 transect numbers.

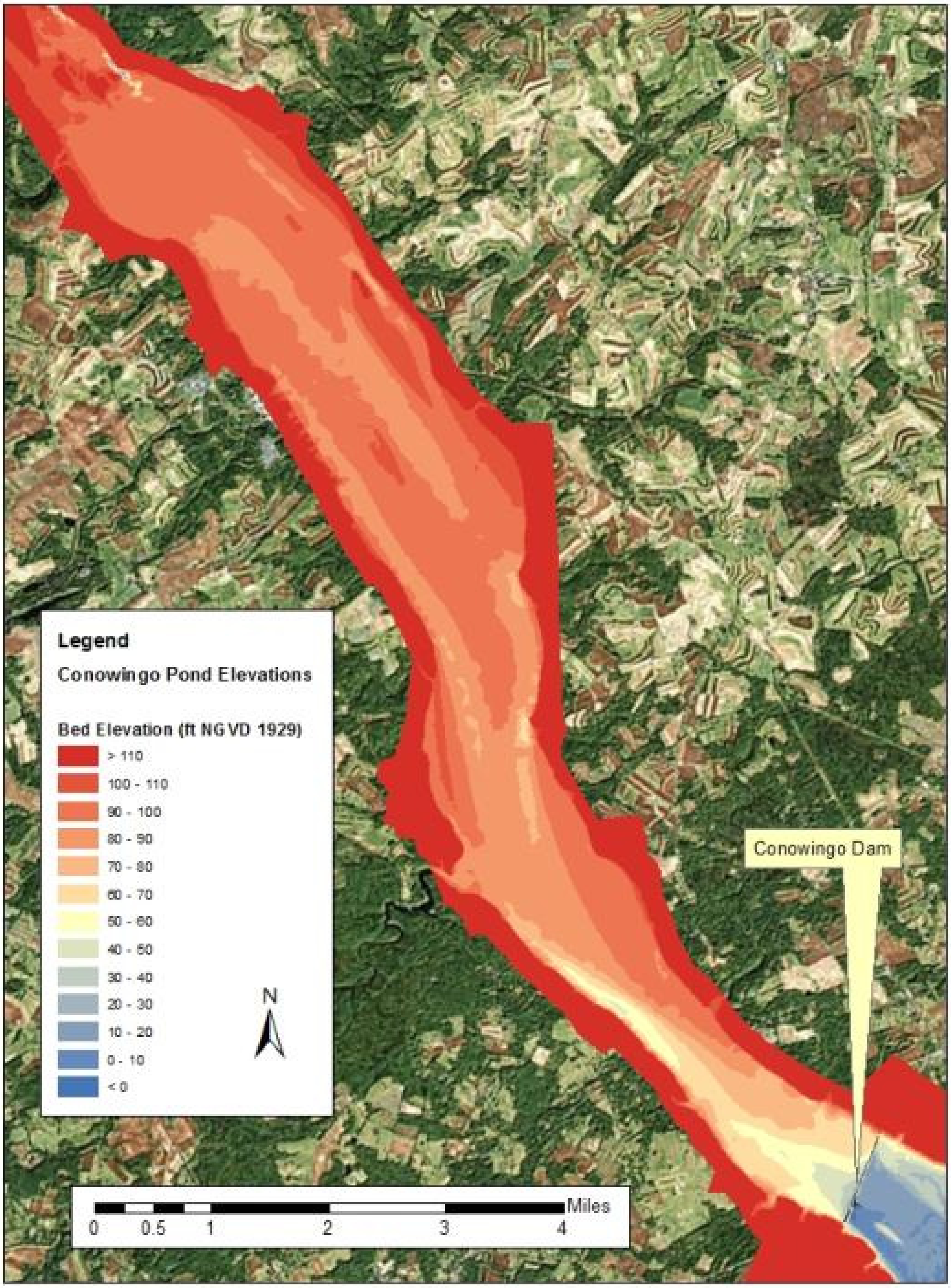


Figure 3: Composite elevation data set including 2011 Conowingo Pond data.

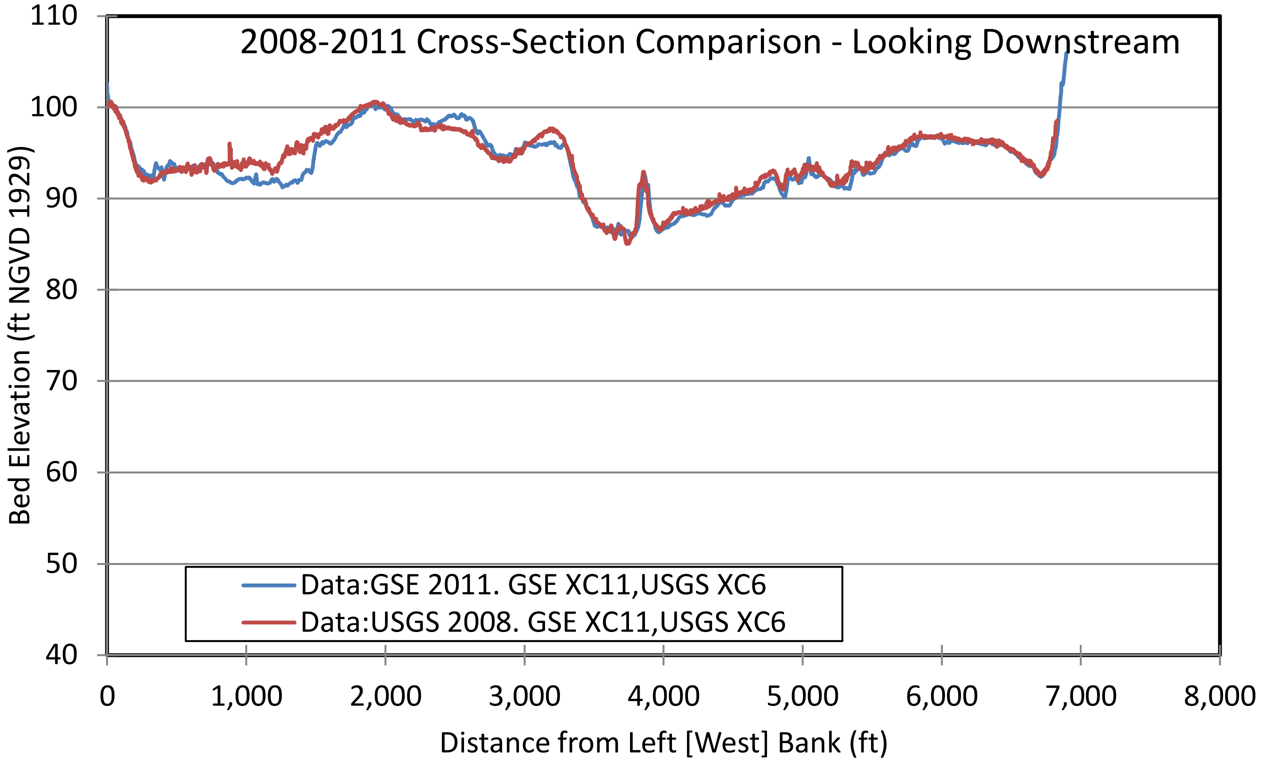


Figure 4: Plot comparing USGS 2008 and GSE 2011 cross-sections at USGS XC 2, located approximately 11.3 miles upstream of Conowingo Dam.

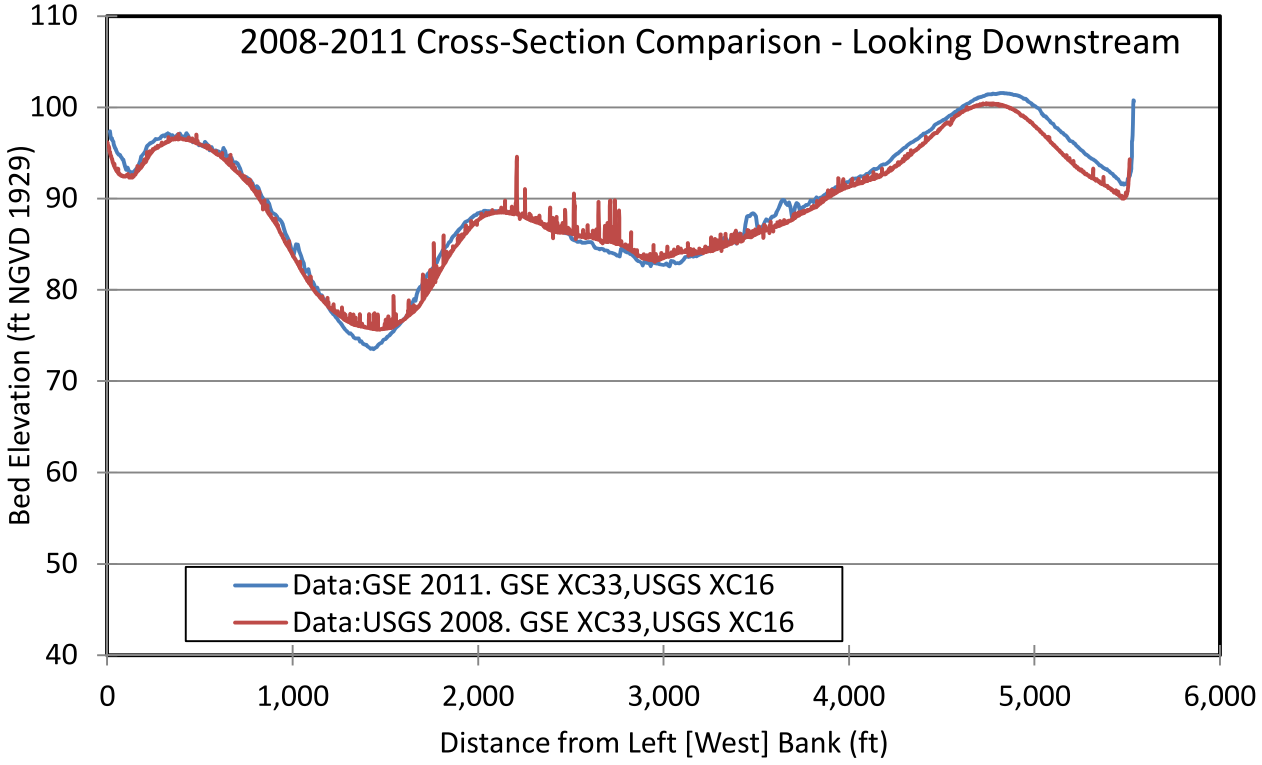
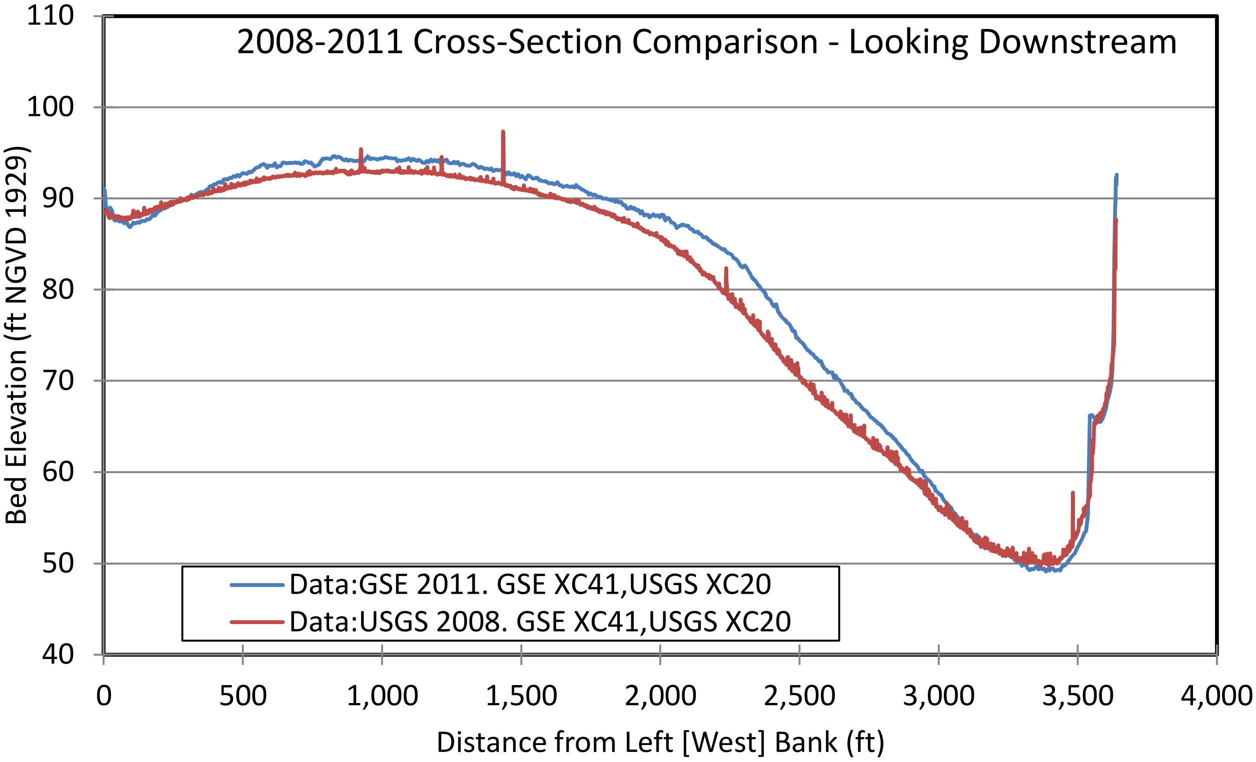


Figure 5: Plot comparing USGS 2008 and GSE 2011 cross-sections at USGS XC 16, located approximately 4.7 miles upstream of Conowingo Dam.



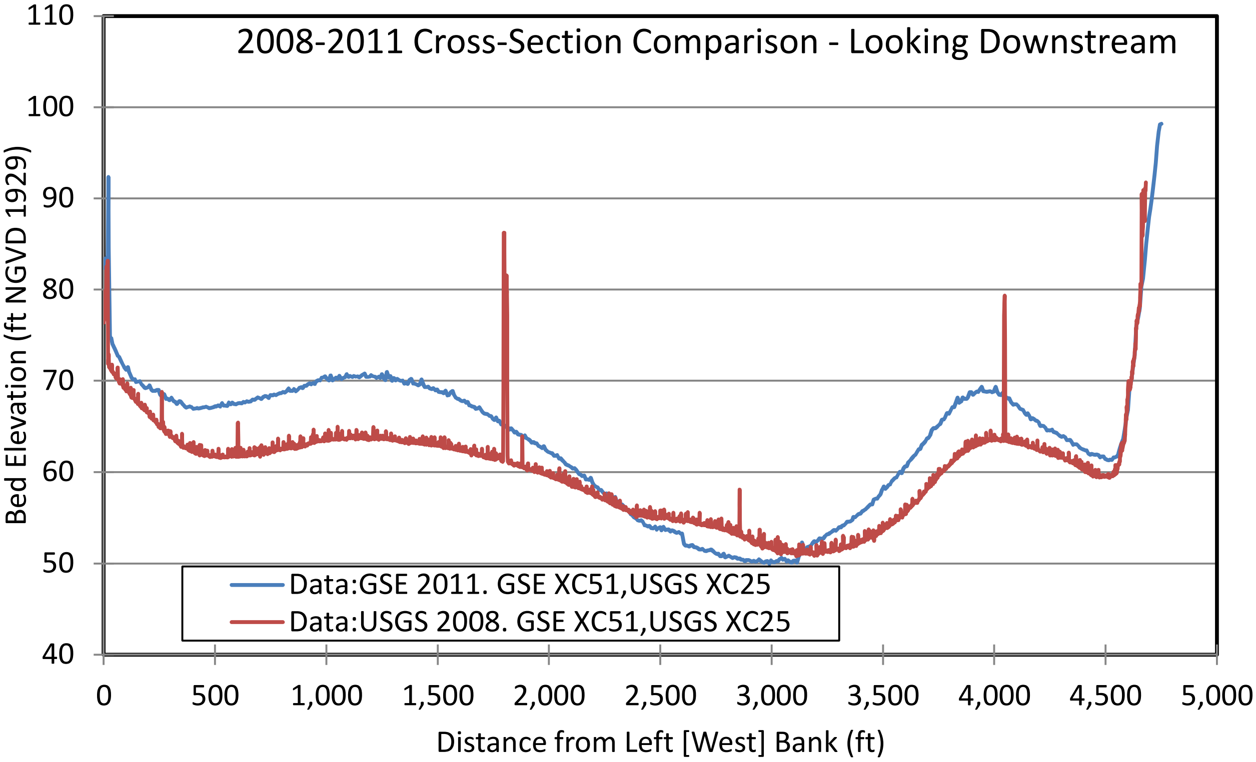


Figure 6: Comparison of two lower Pond transects. USGS XC 20 and 25 located 2.7 and 0.6 miles upstream of Conowingo Dam, respectively.

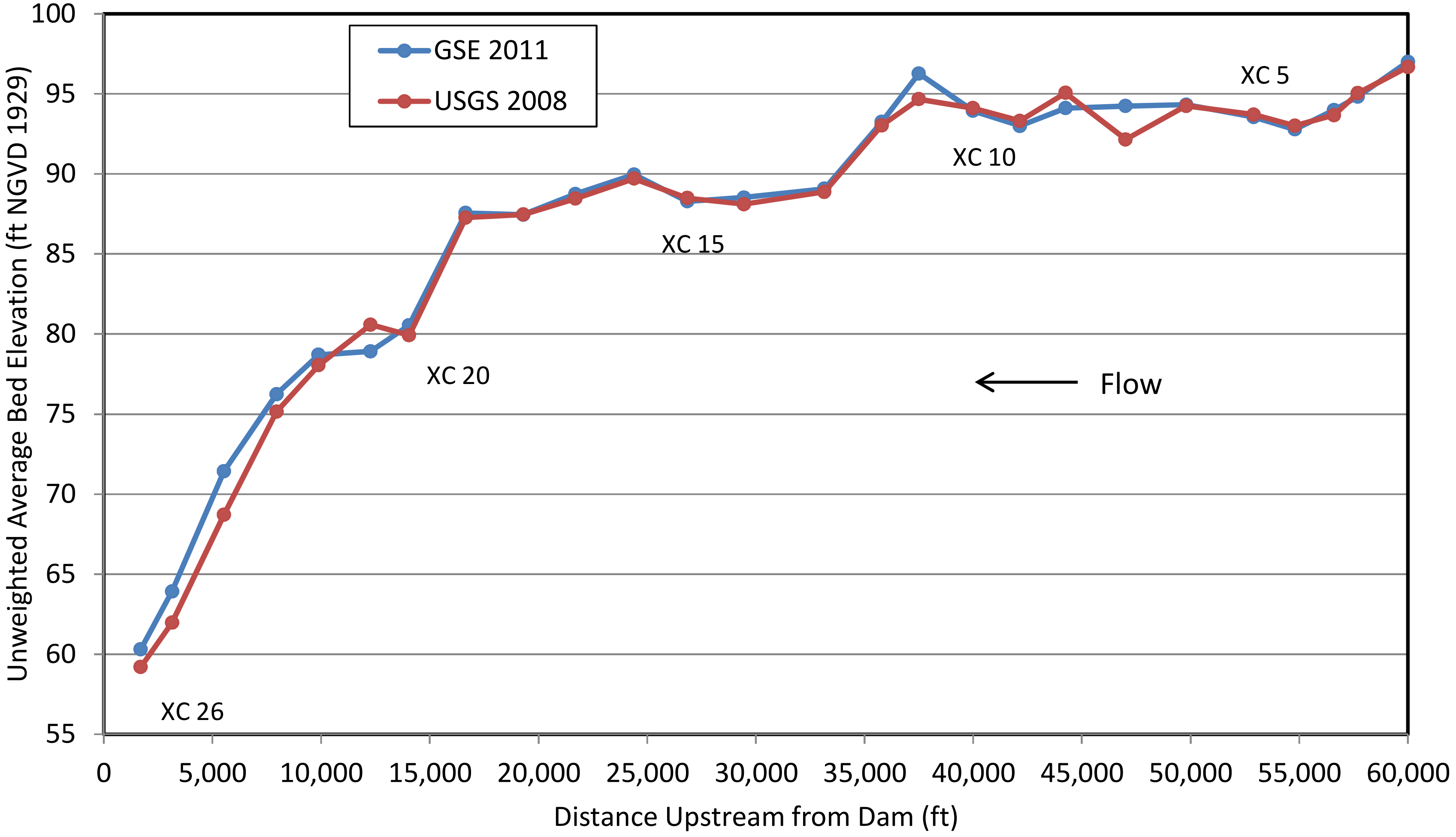


Figure 7: Unweighted average transect bed elevation versus distance upstream from Conowingo Dam.

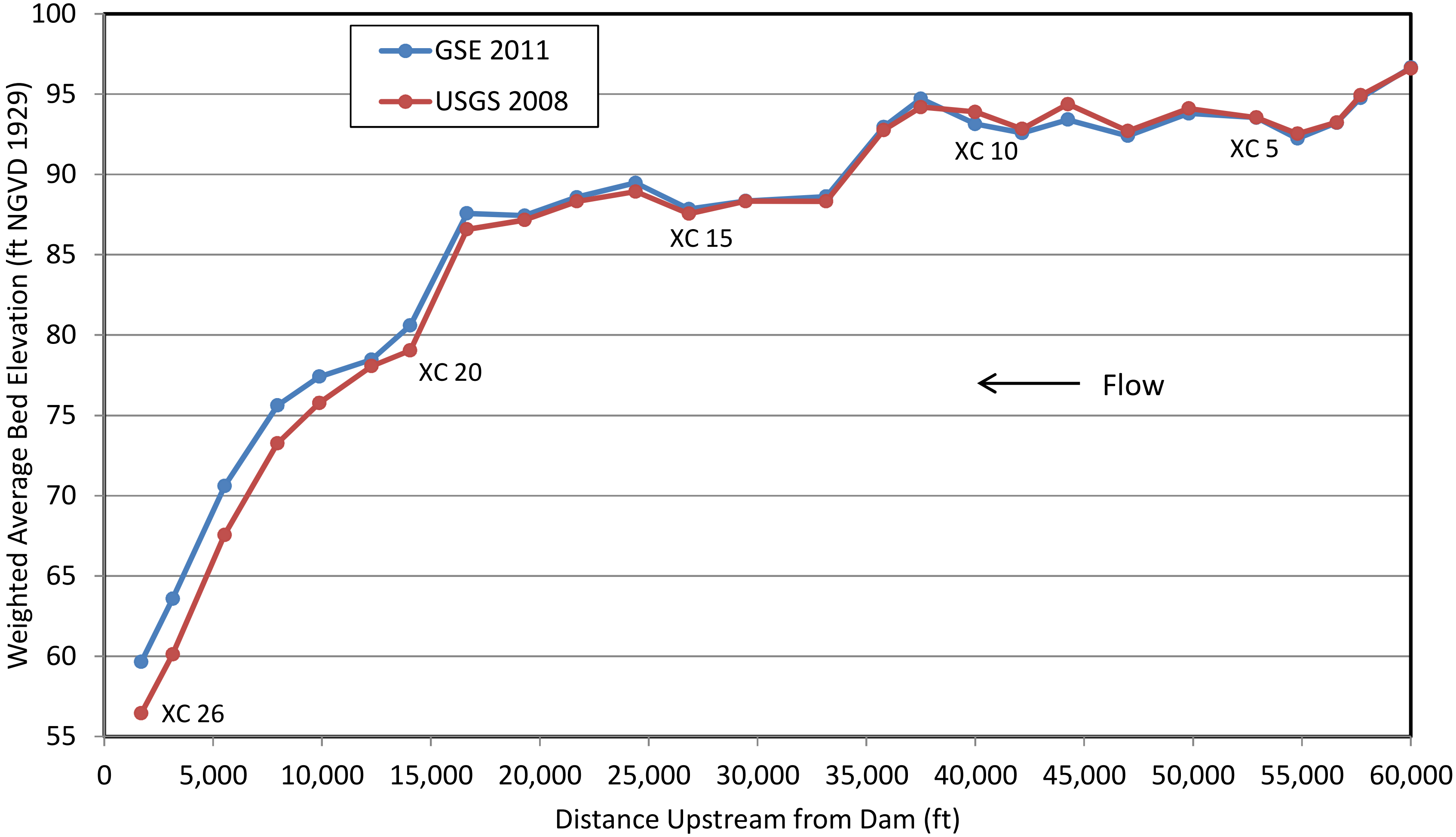


Figure 8: Weighted average transect bed elevation versus distance upstream from Conowingo Dam.

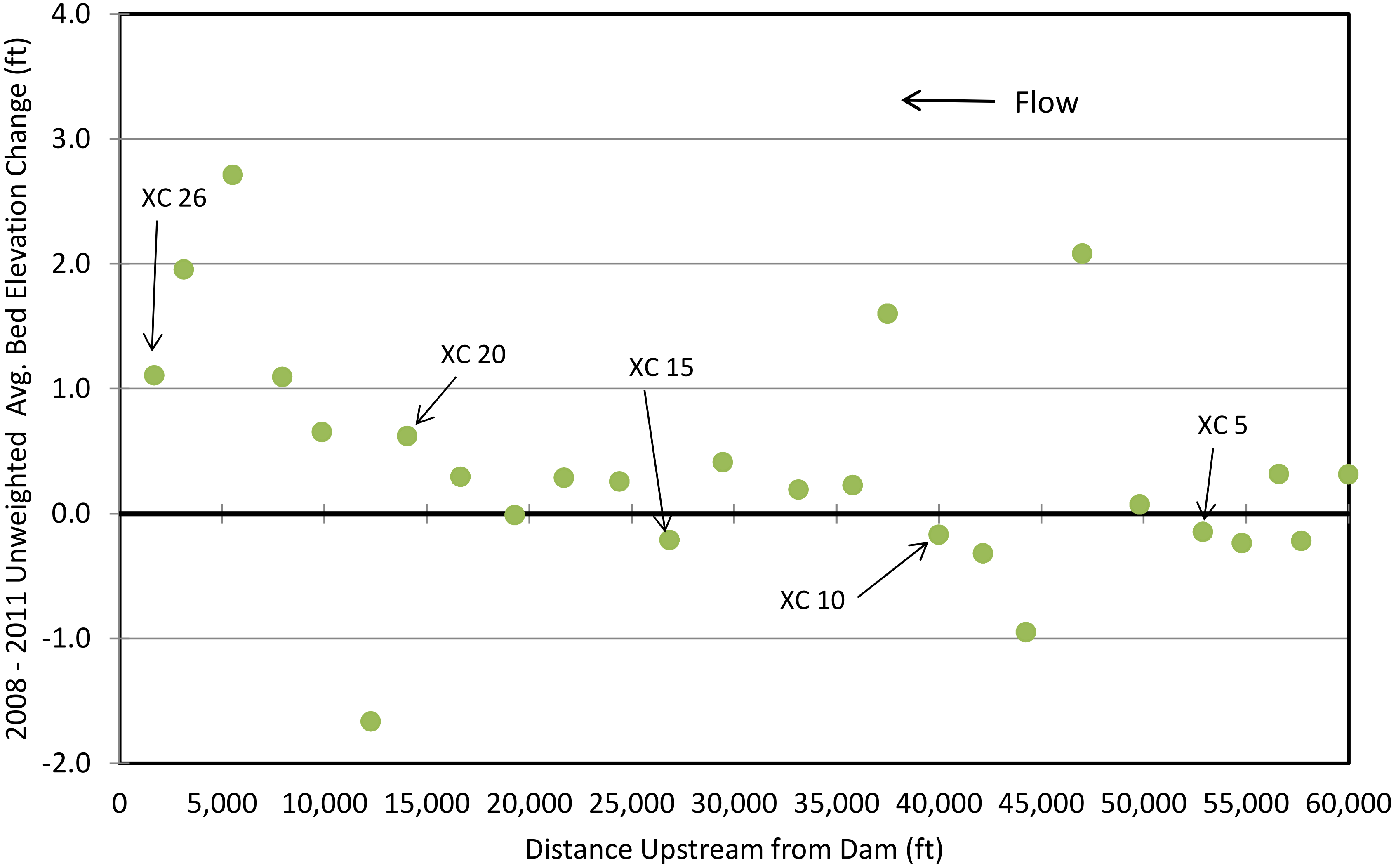


Figure 9: Unweighted average bed elevation change longitudinal profile, showing net deposition (positive values) and net scour (negative values).

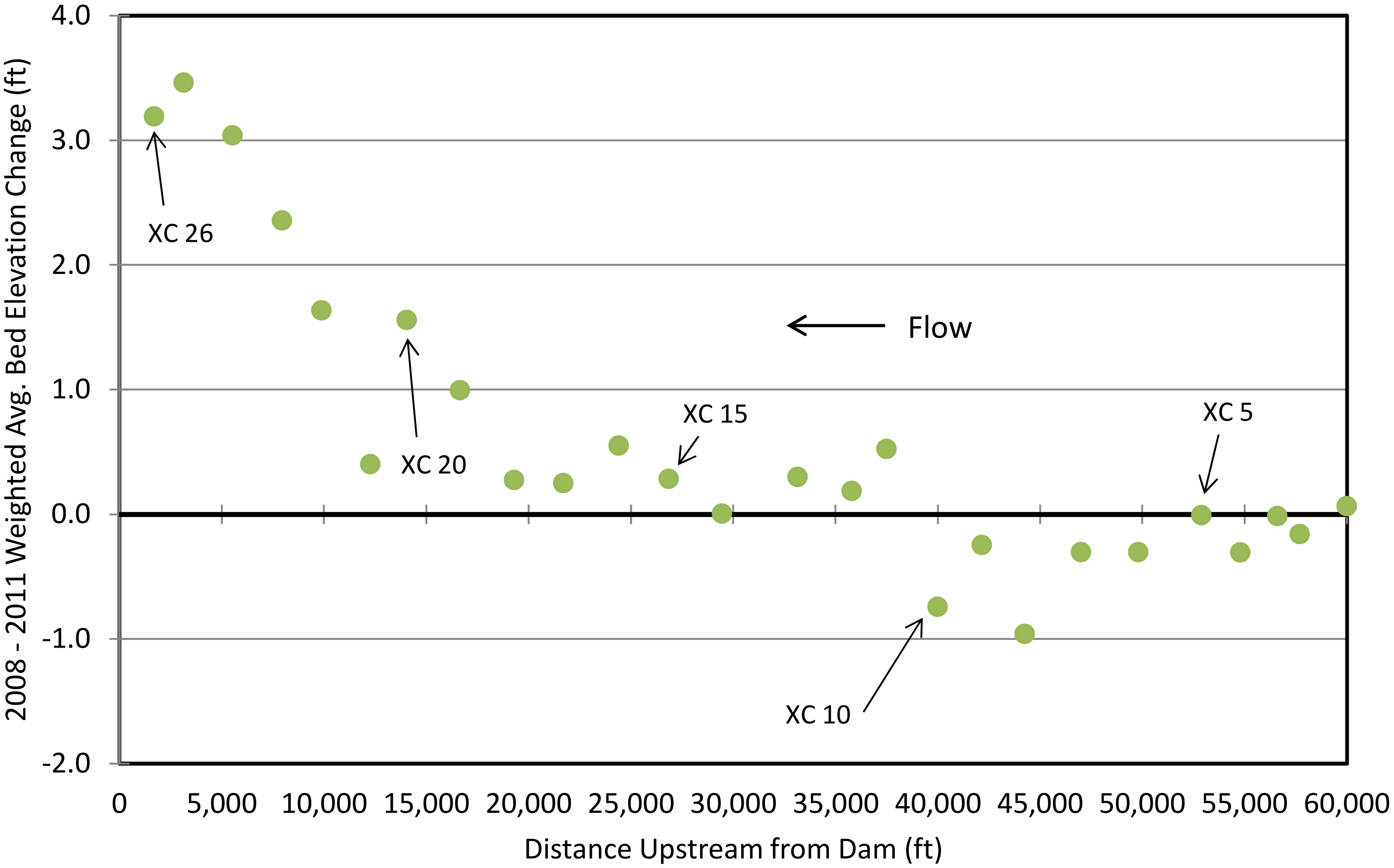
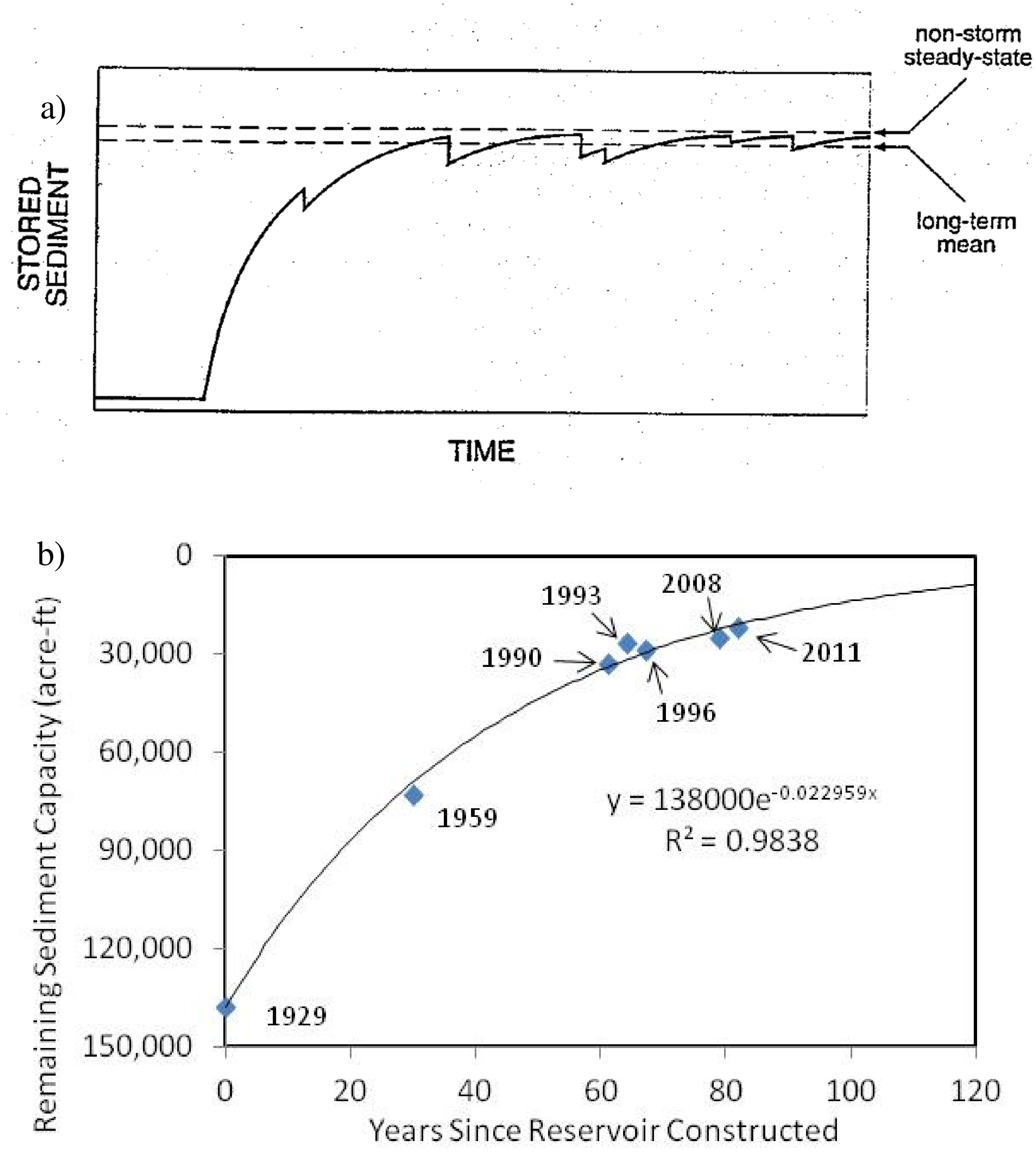


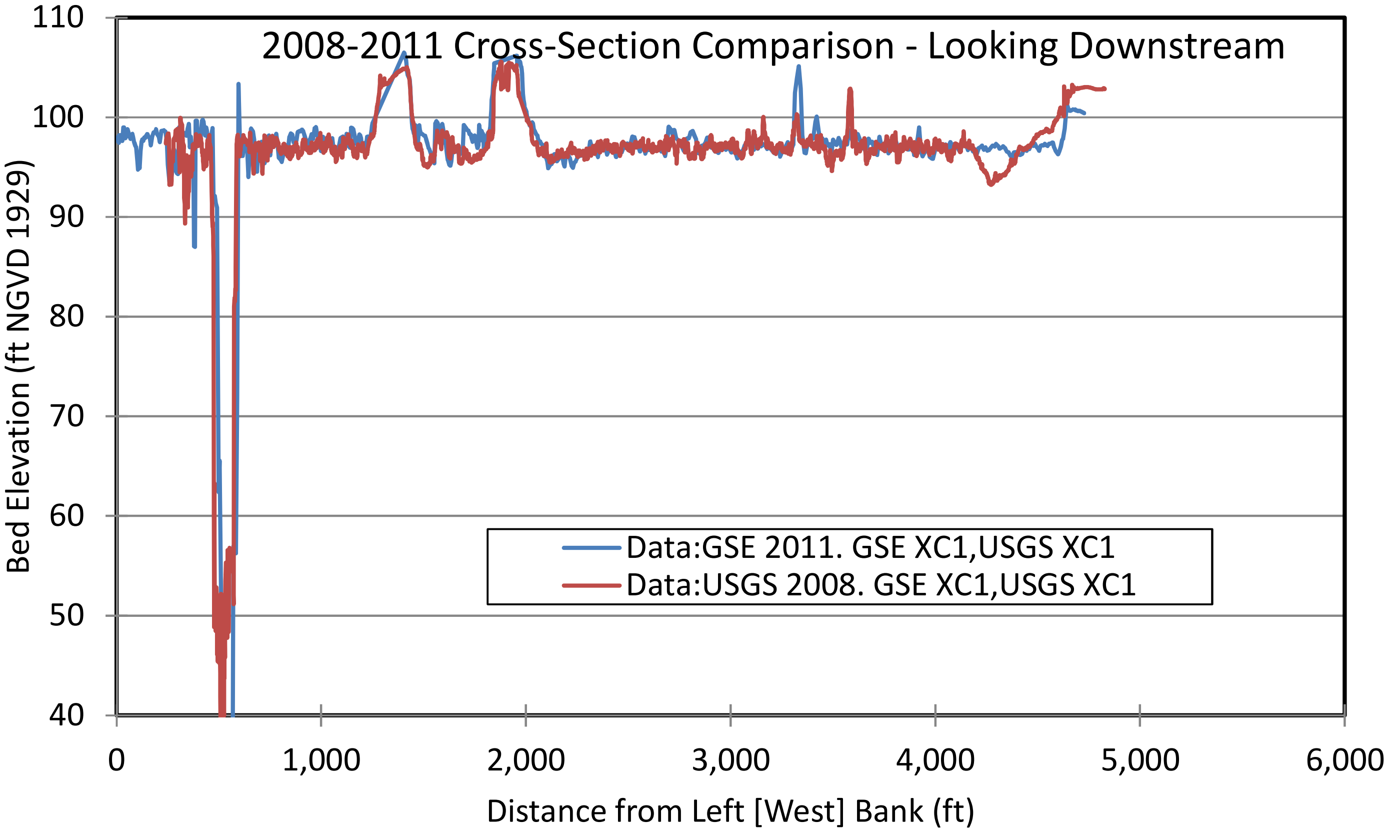
Figure 10: Weighted average bed elevation change longitudinal profile, showing net deposition (positive values) and net scour (negative values).

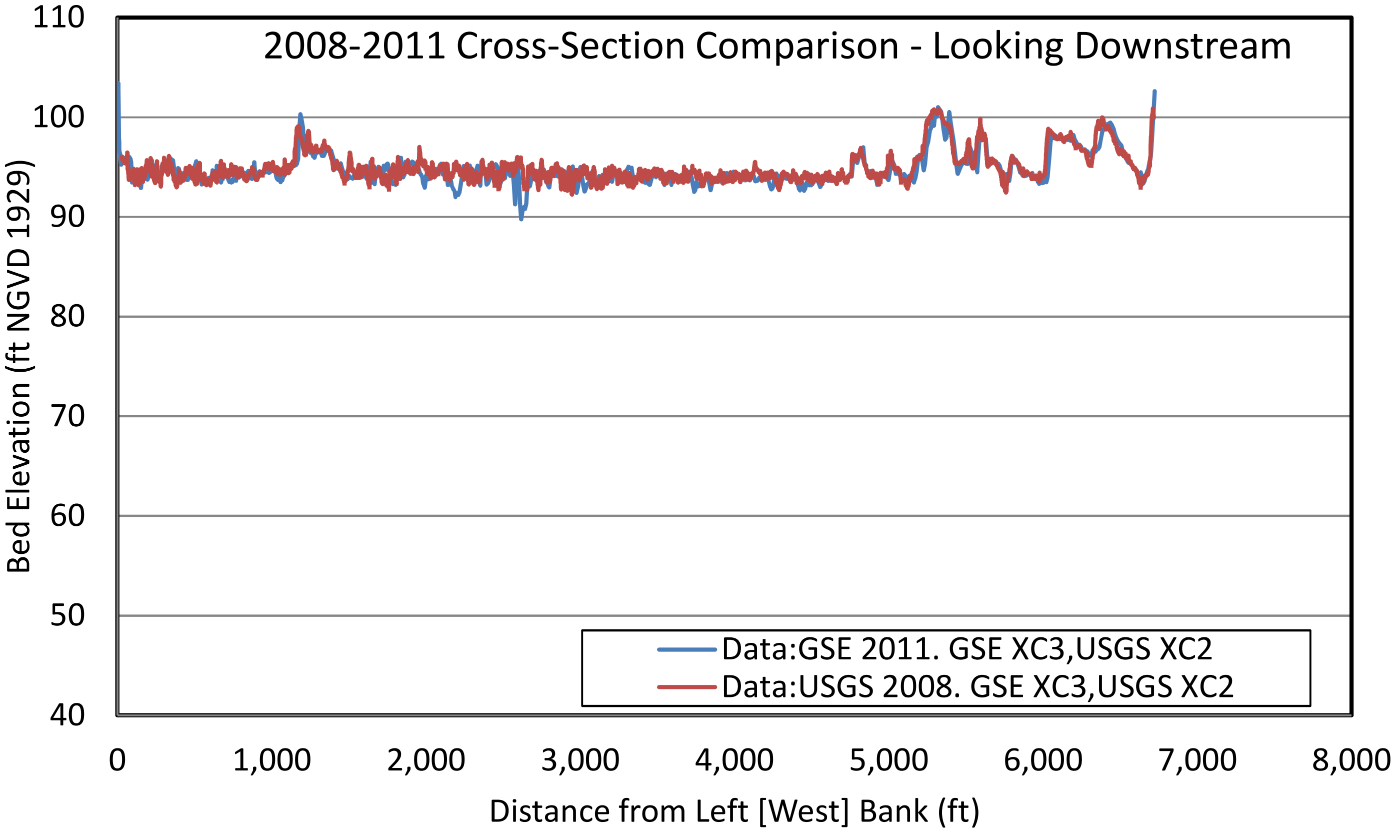


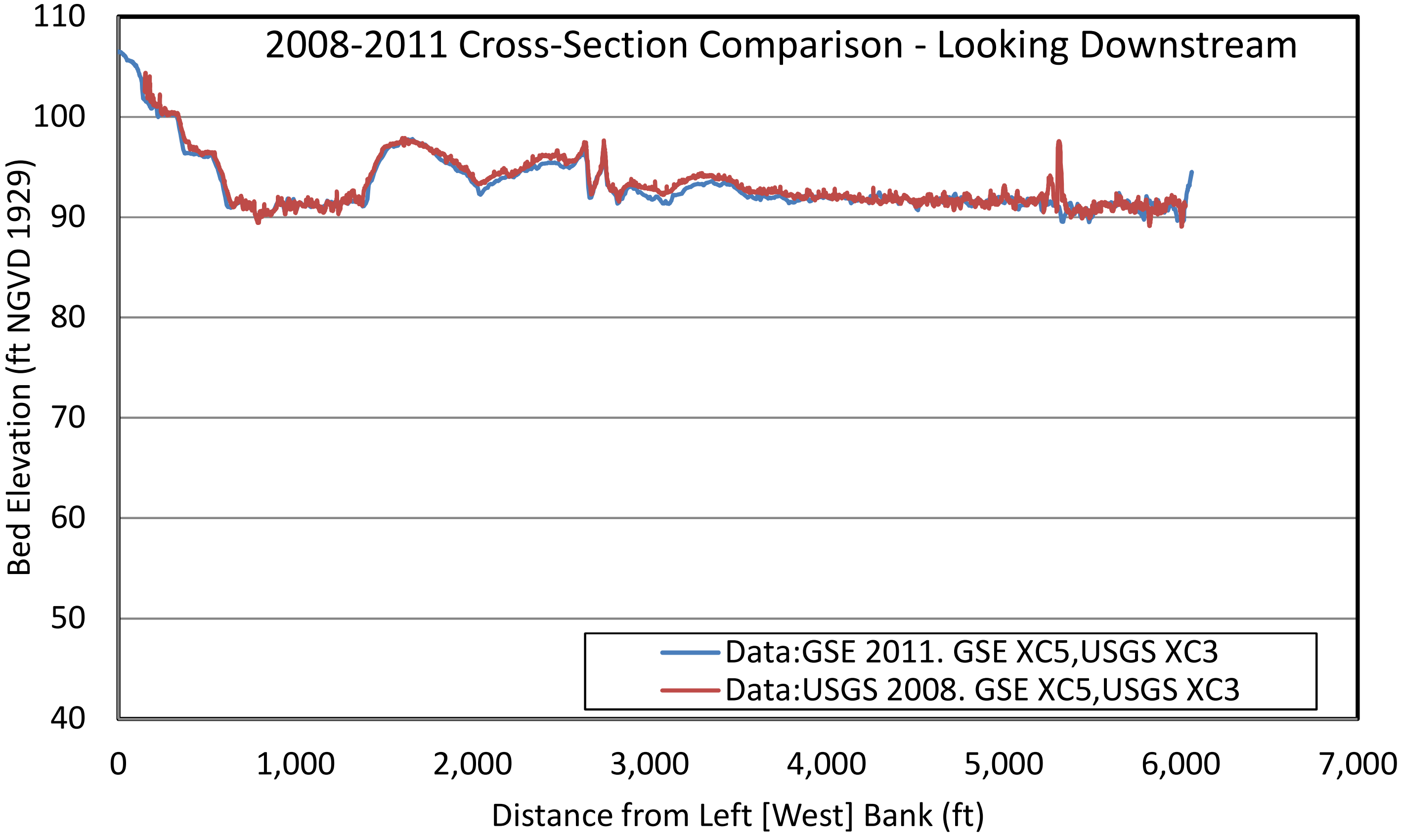
*Calculations assume the steady state reservoir water volume is 142,000 acre-ft

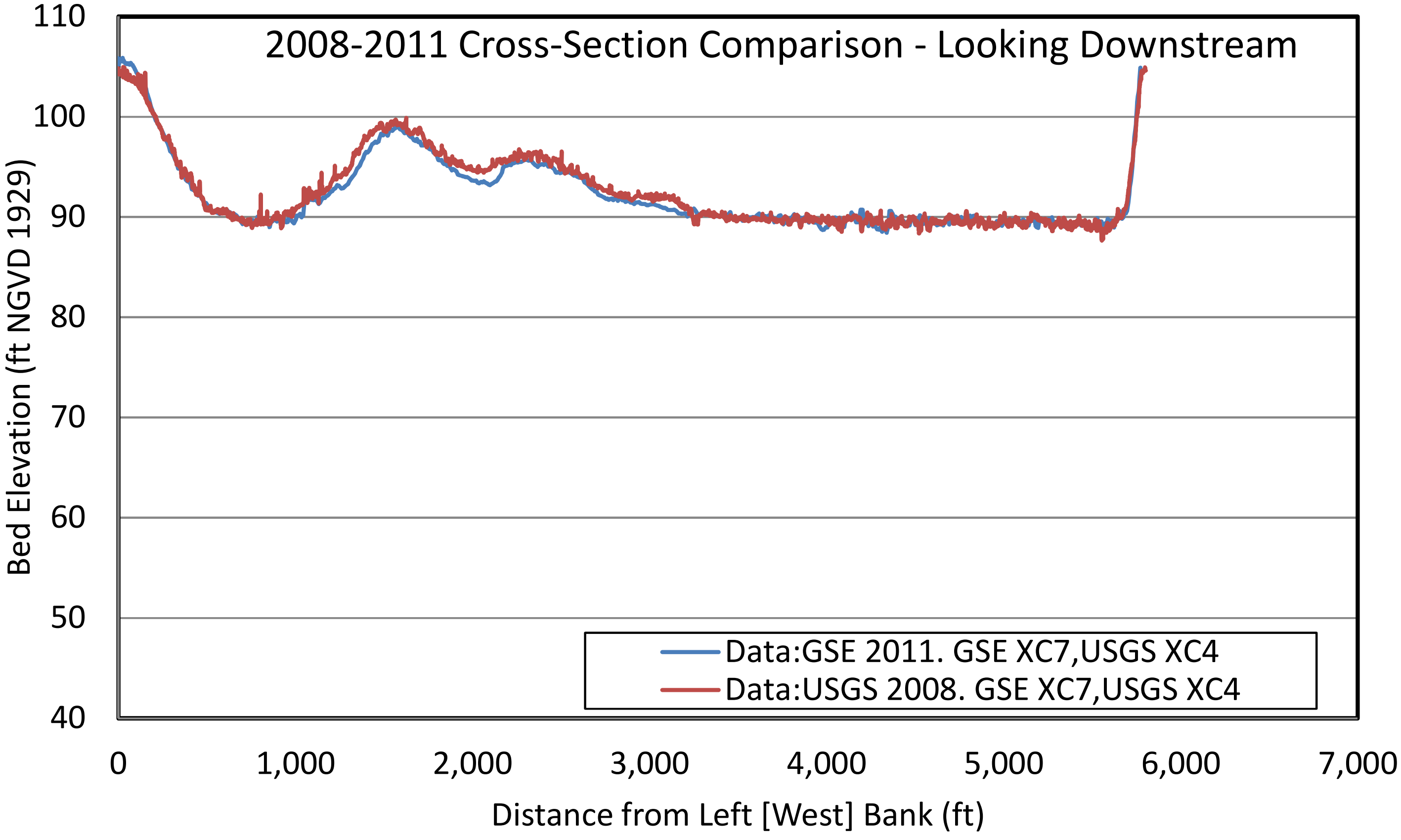
Figure 11: Comparison of a) sediment stored versus time for a general reservoir, taken from Academy of Natural Sciences (1994); and b) Conowingo Pond's estimated remaining sediment capacity versus time since the reservoir was constructed.

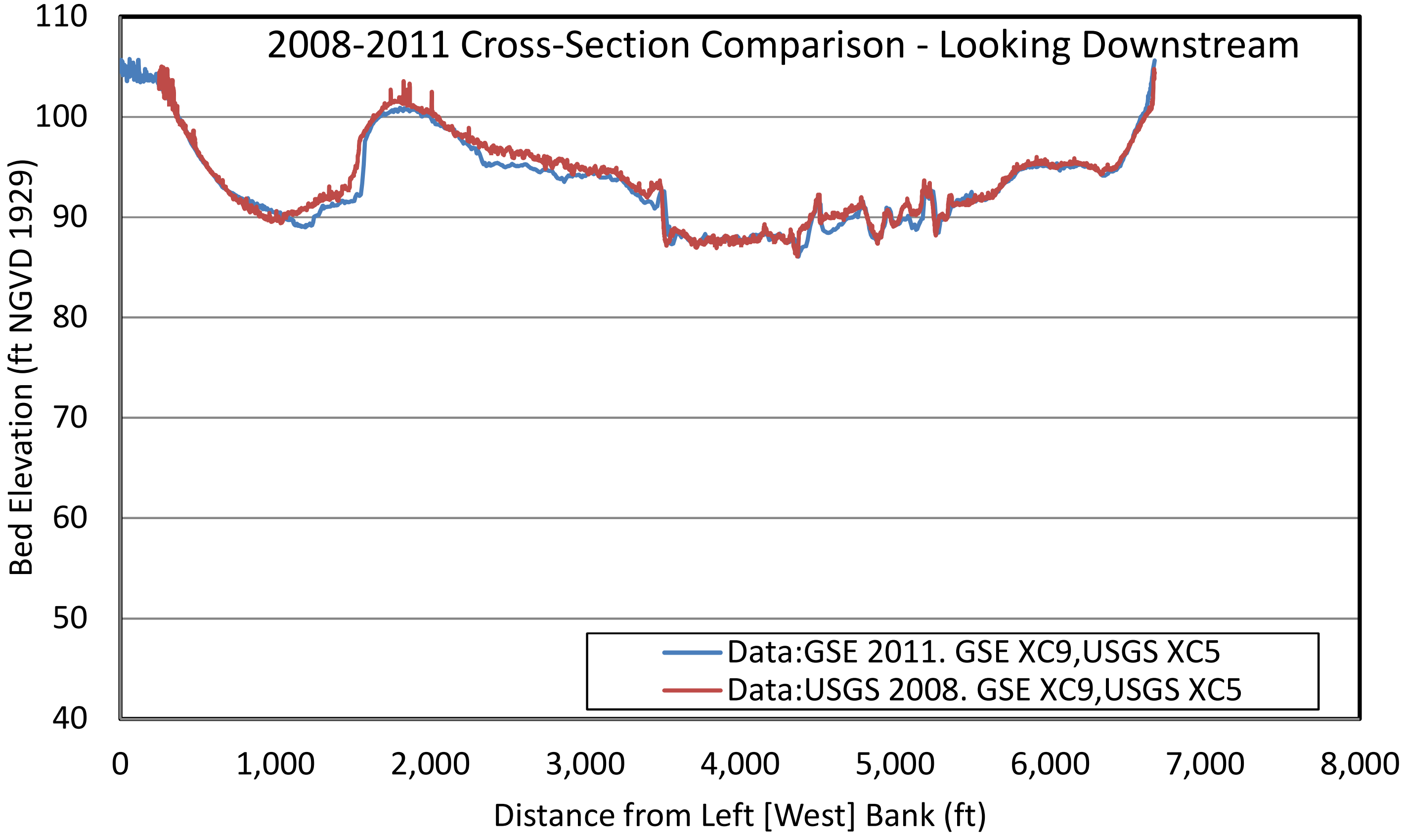
Appendix A: Historic Cross-Section Comparison

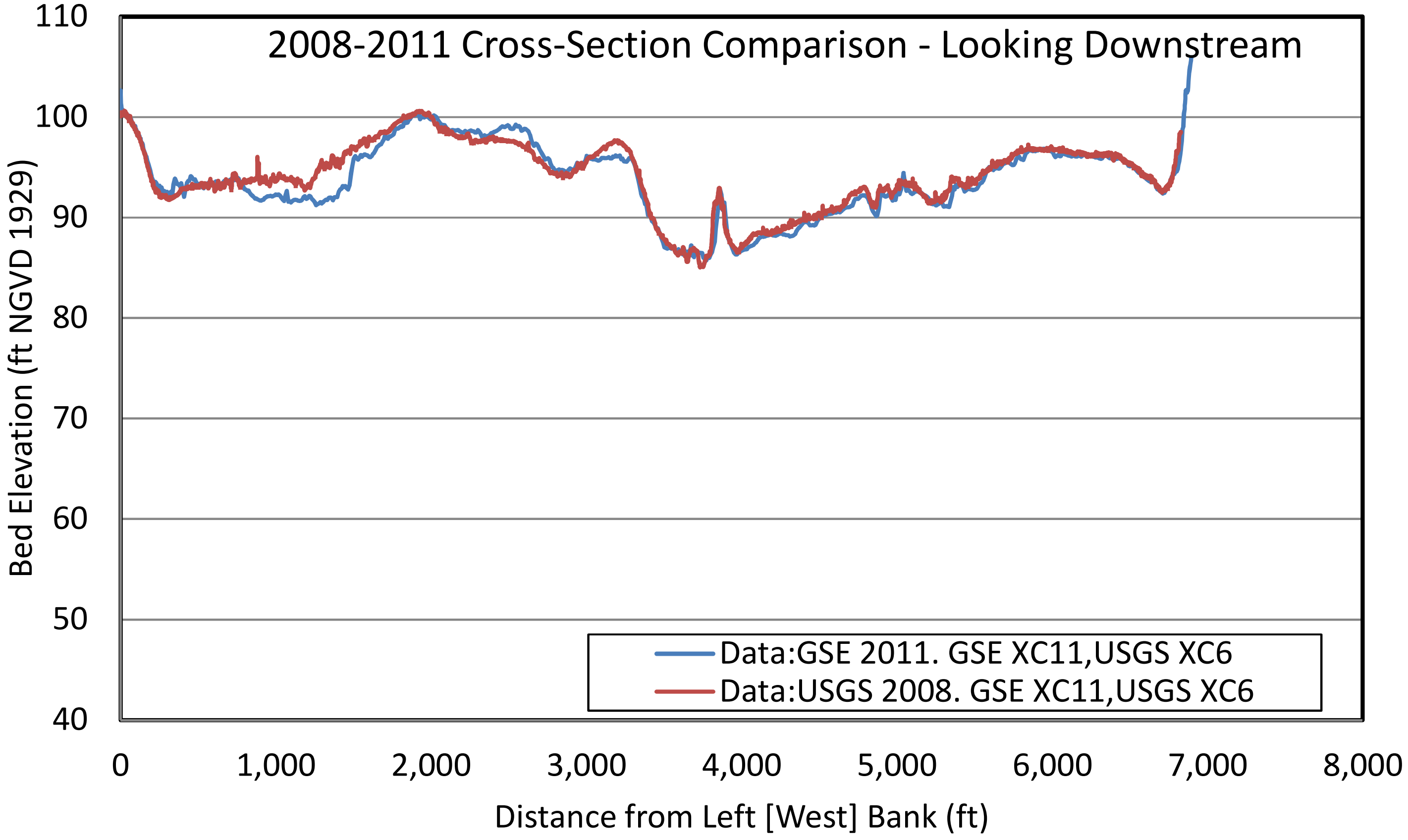


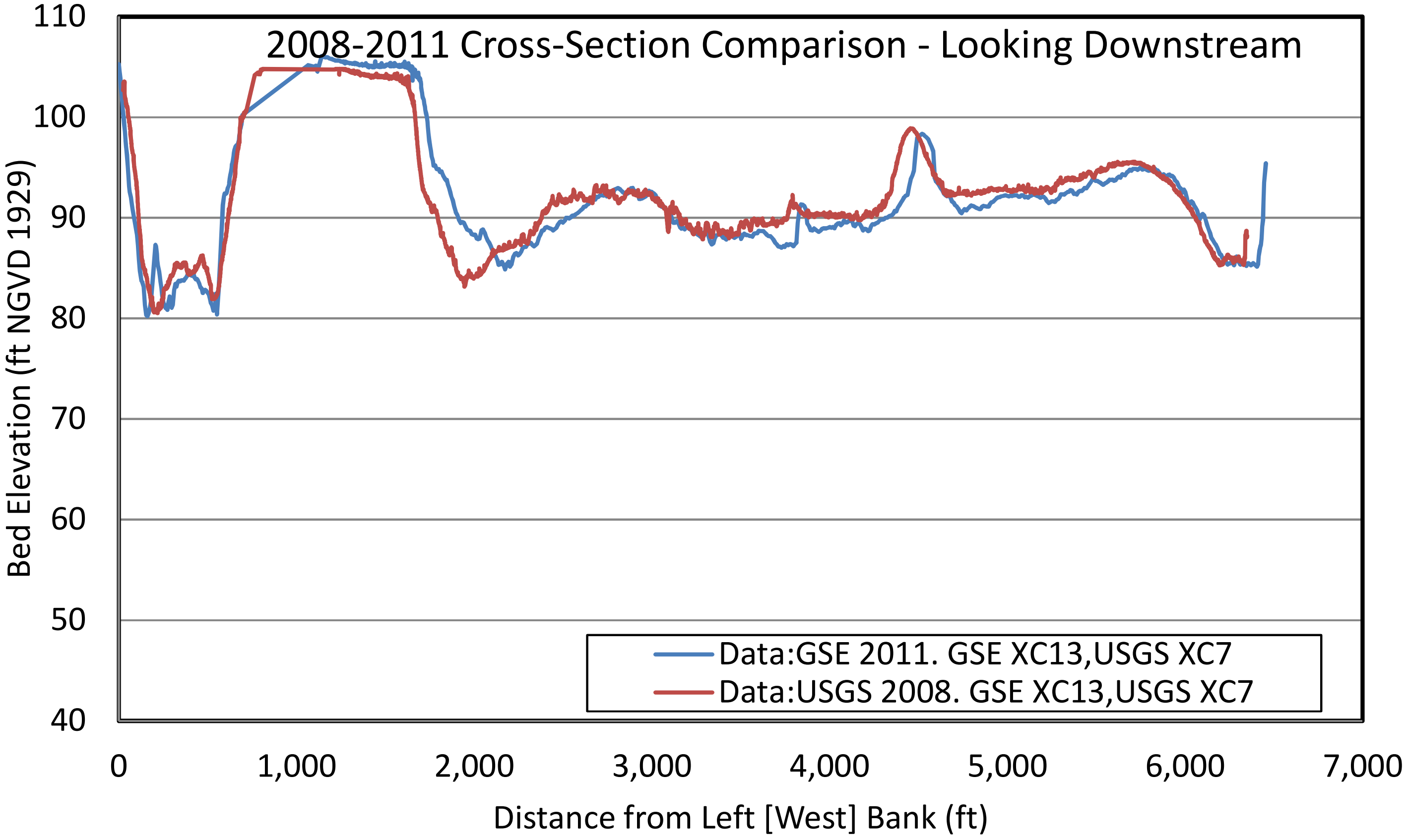


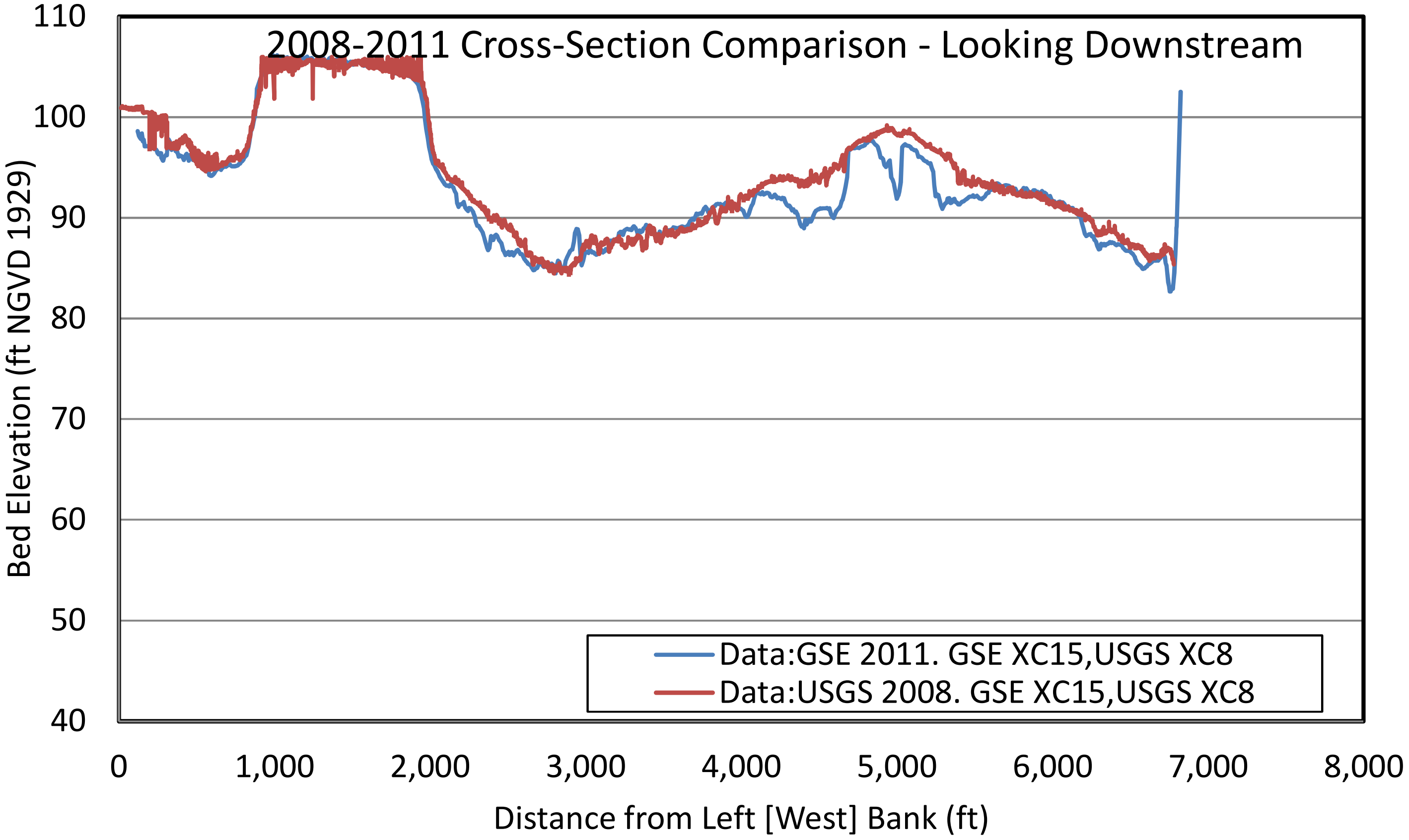

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC5,USGS XC3
Data:USGS 2008. GSE XC5,USGS XC3

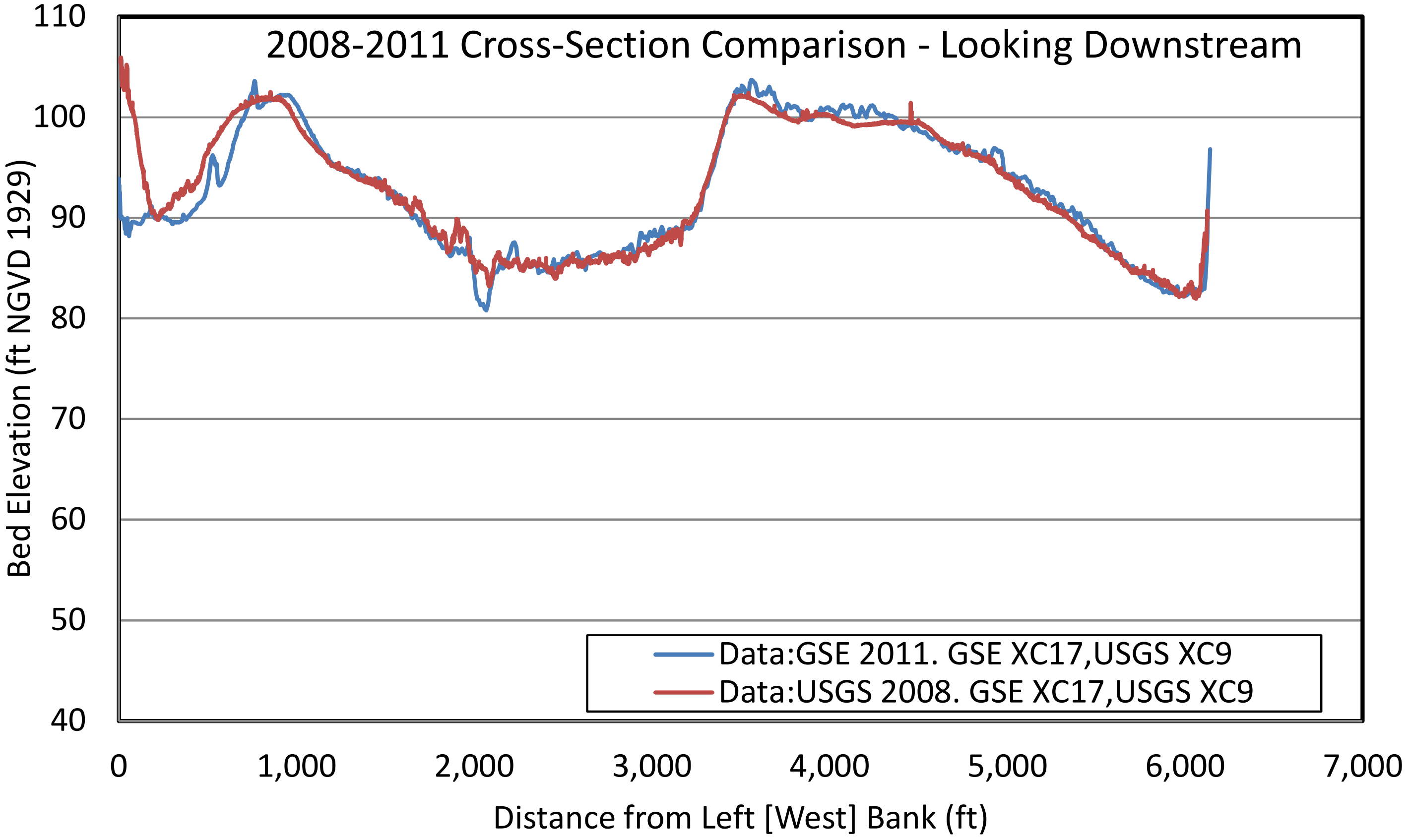

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC7,USGS XC4
Data:USGS 2008. GSE XC7,USGS XC4

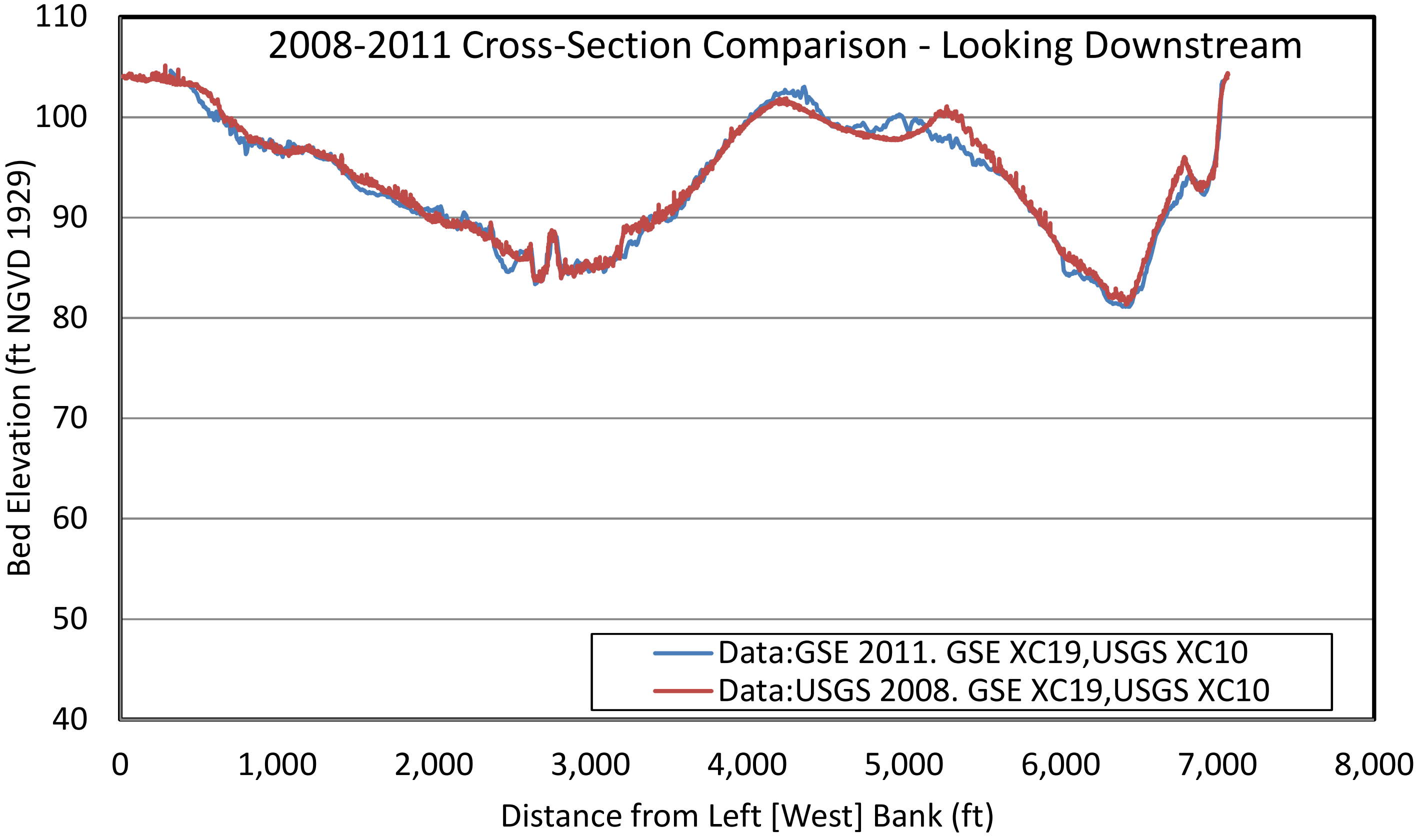

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC9,USGS XC5
Data:USGS 2008. GSE XC9,USGS XC5

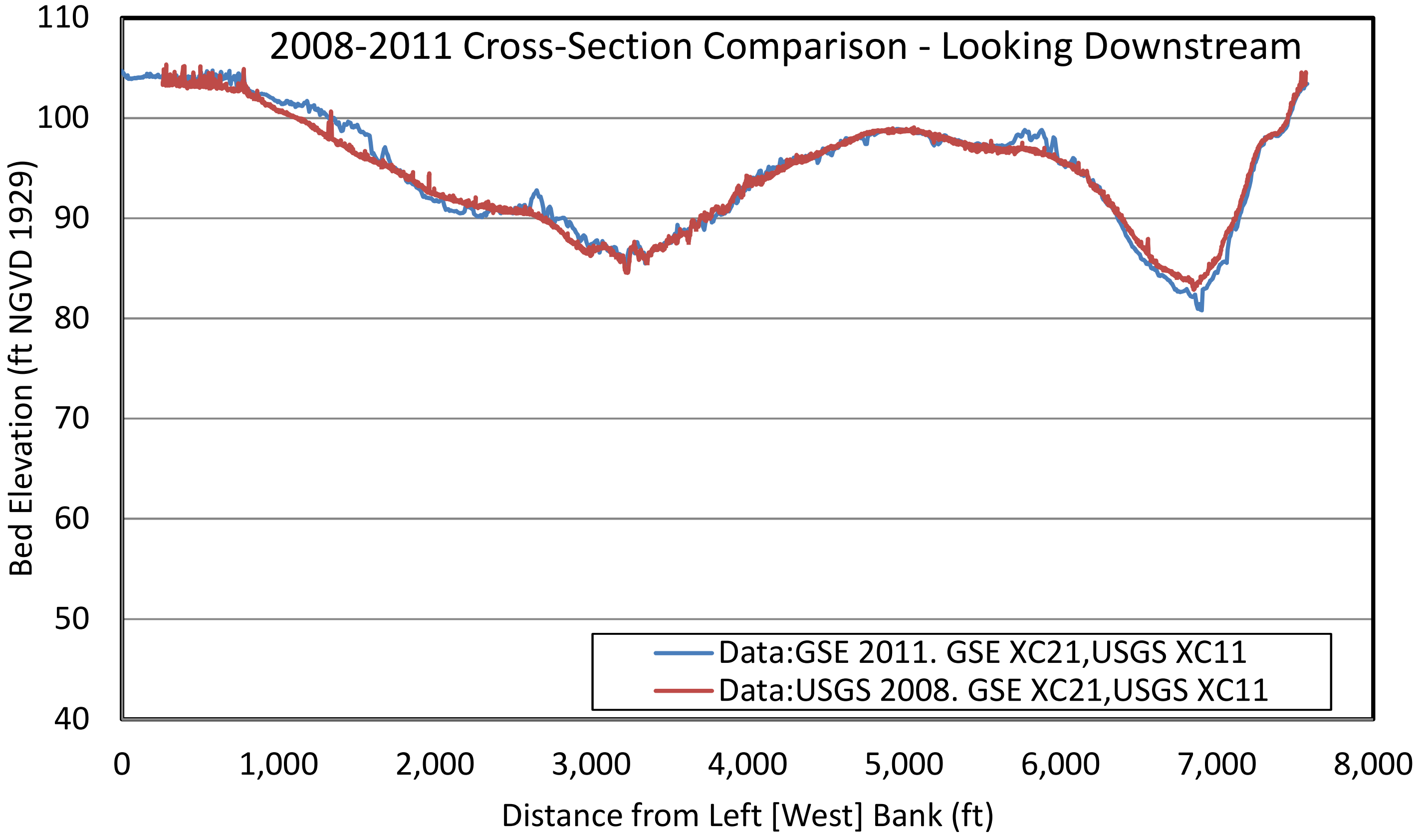

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC11,USGS XC6
Data:USGS 2008. GSE XC11,USGS XC6

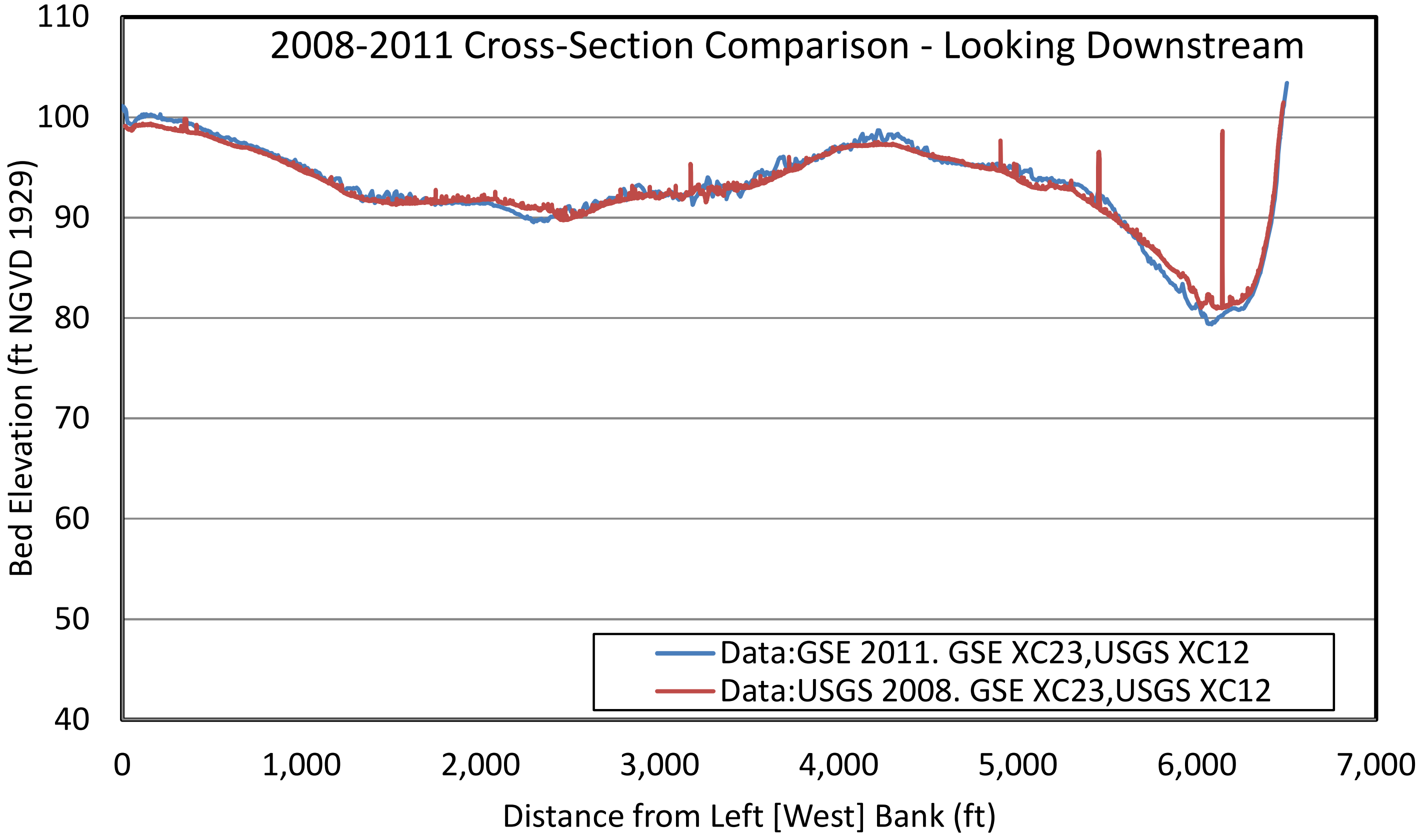

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC13,USGS XC7
Data:USGS 2008. GSE XC13,USGS XC7

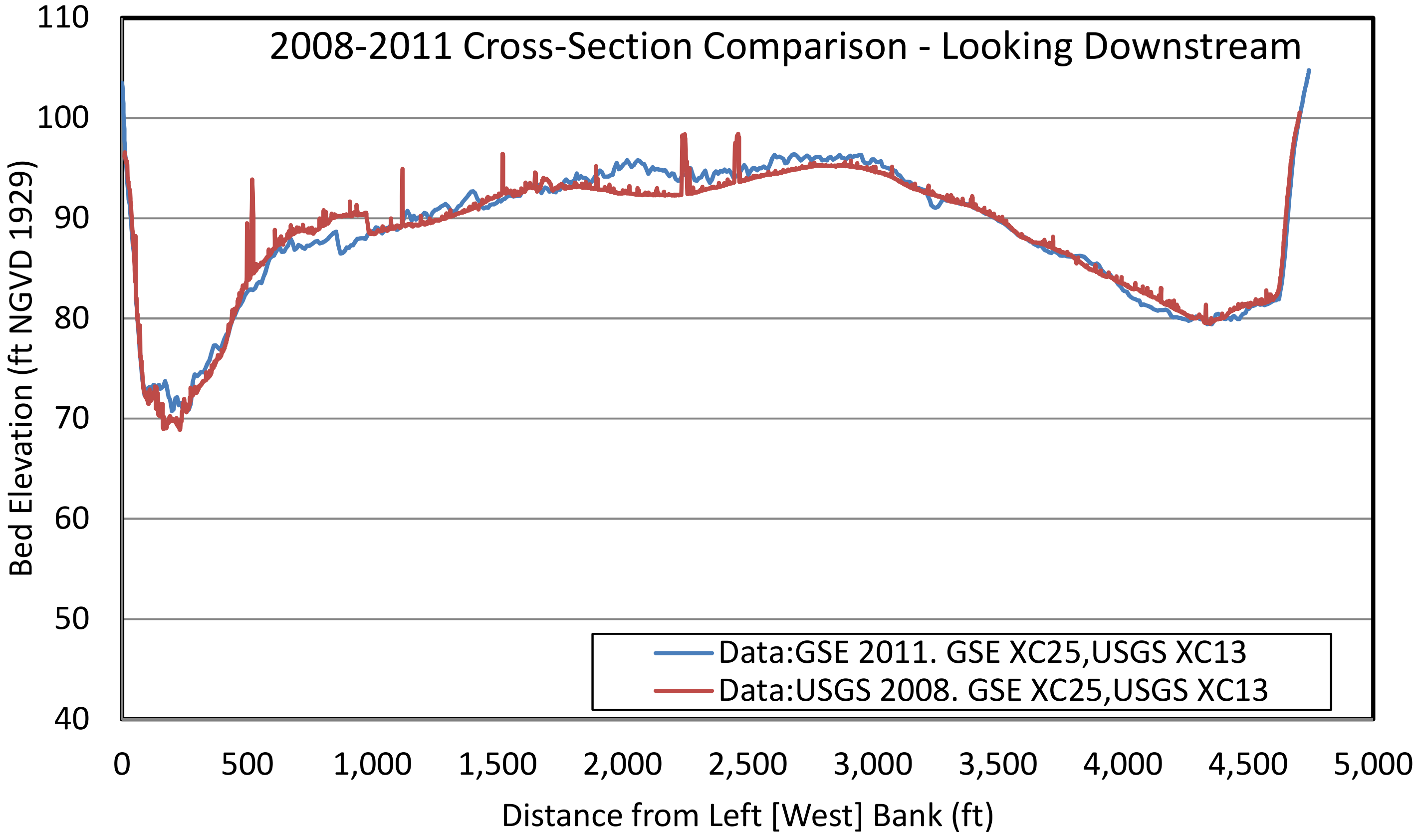

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC15,USGS XC8
Data:USGS 2008. GSE XC15,USGS XC8

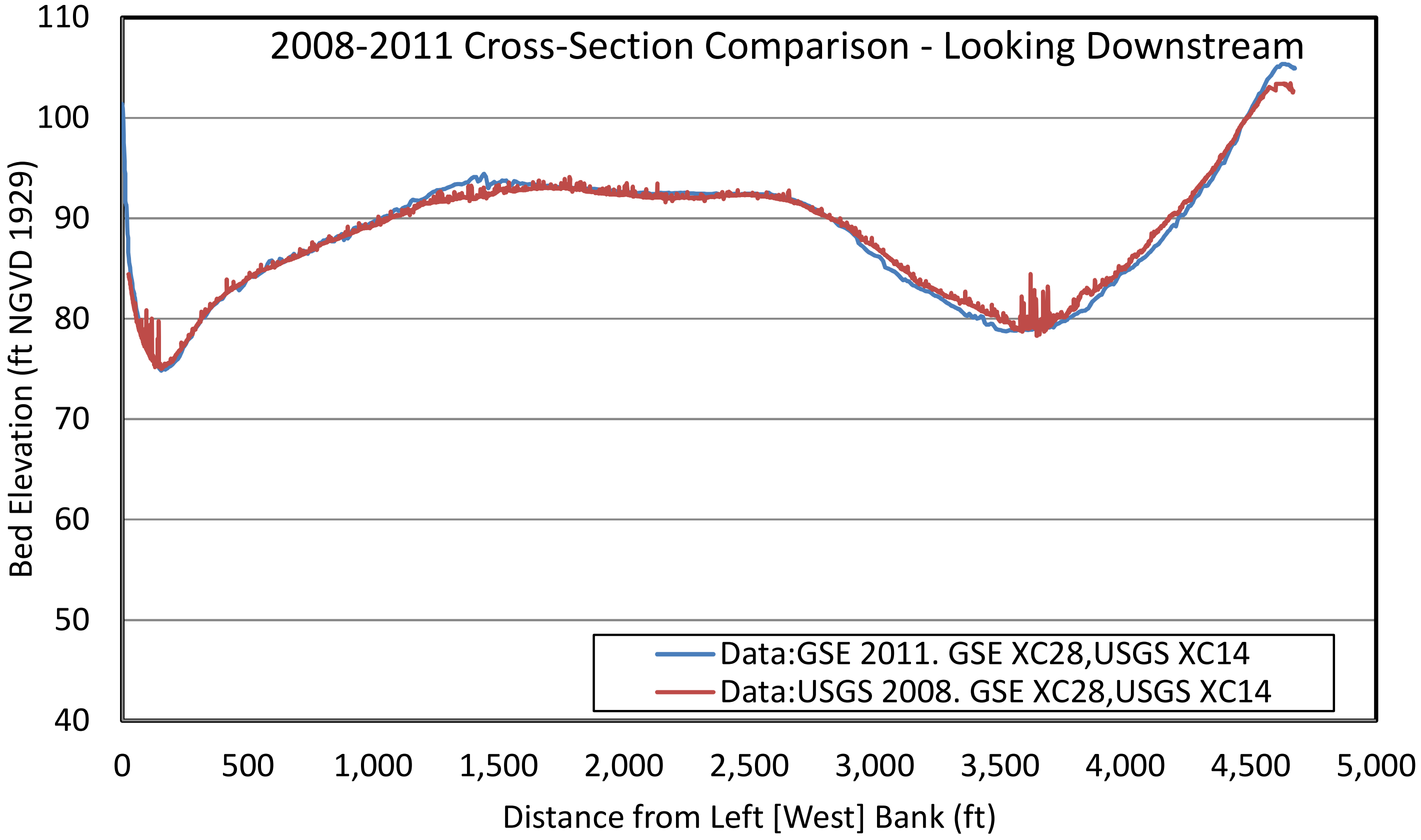

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC17,USGS XC9
Data:USGS 2008. GSE XC17,USGS XC9

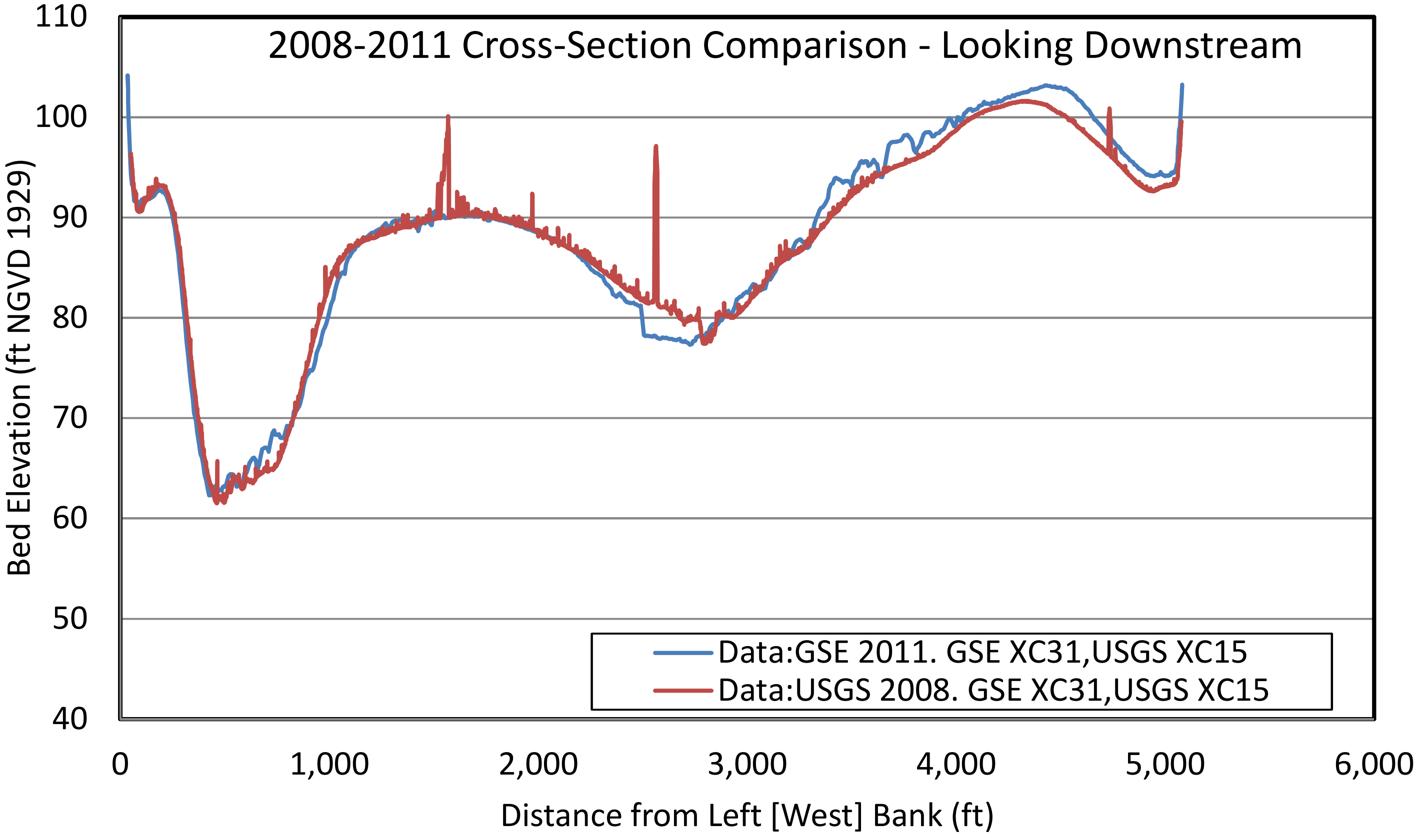

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC19,USGS XC10
Data:USGS 2008. GSE XC19,USGS XC10

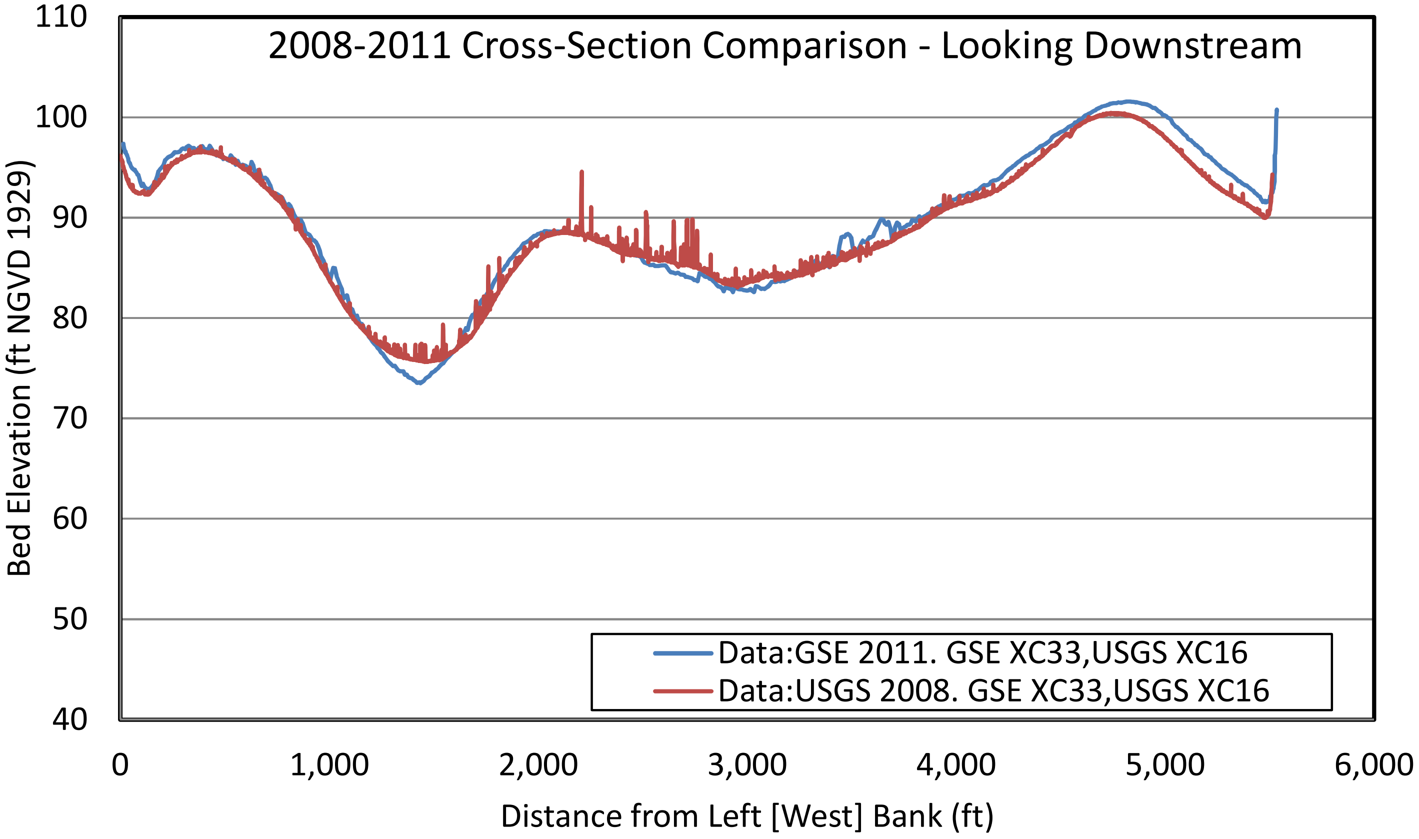

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC21,USGS XC11
Data:USGS 2008. GSE XC21,USGS XC11

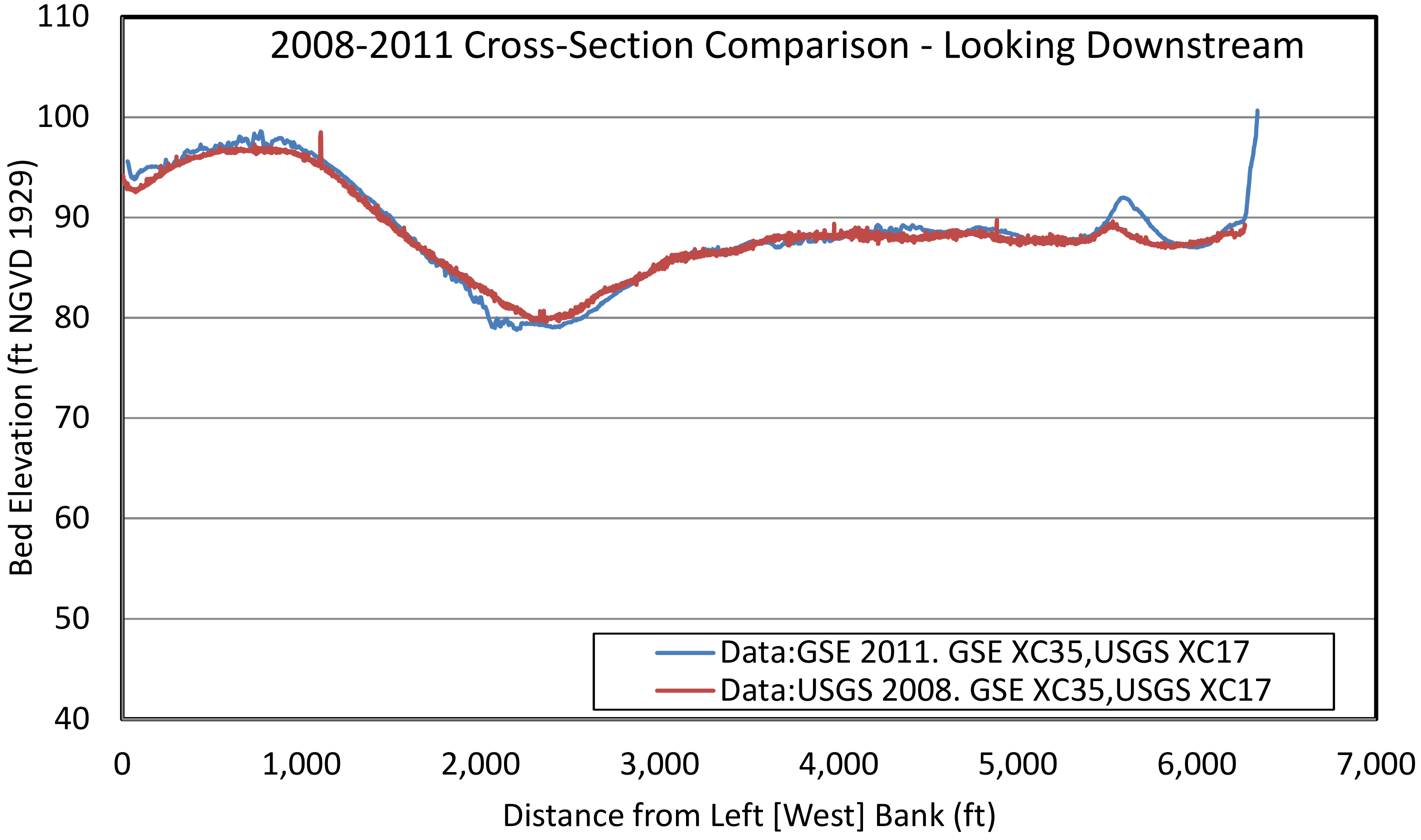

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC23,USGS XC12
Data:USGS 2008. GSE XC23,USGS XC12

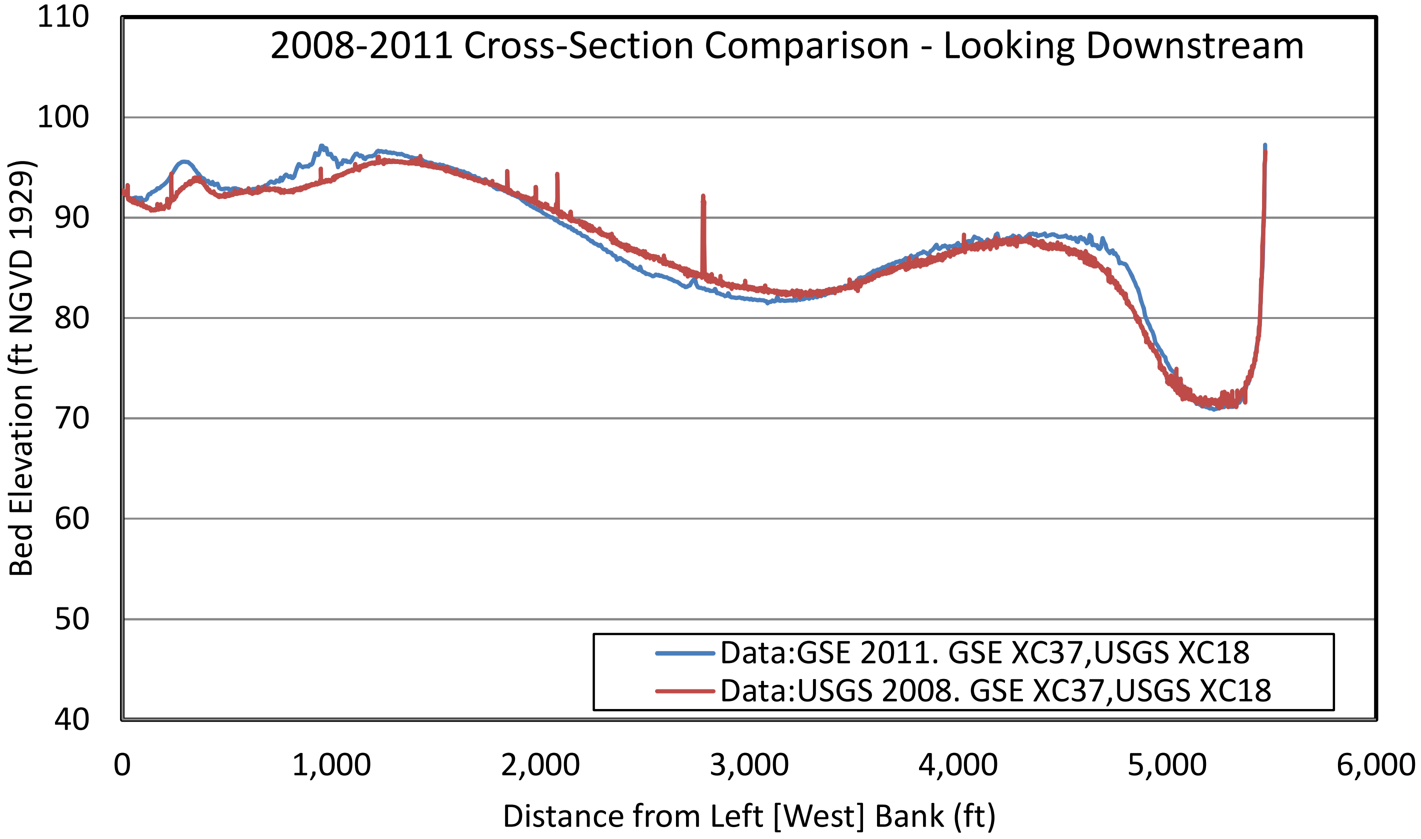

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC25,USGS XC13
Data:USGS 2008. GSE XC25,USGS XC13

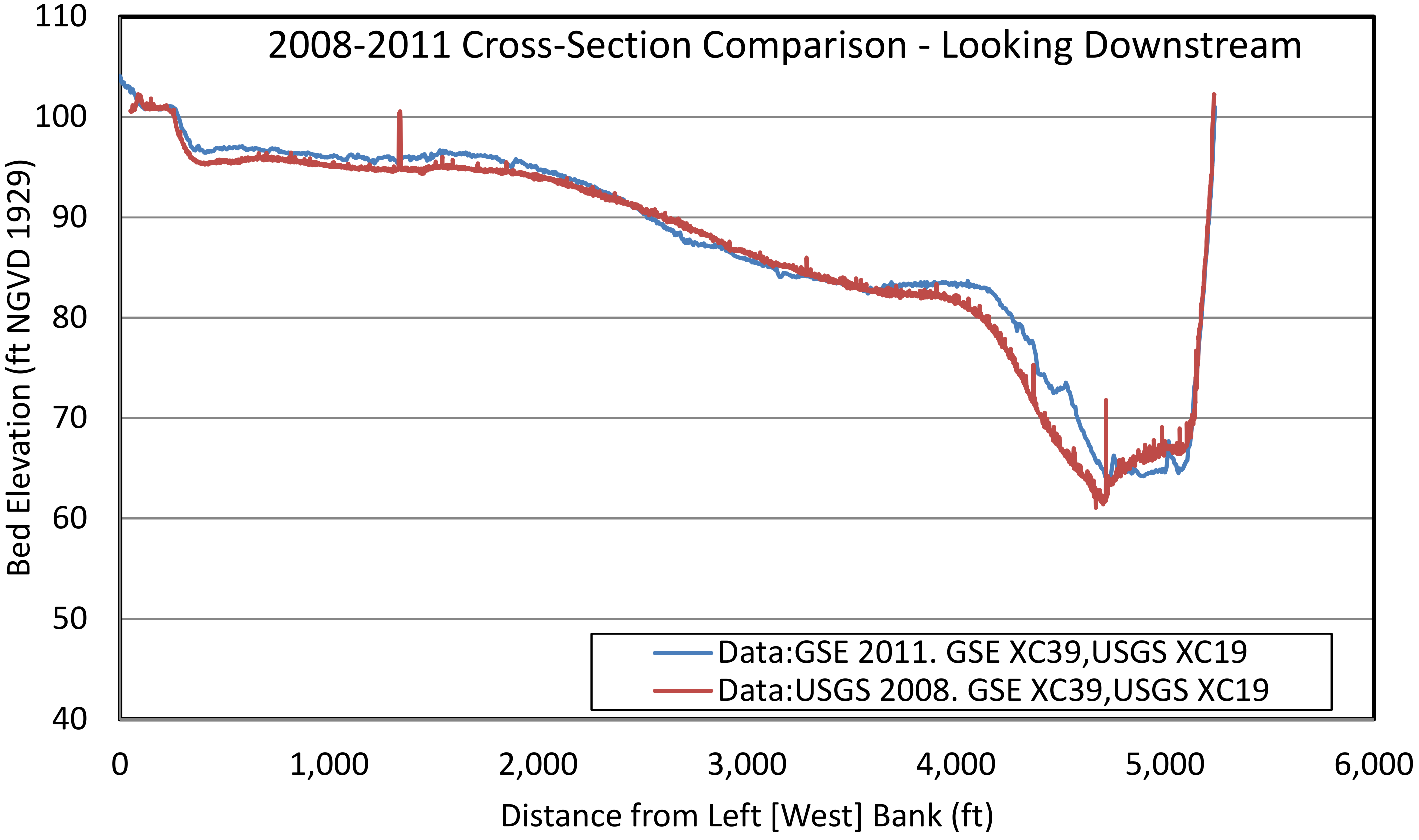

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC28,USGS XC14
Data:USGS 2008. GSE XC28,USGS XC14

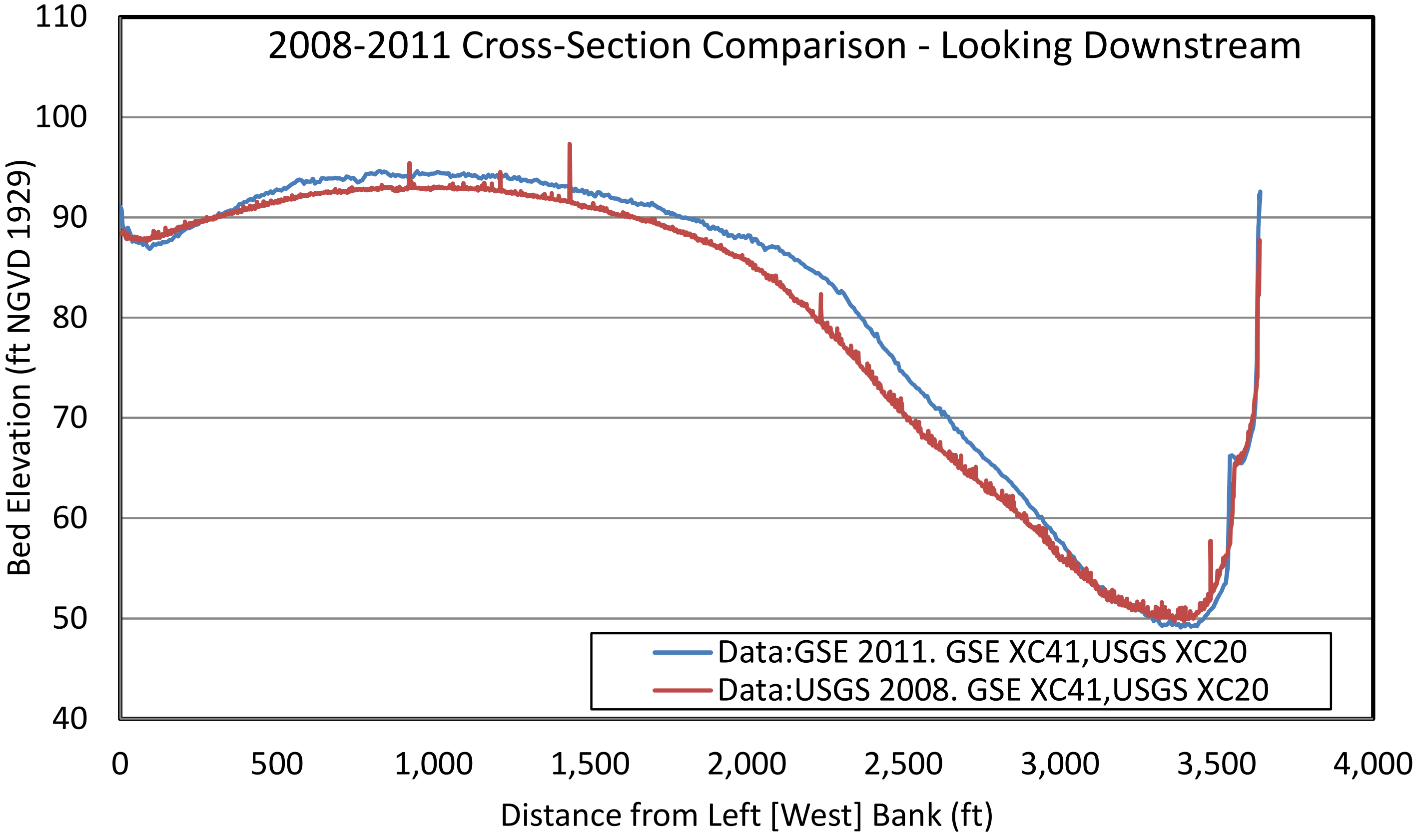

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC31,USGS XC15
Data:USGS 2008. GSE XC31,USGS XC15

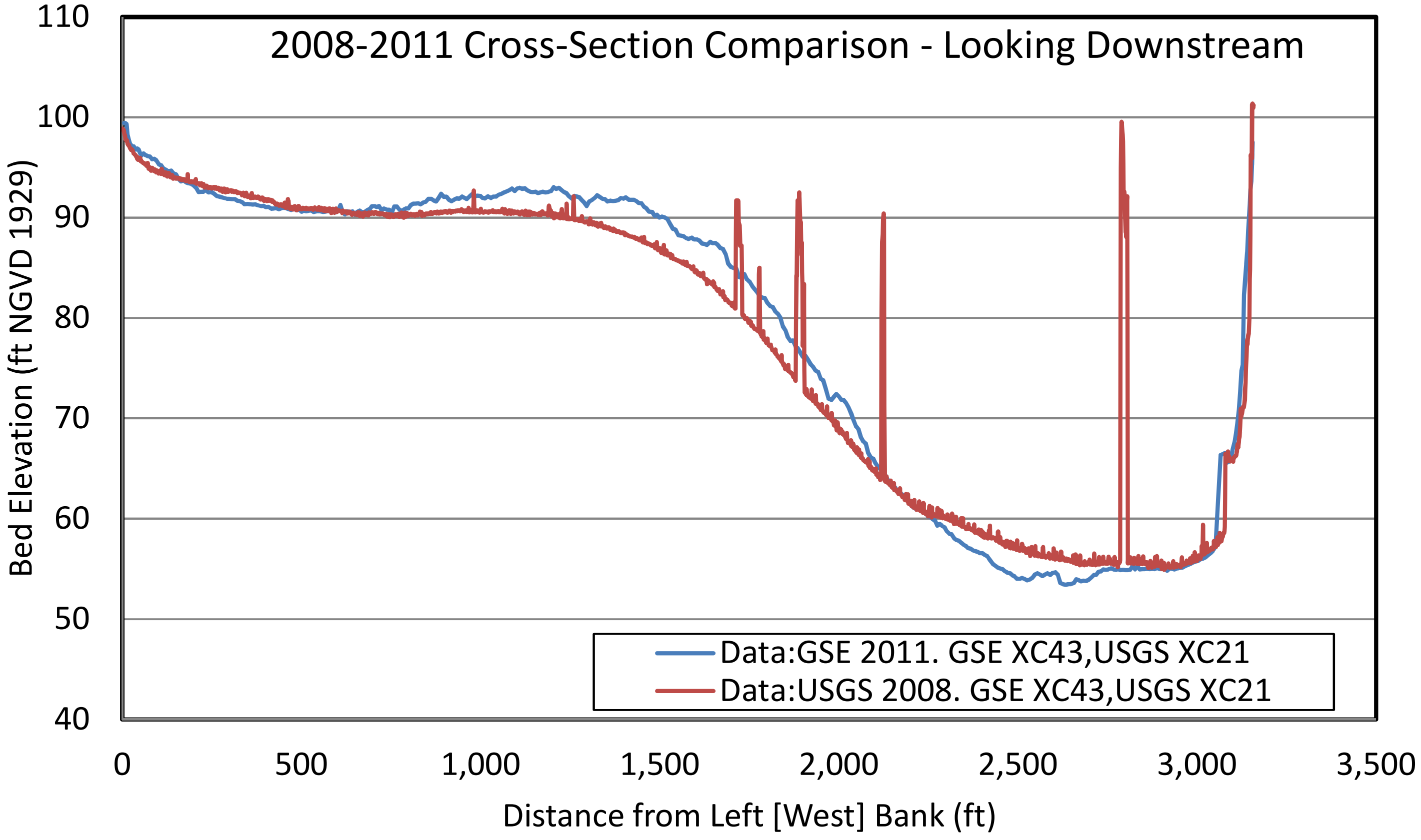

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC33,USGS XC16
Data:USGS 2008. GSE XC33,USGS XC16

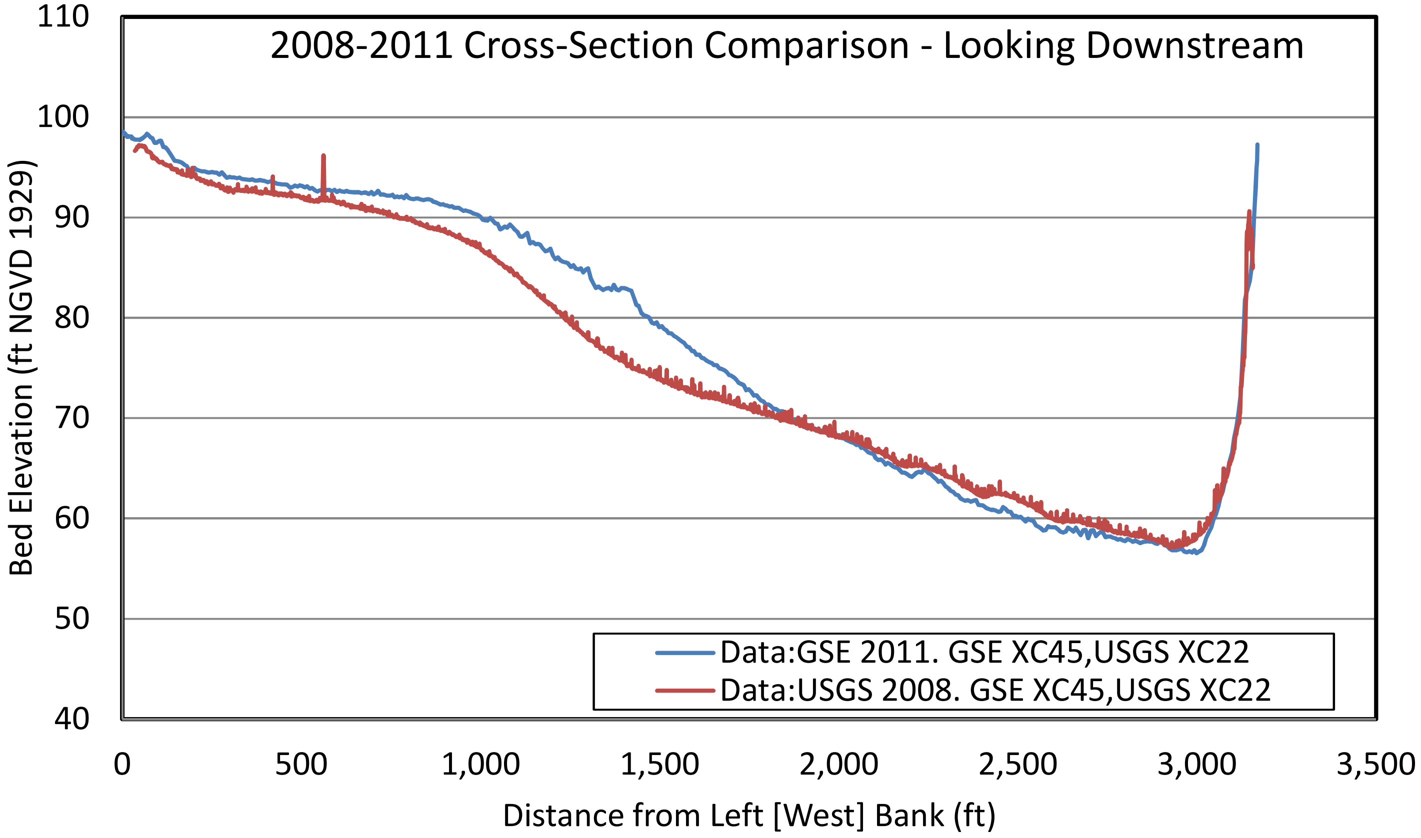

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC35,USGS XC17
Data:USGS 2008. GSE XC35,USGS XC17

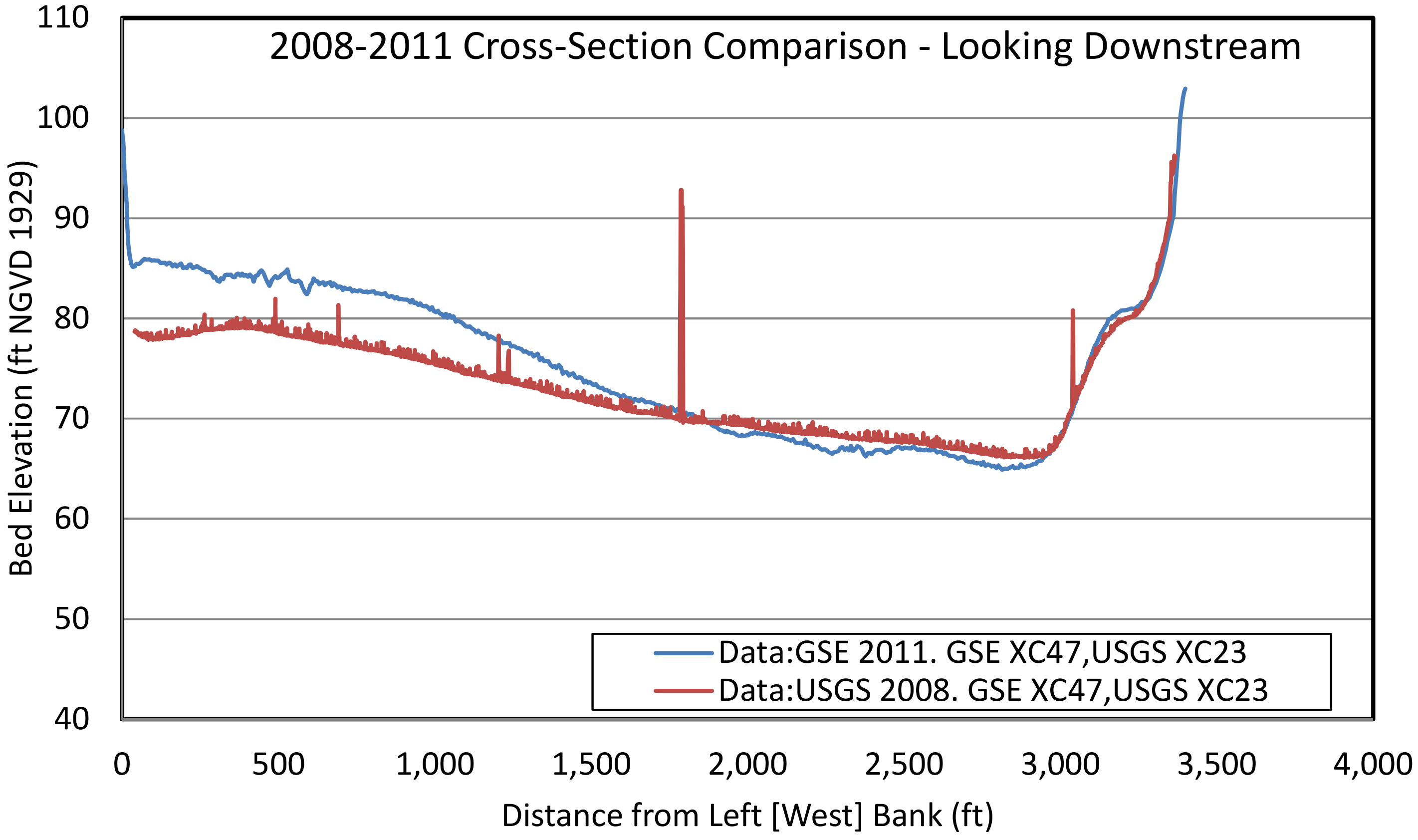

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC37,USGS XC18
Data:USGS 2008. GSE XC37,USGS XC18

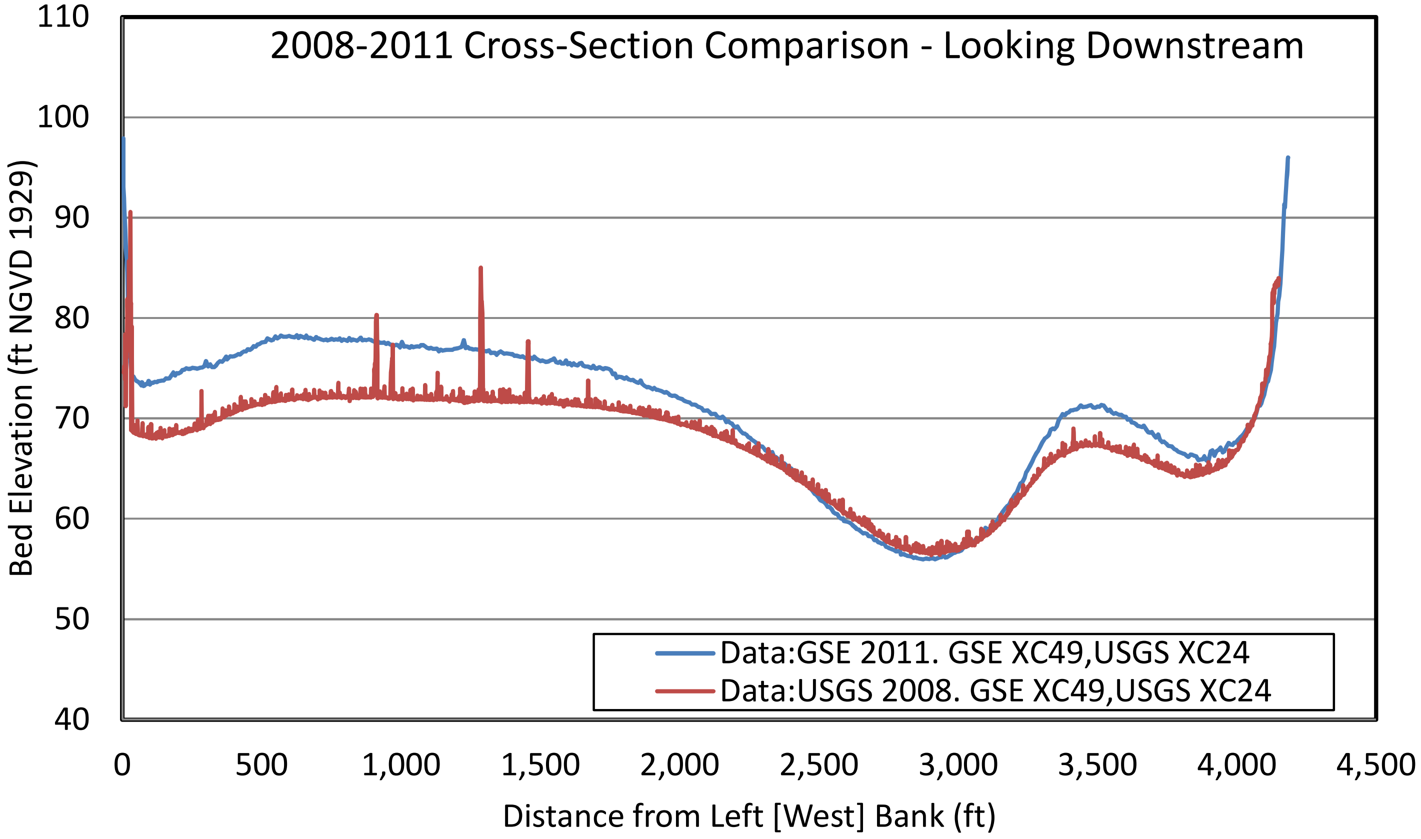

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC39,USGS XC19
Data:USGS 2008. GSE XC39,USGS XC19

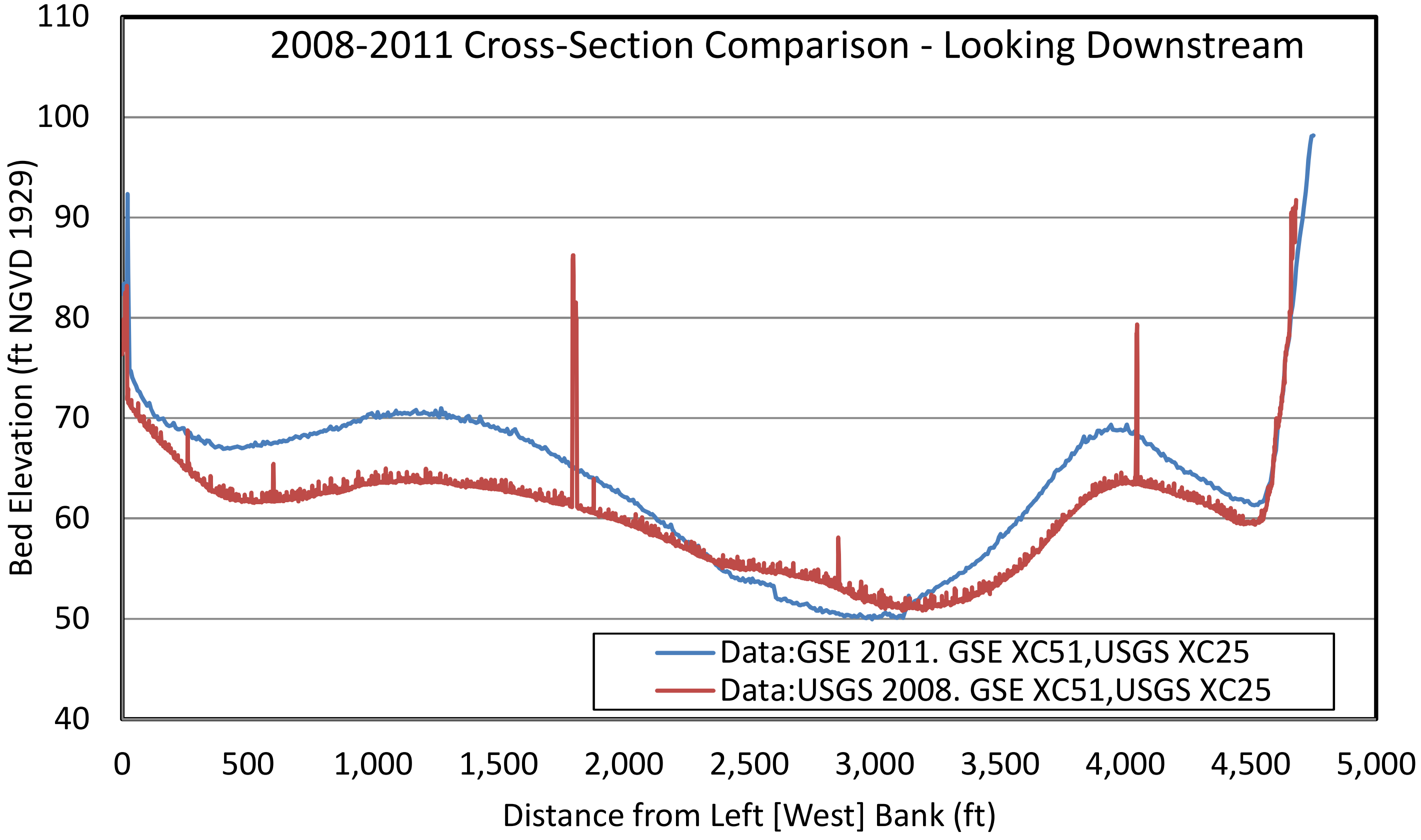

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC41,USGS XC20
Data:USGS 2008. GSE XC41,USGS XC20

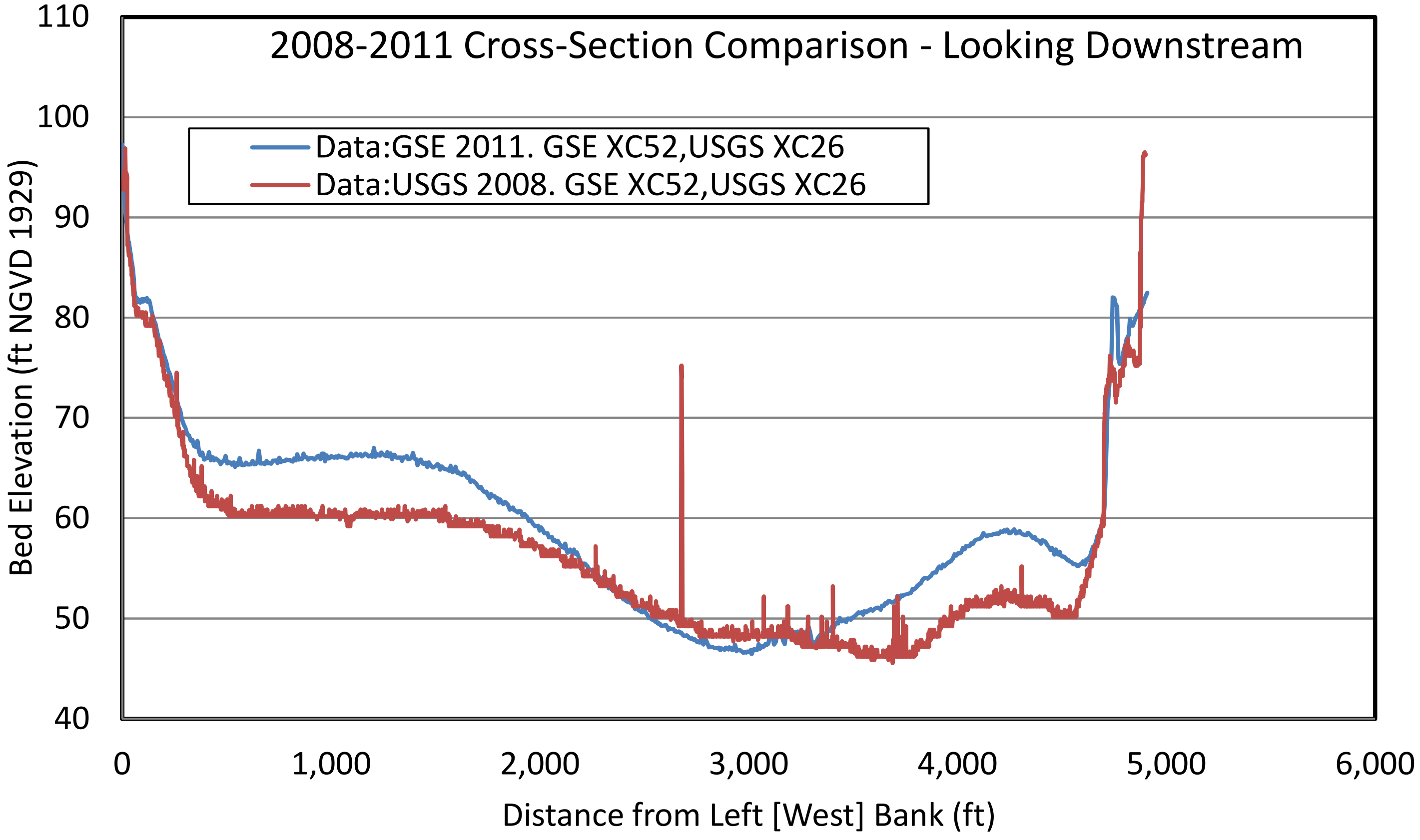

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC43,USGS XC21
Data:USGS 2008. GSE XC43,USGS XC21


2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC45,USGS XC22
Data:USGS 2008. GSE XC45,USGS XC22

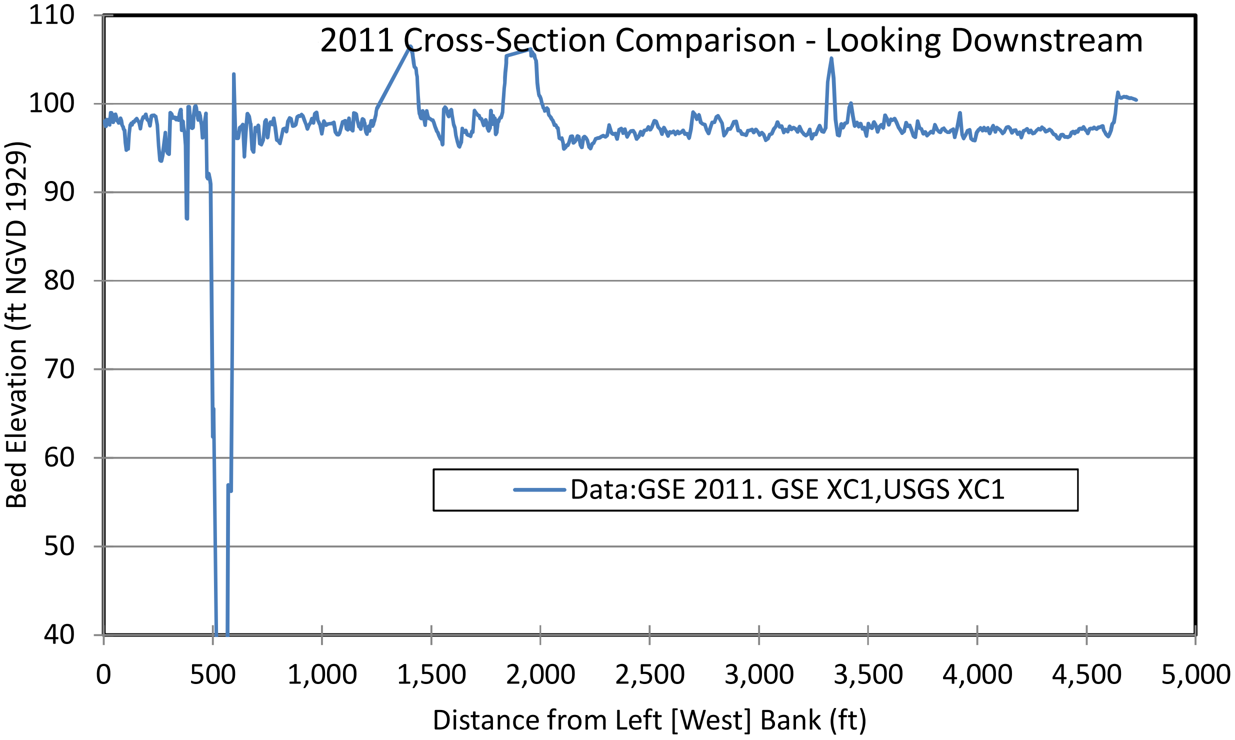

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC47,USGS XC23
Data:USGS 2008. GSE XC47,USGS XC23

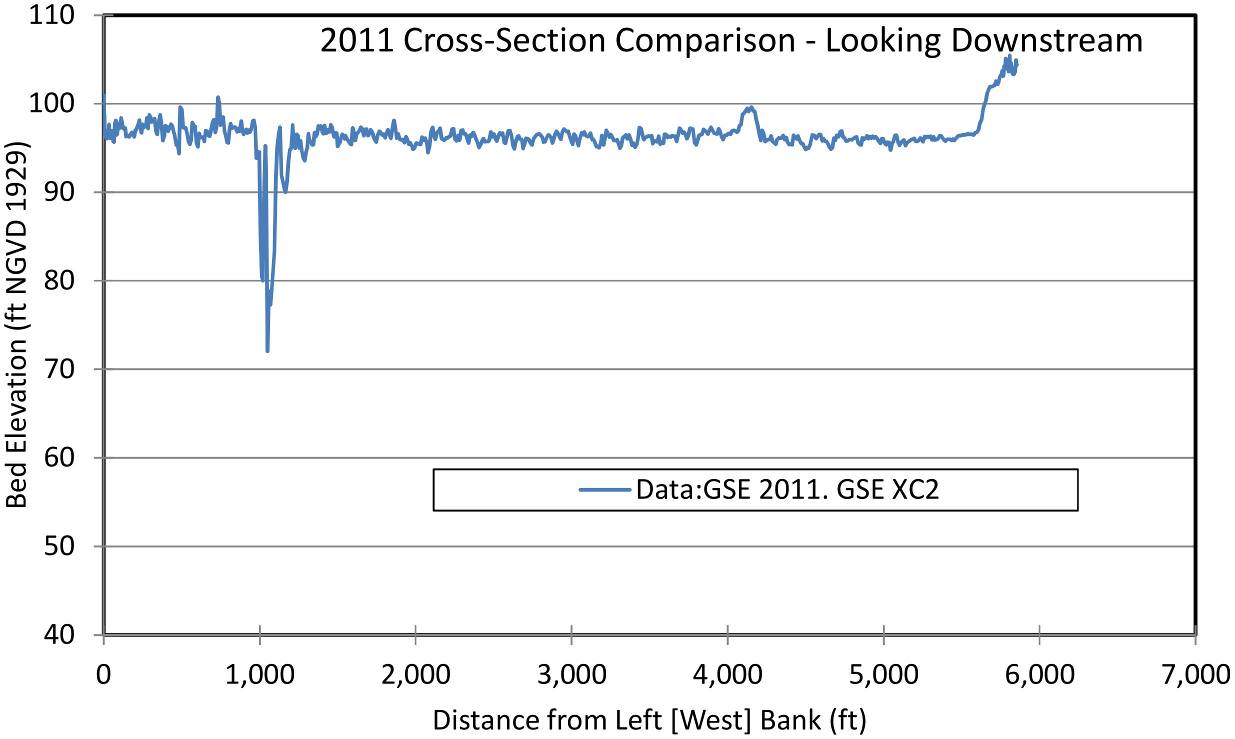

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC49,USGS XC24
Data:USGS 2008. GSE XC49,USGS XC24


2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC51,USGS XC25
Data:USGS 2008. GSE XC51,USGS XC25


2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
Data:GSE 2011. GSE XC52,USGS XC26
Data:USGS 2008. GSE XC52,USGS XC26
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)

Appendix B: 2011 Cross-Section Plots[8]





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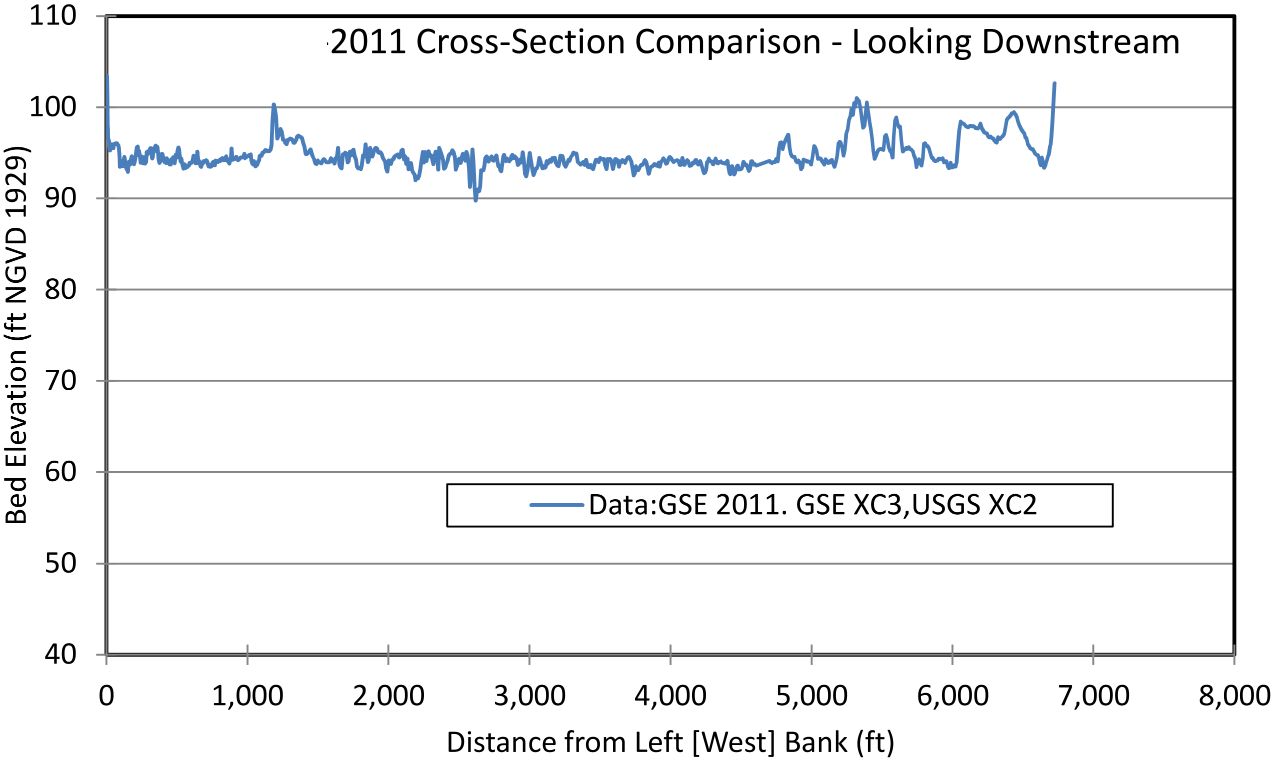
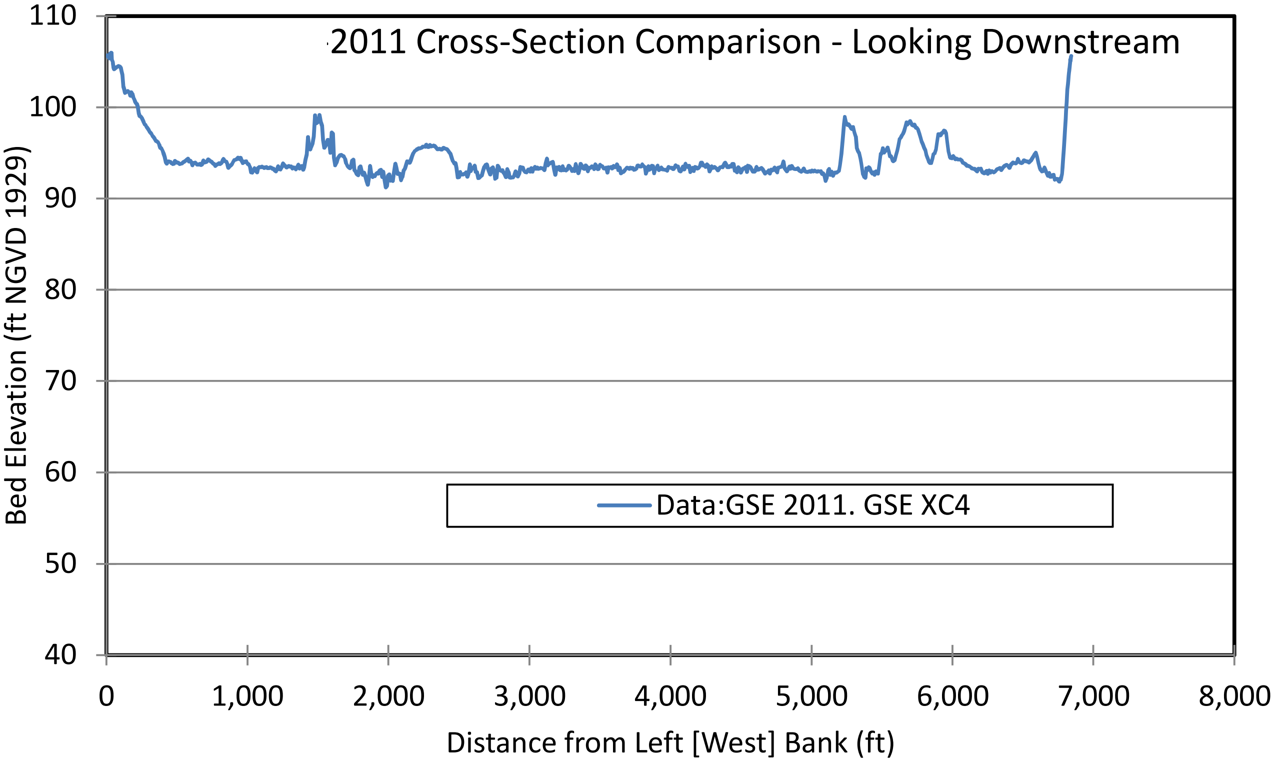
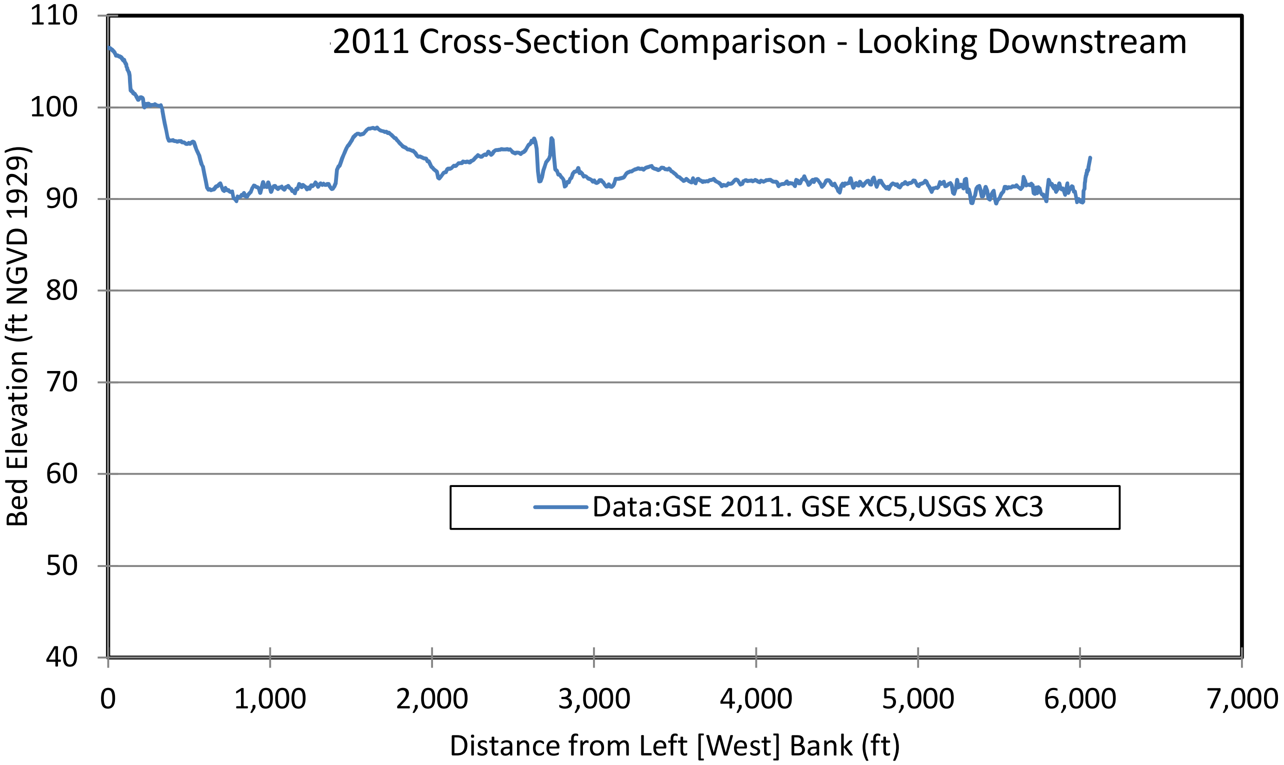
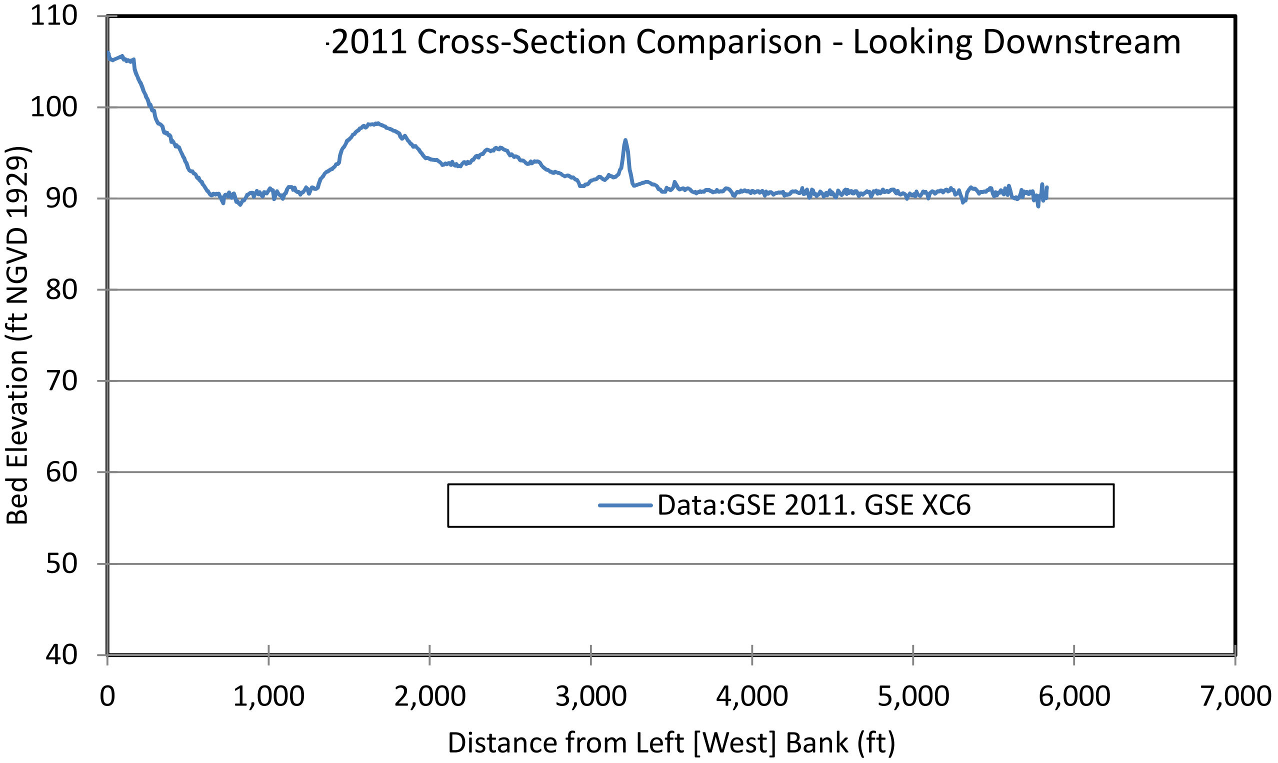
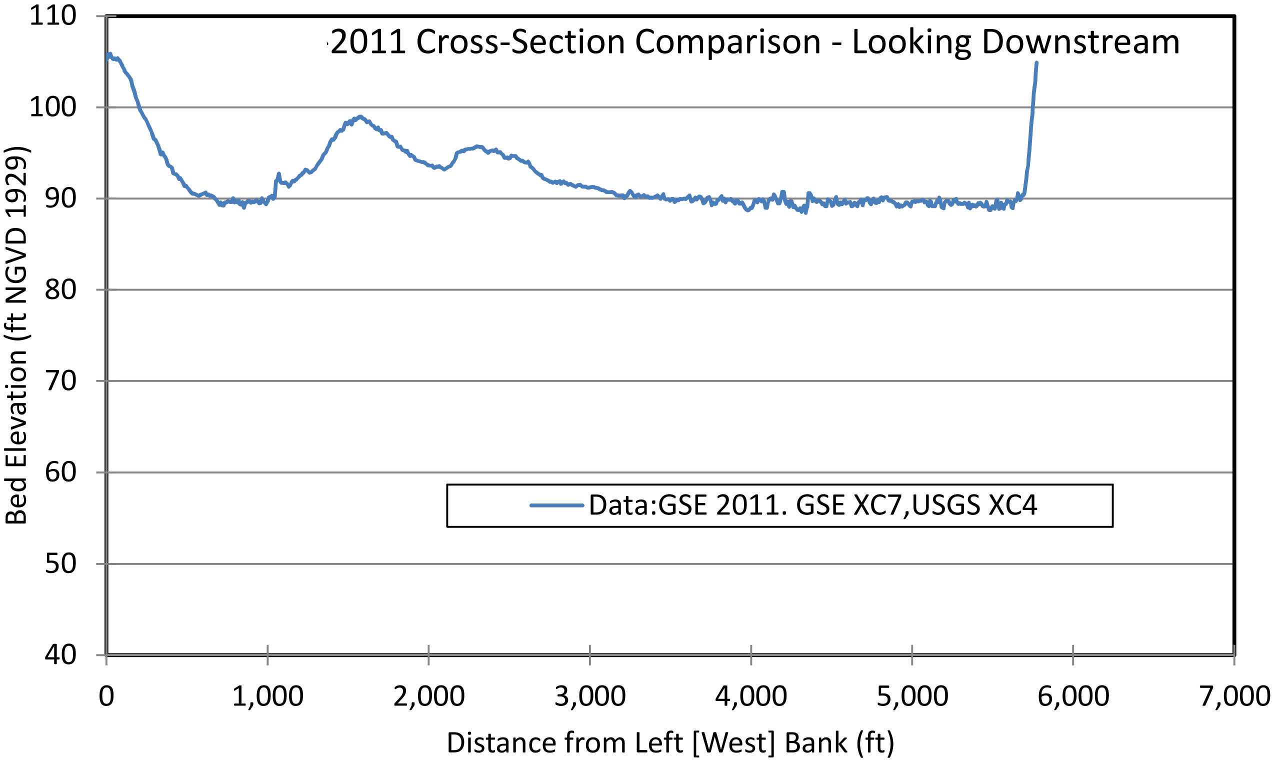
[8] Only 2011 cross-sections are shown in this appendix, but XC numbering for both surveys (2008 and 2011) are shown. Where GSE cross-sections overlapped with USGS cross-sections, both cross-section numbers are included. Appendix A compares overlapping cross-sections.

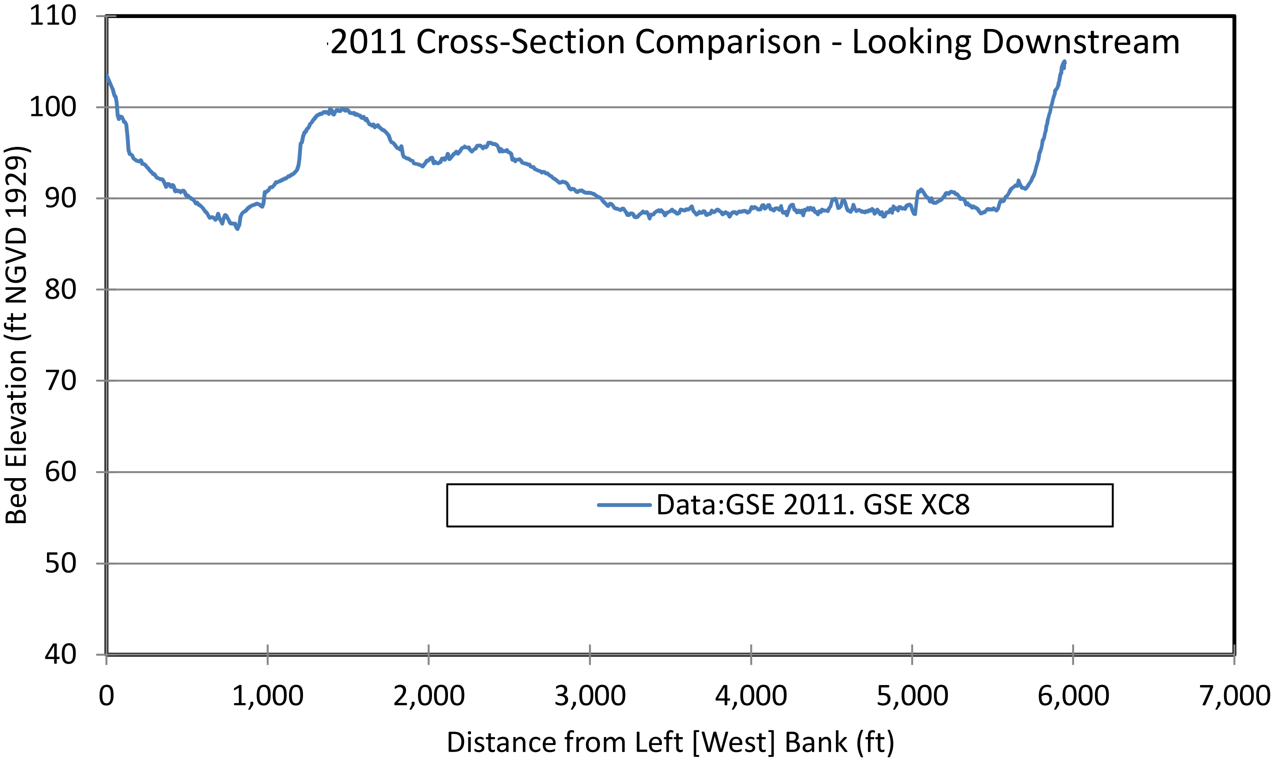

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC3,USGS XC2

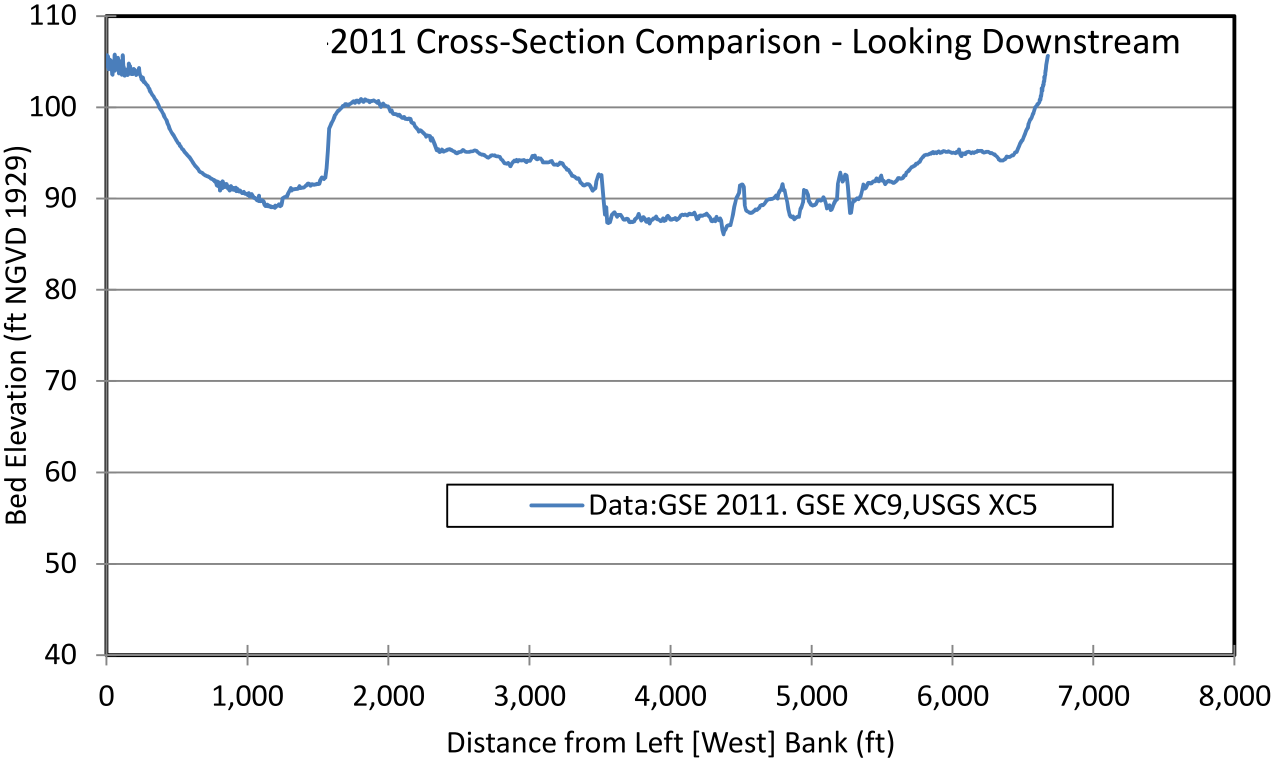

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC4


2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC5,USGS XC3

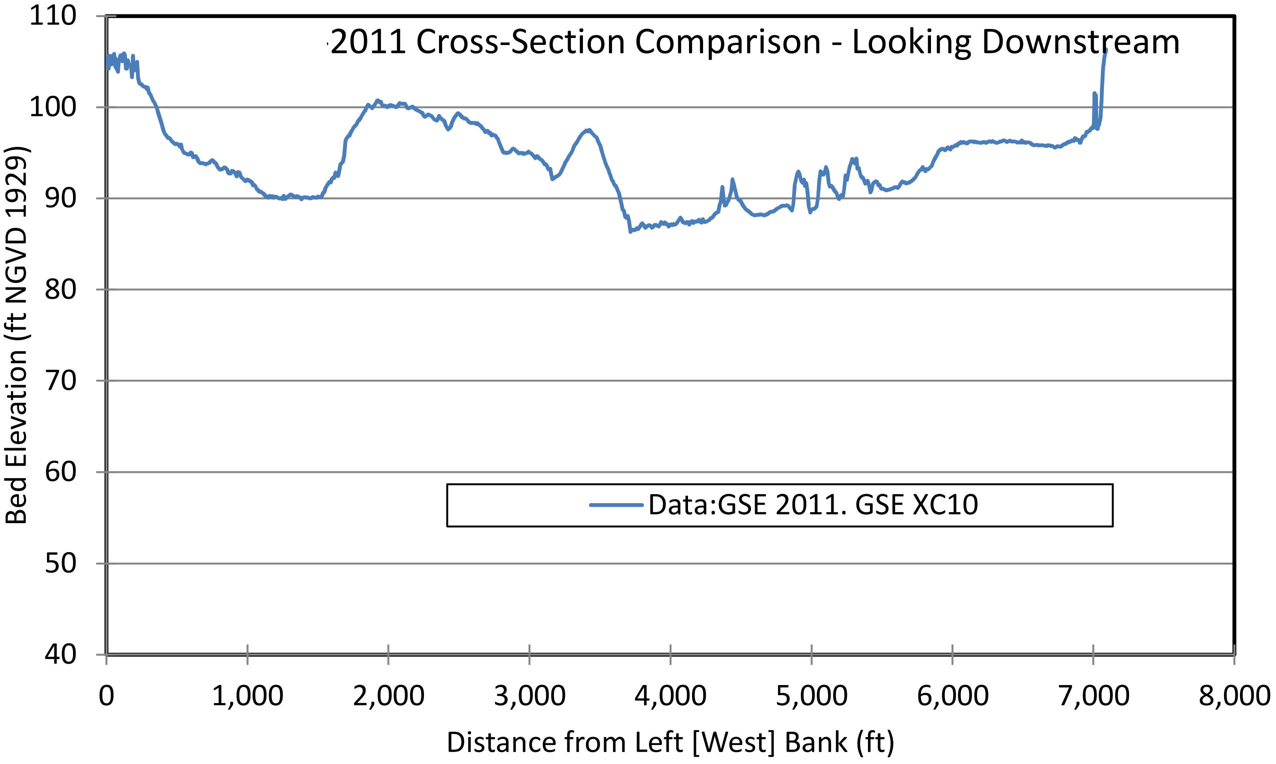

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC6


2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC7,USGS XC4

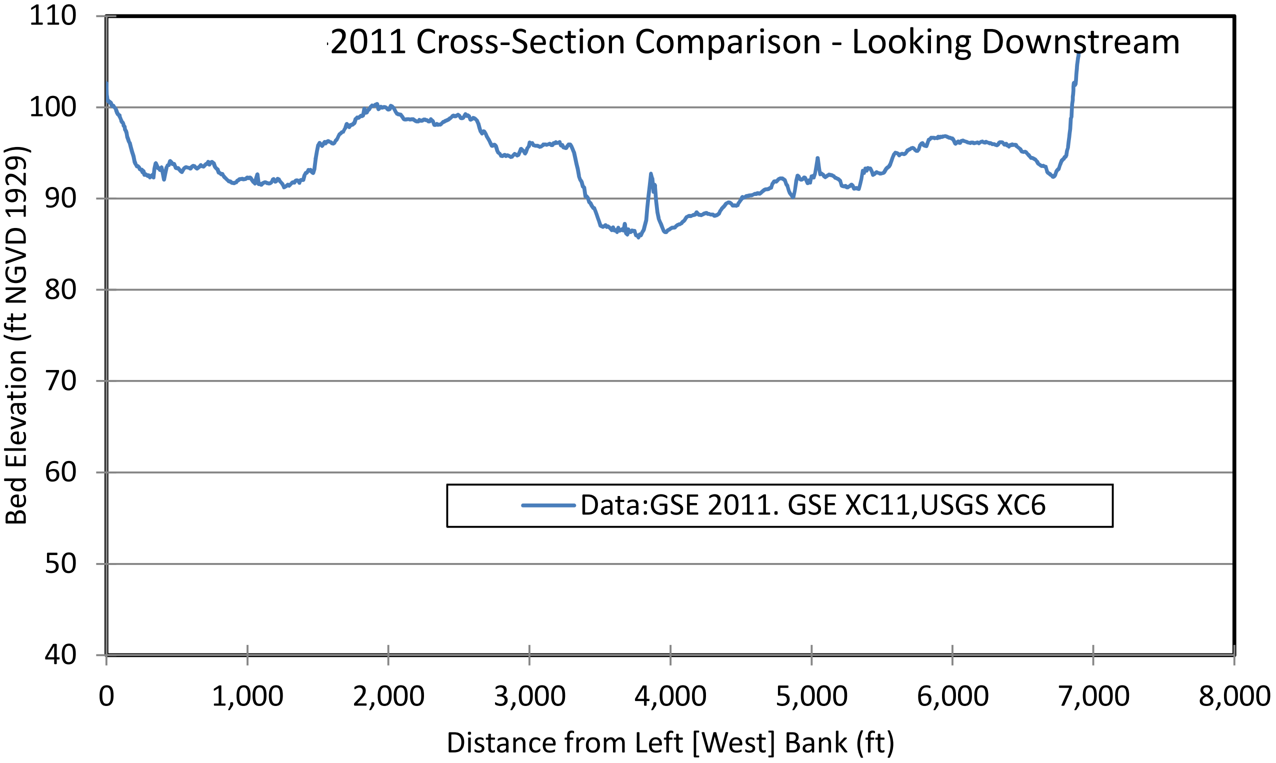

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC8

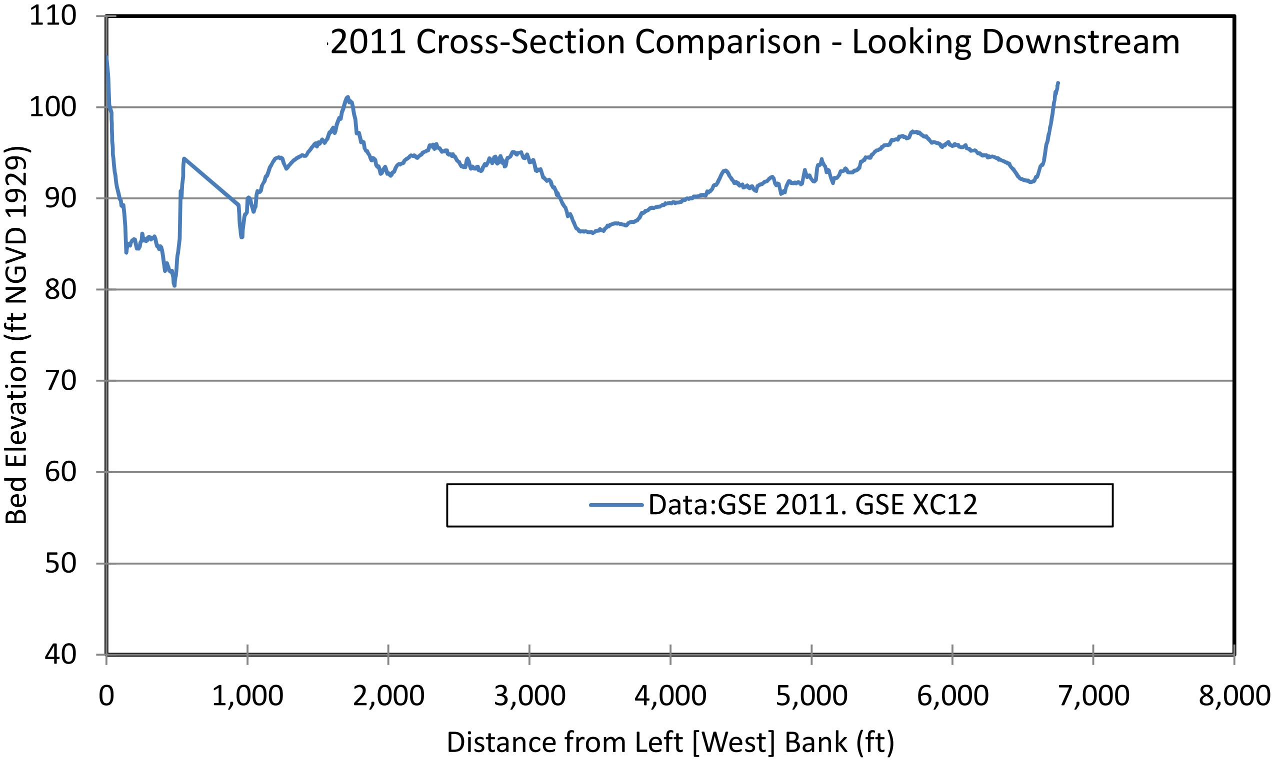


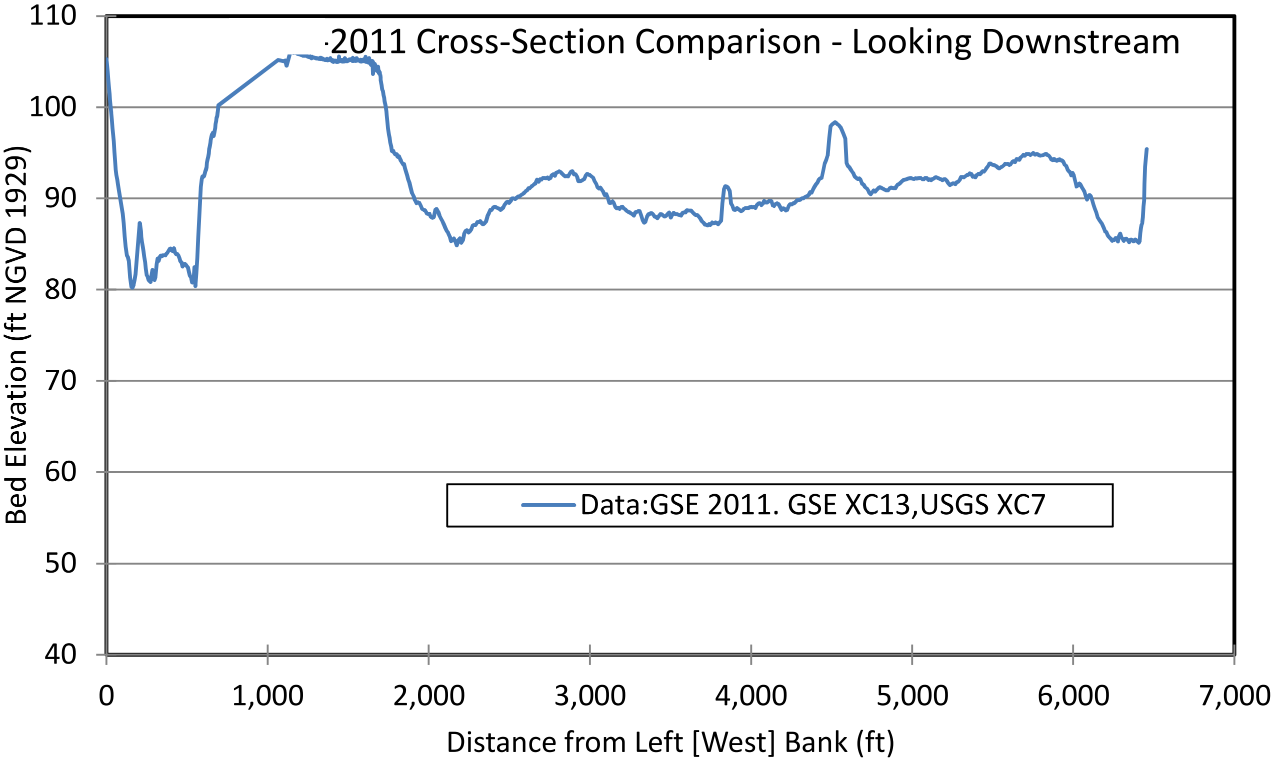
2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
Data:GSE 2011. GSE XC9,USGS XC5
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)

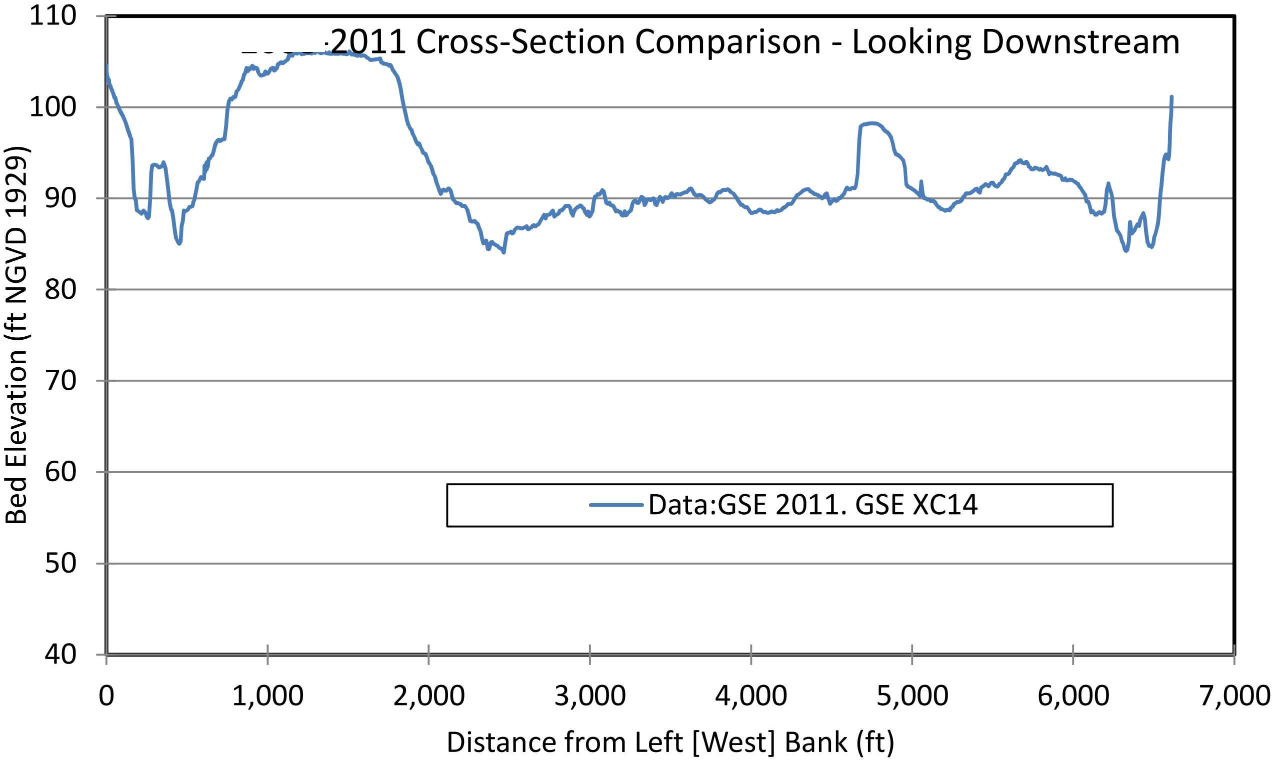


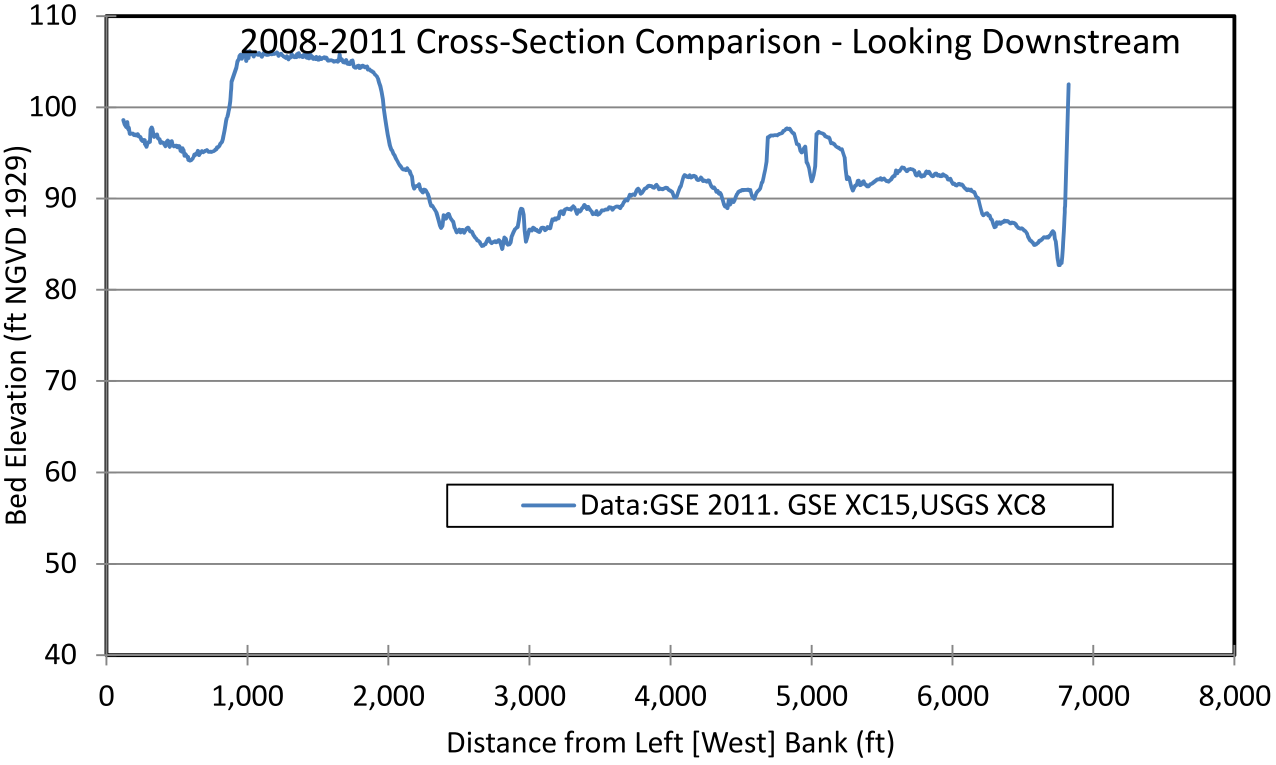
2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
Data:GSE 2011. GSE XC10
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)

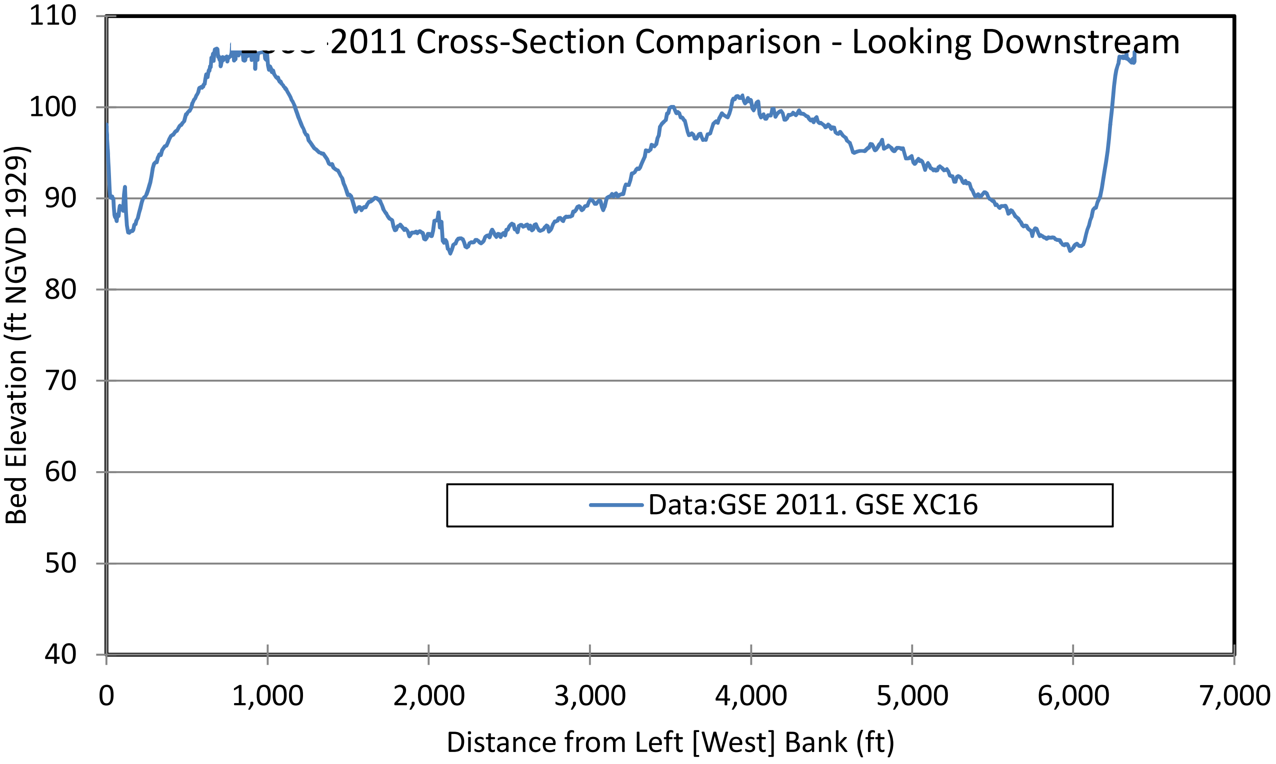

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC11,USGS XC6

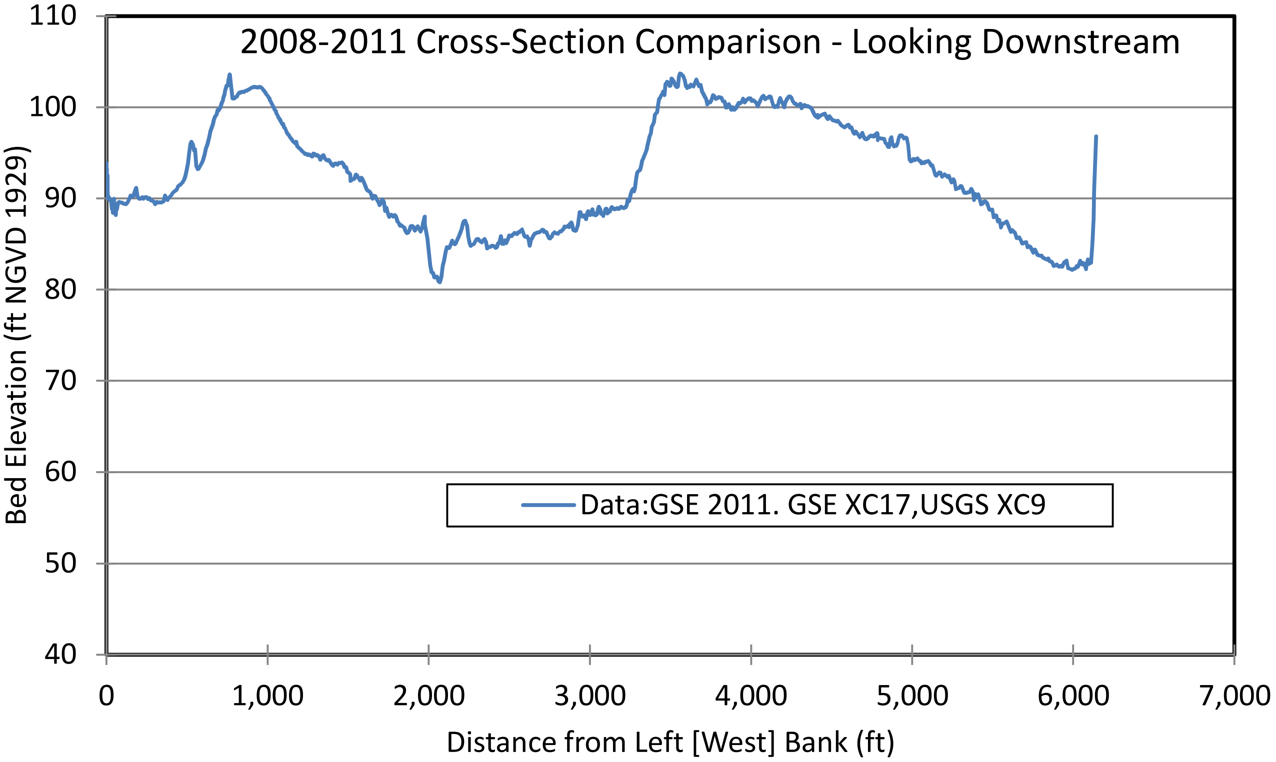

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC12

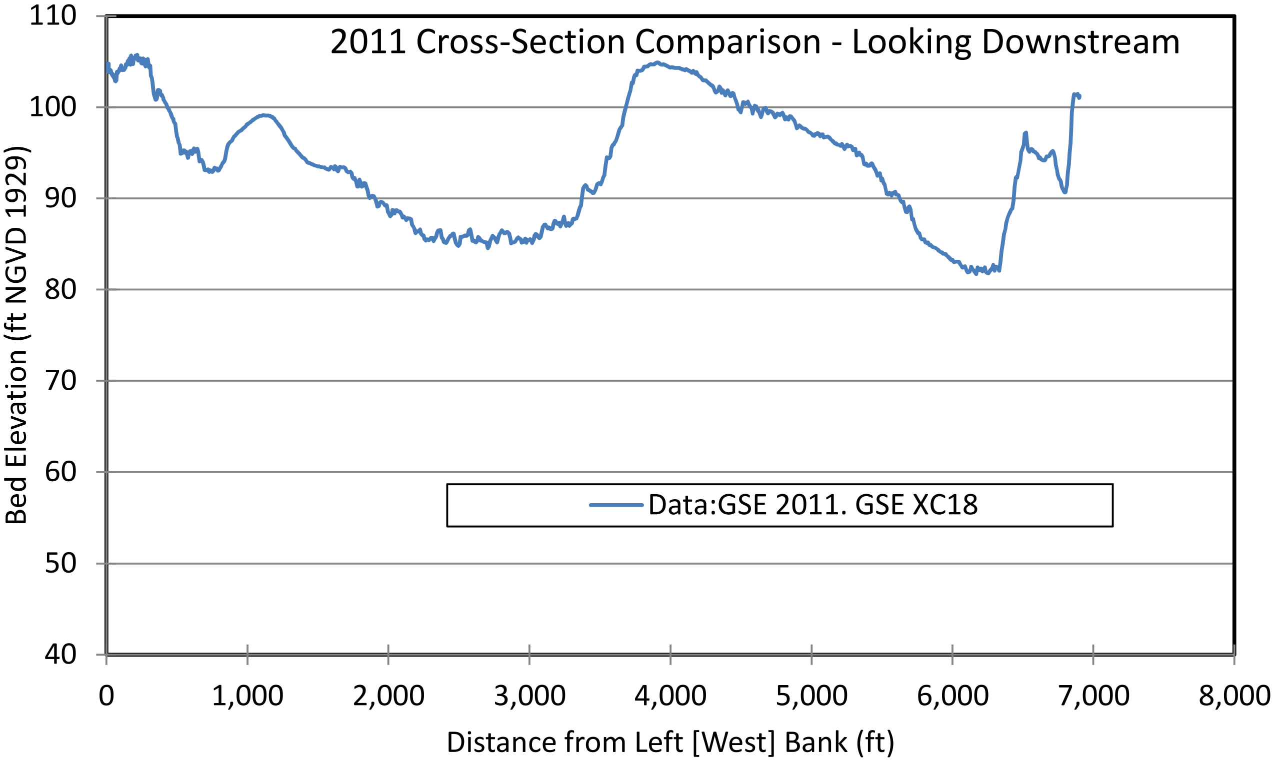

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC13,USGS XC7

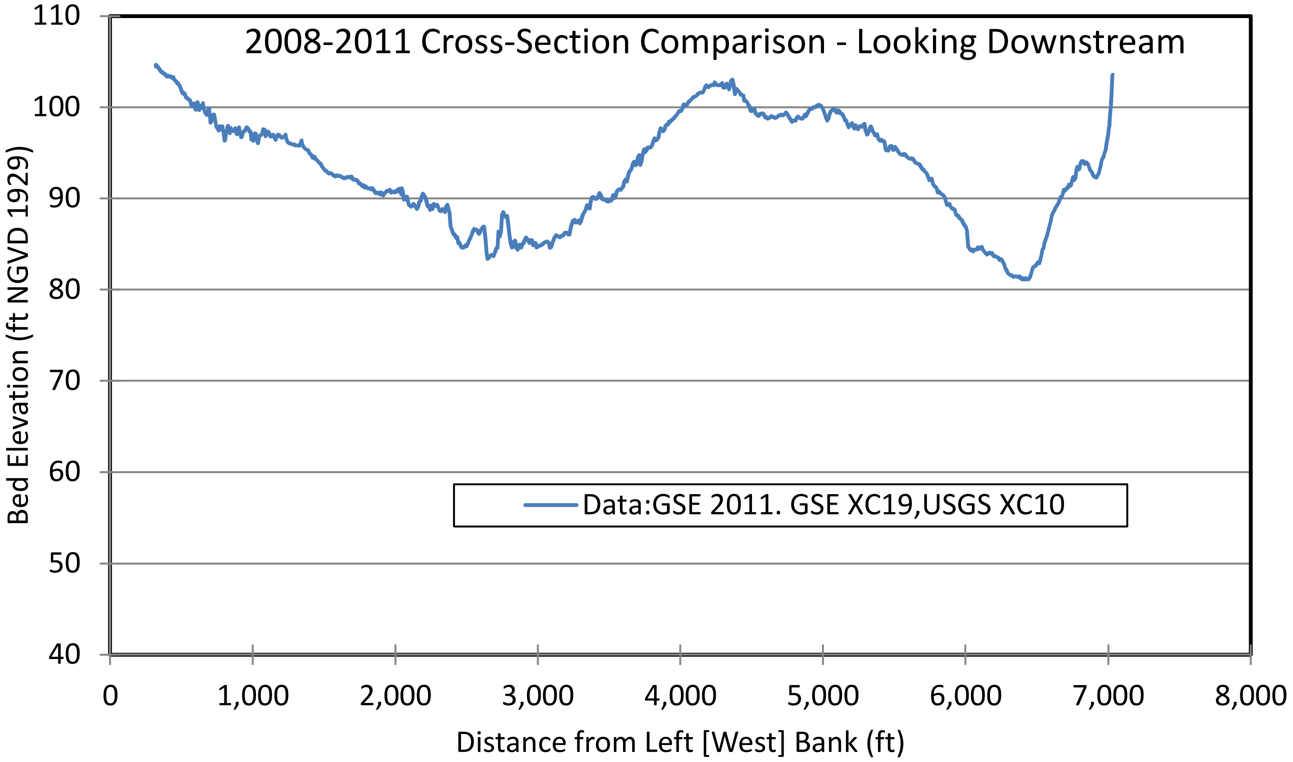

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC14

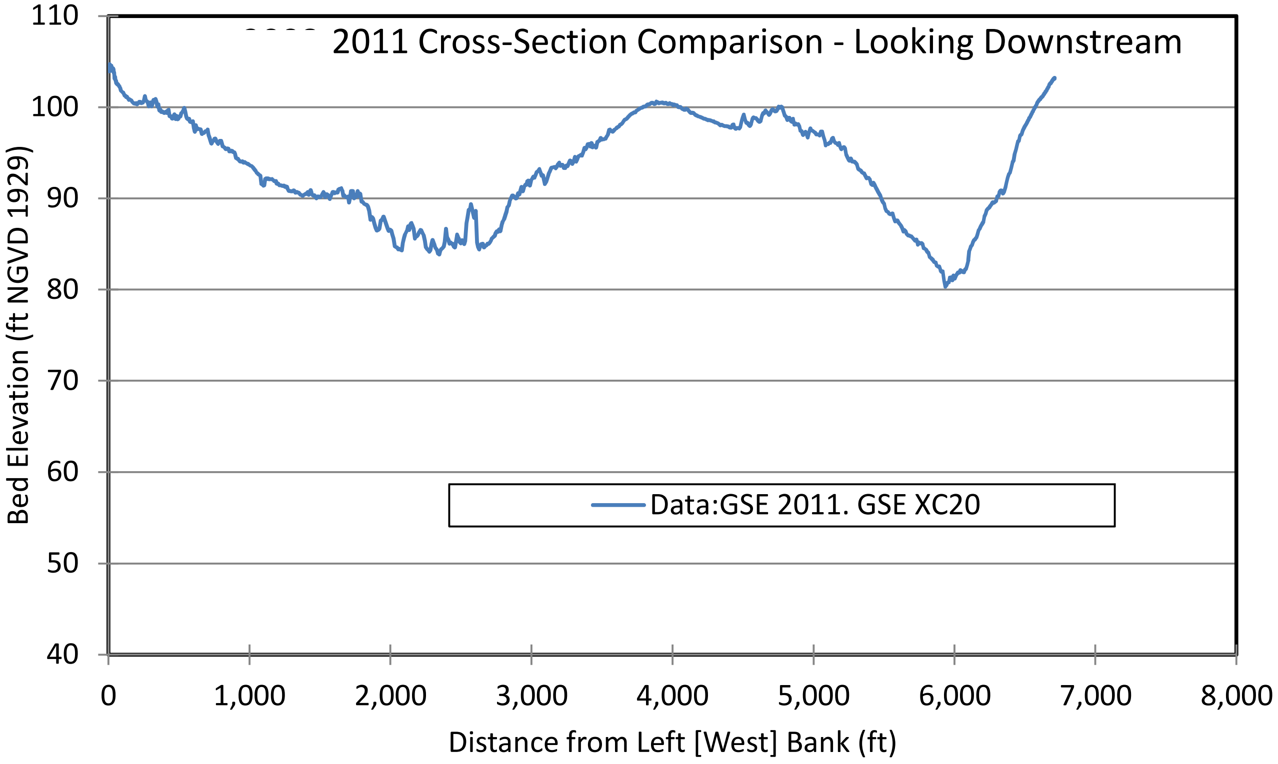

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC15,USGS XC8

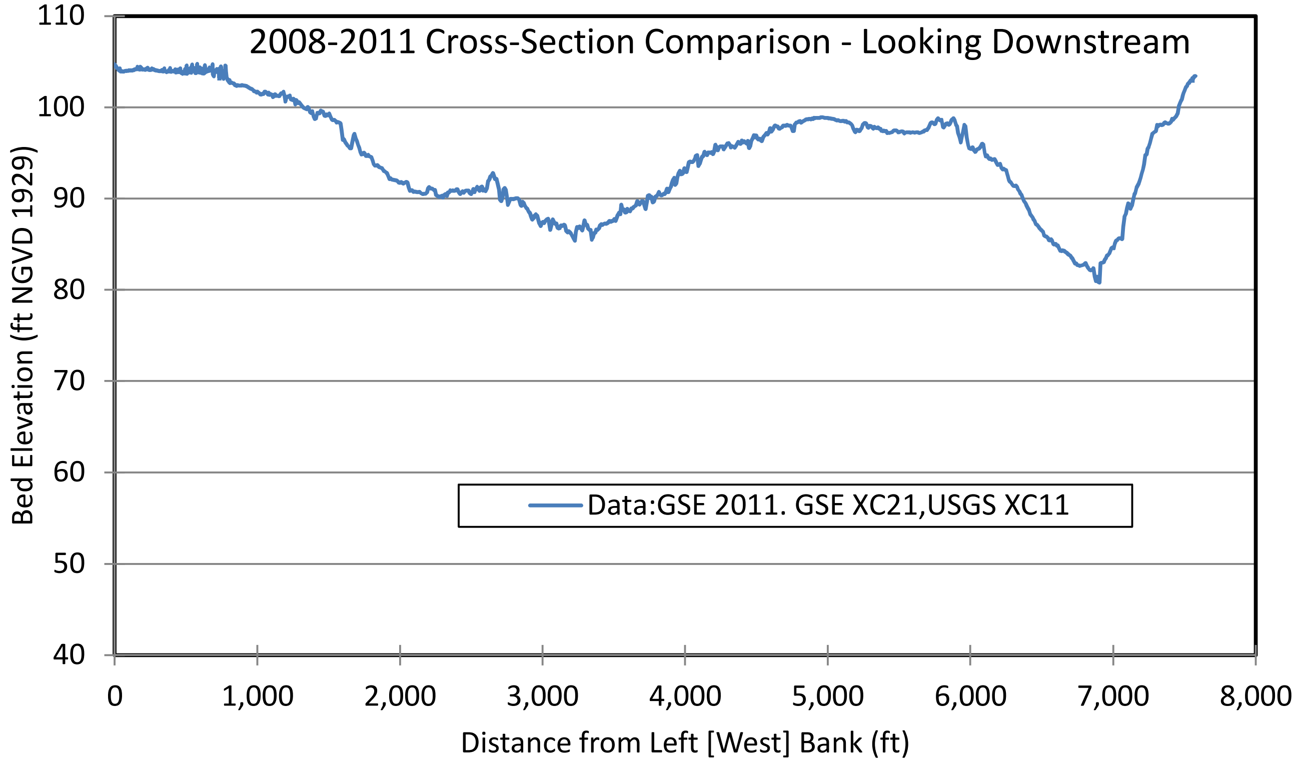

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC16

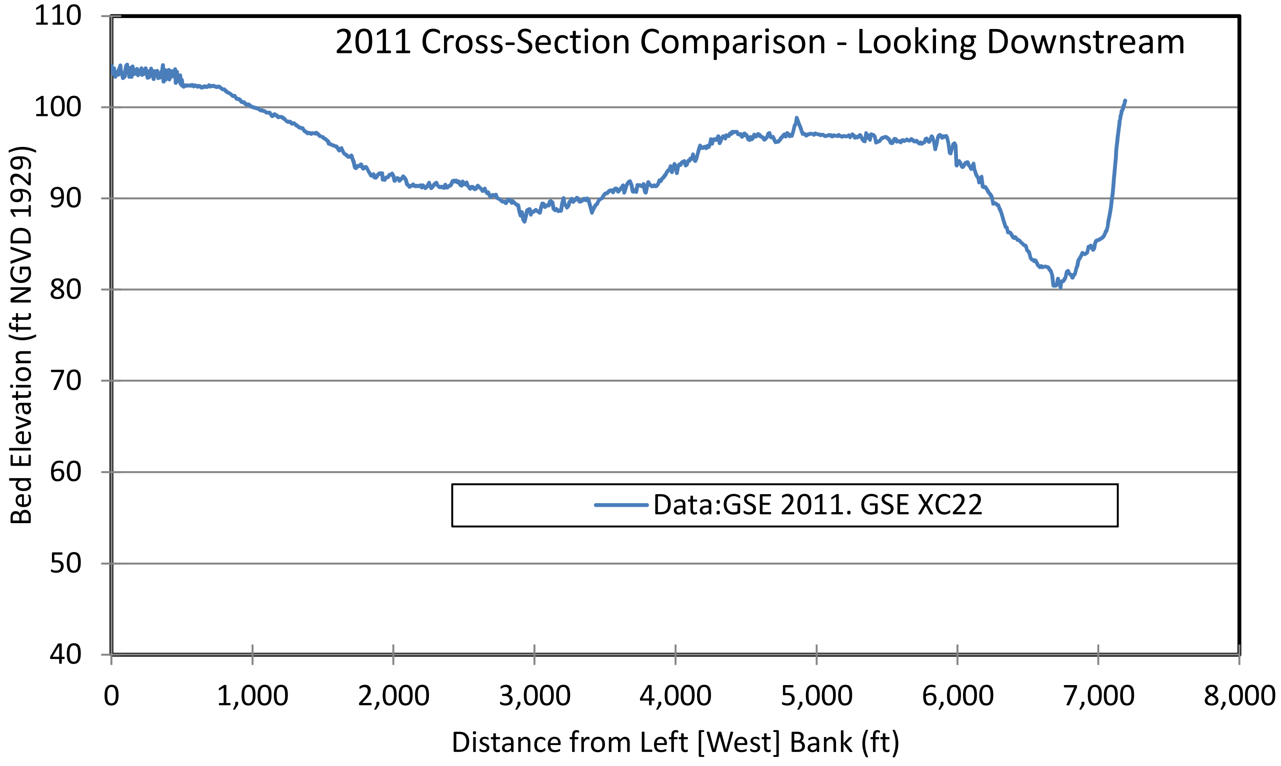

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC17,USGS XC9

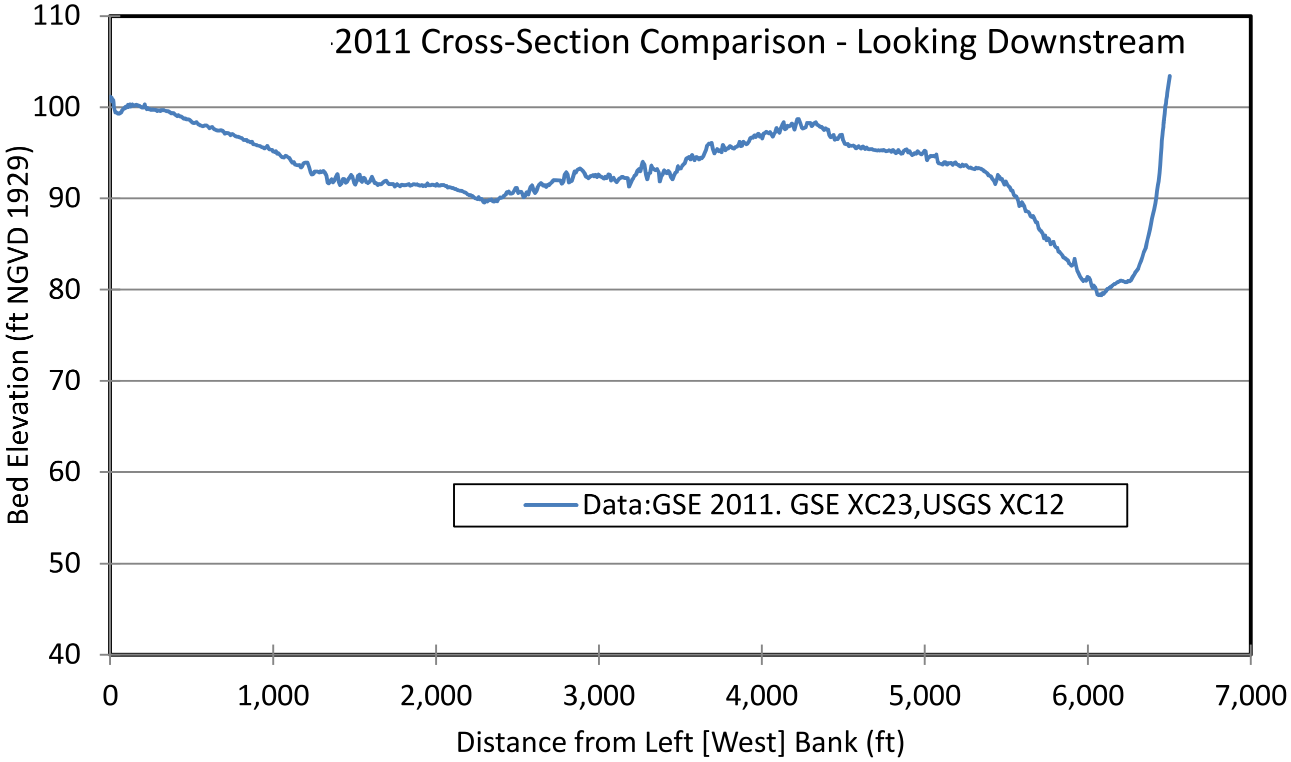

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC18

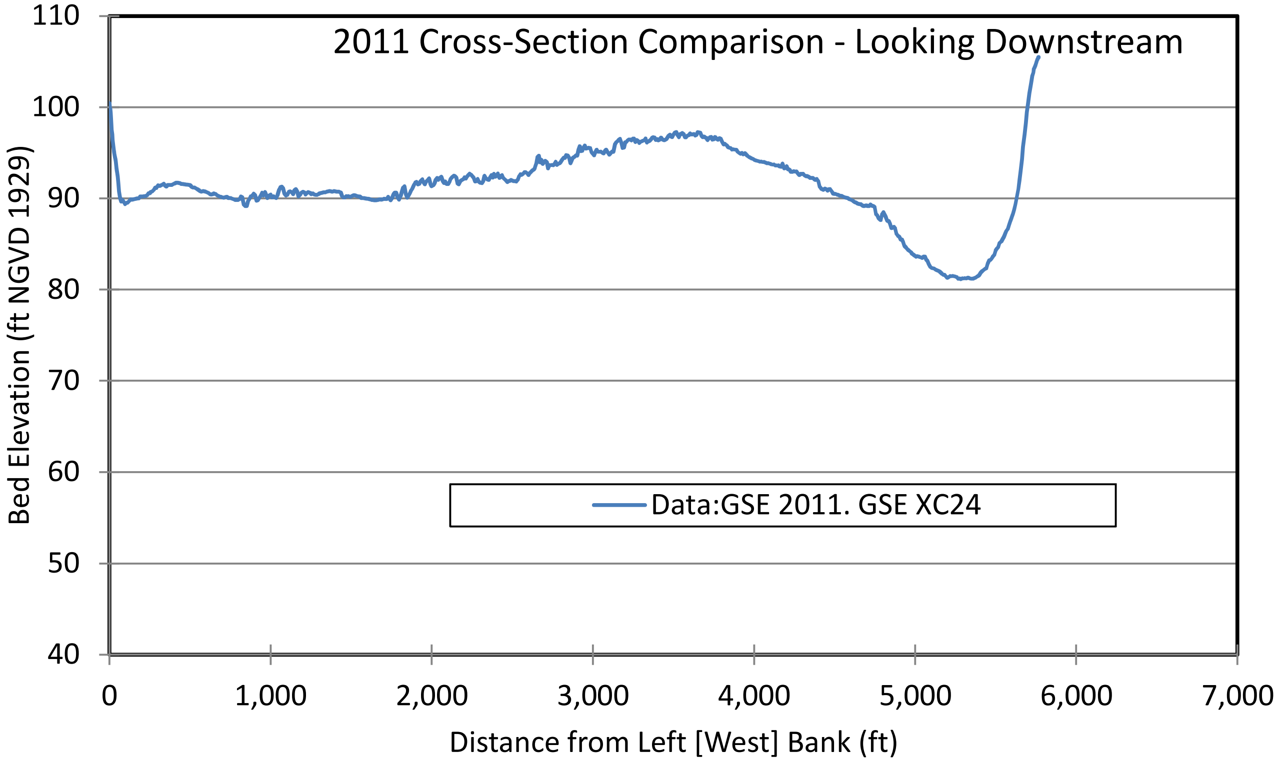

2008-2011 Cross-Section Comparison - Looking Downstream
Data:GSE 2011. GSE XC19,USGS XC10
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)

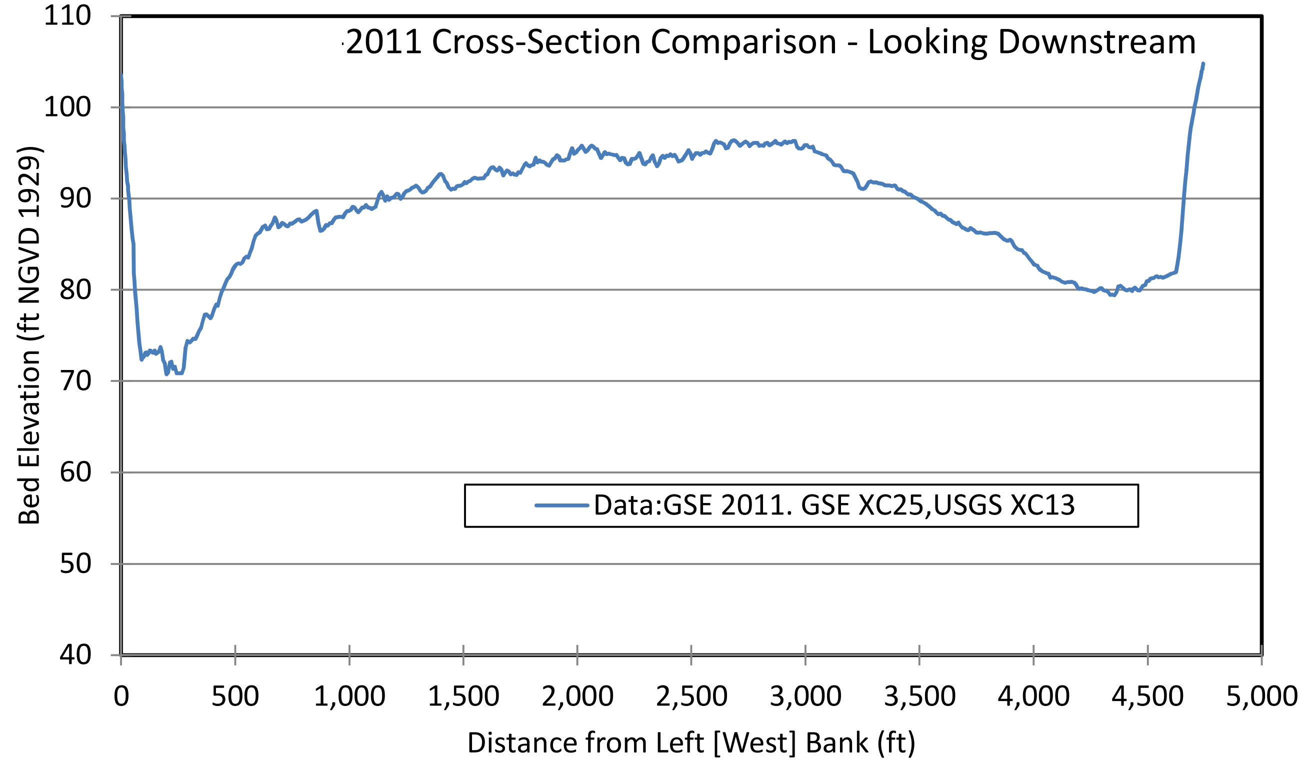

2011 Cross-Section Comparison - Looking Downstream
Data:GSE 2011. GSE XC20
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)


2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC21,USGS XC11

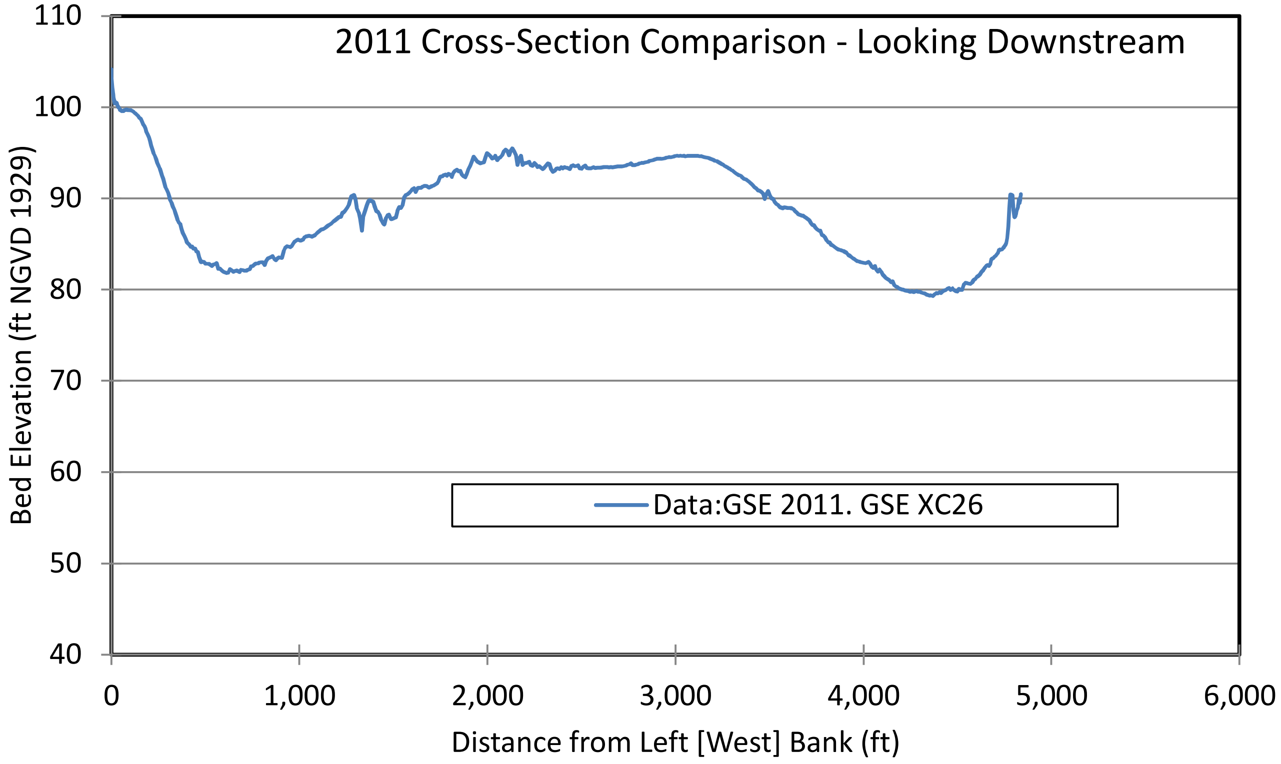

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
8,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC22


2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC23,USGS XC12

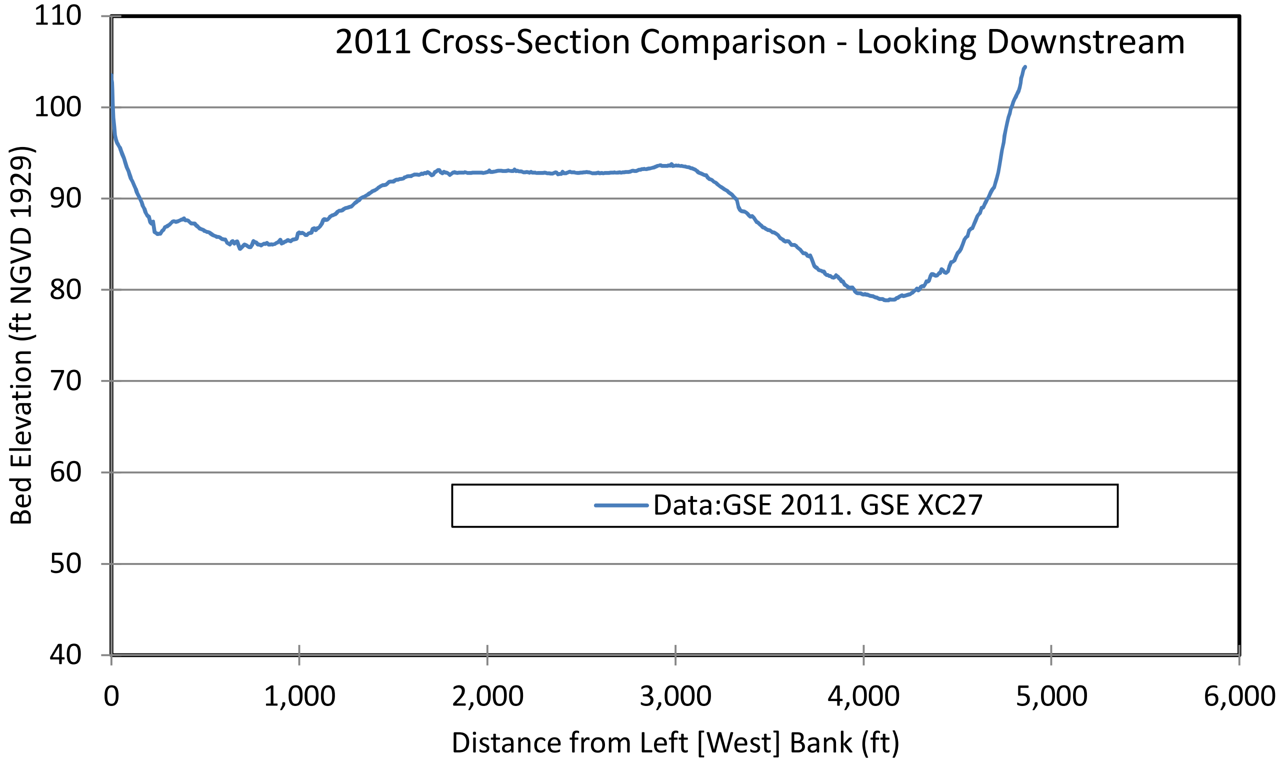

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC24

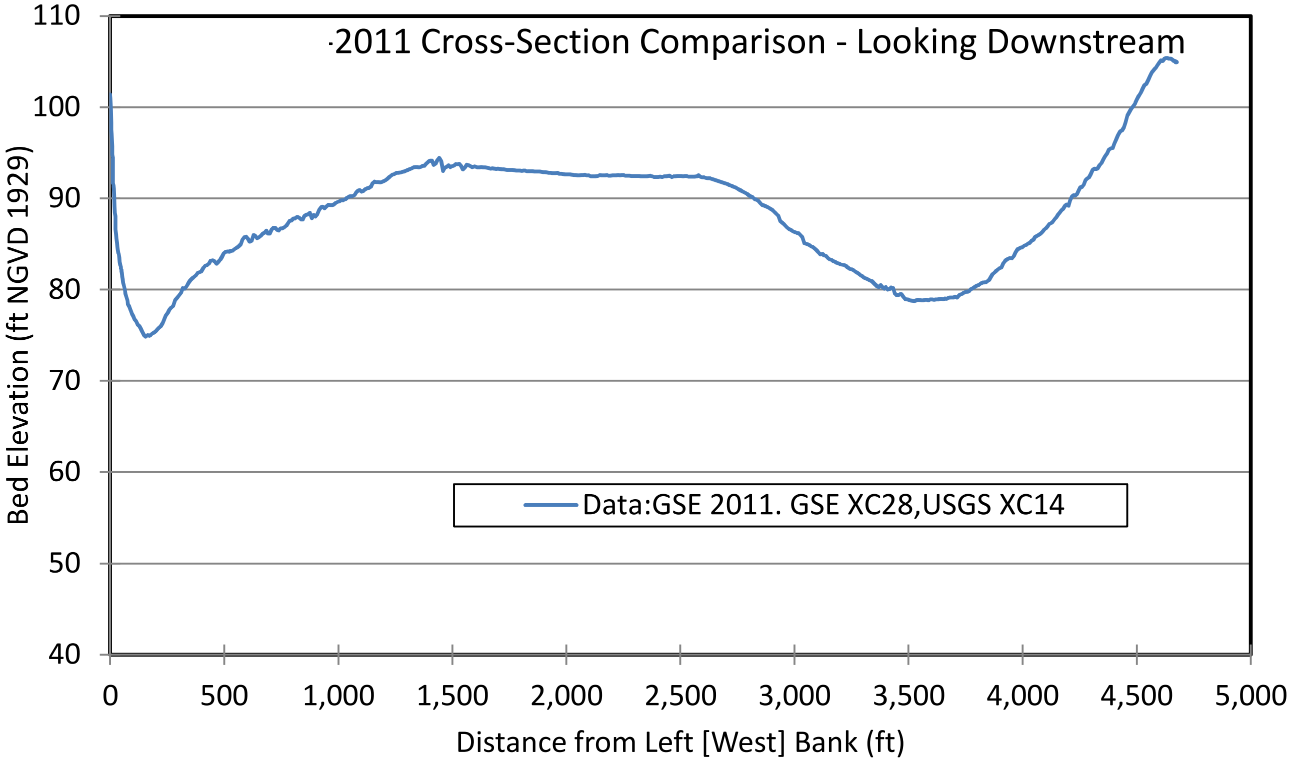


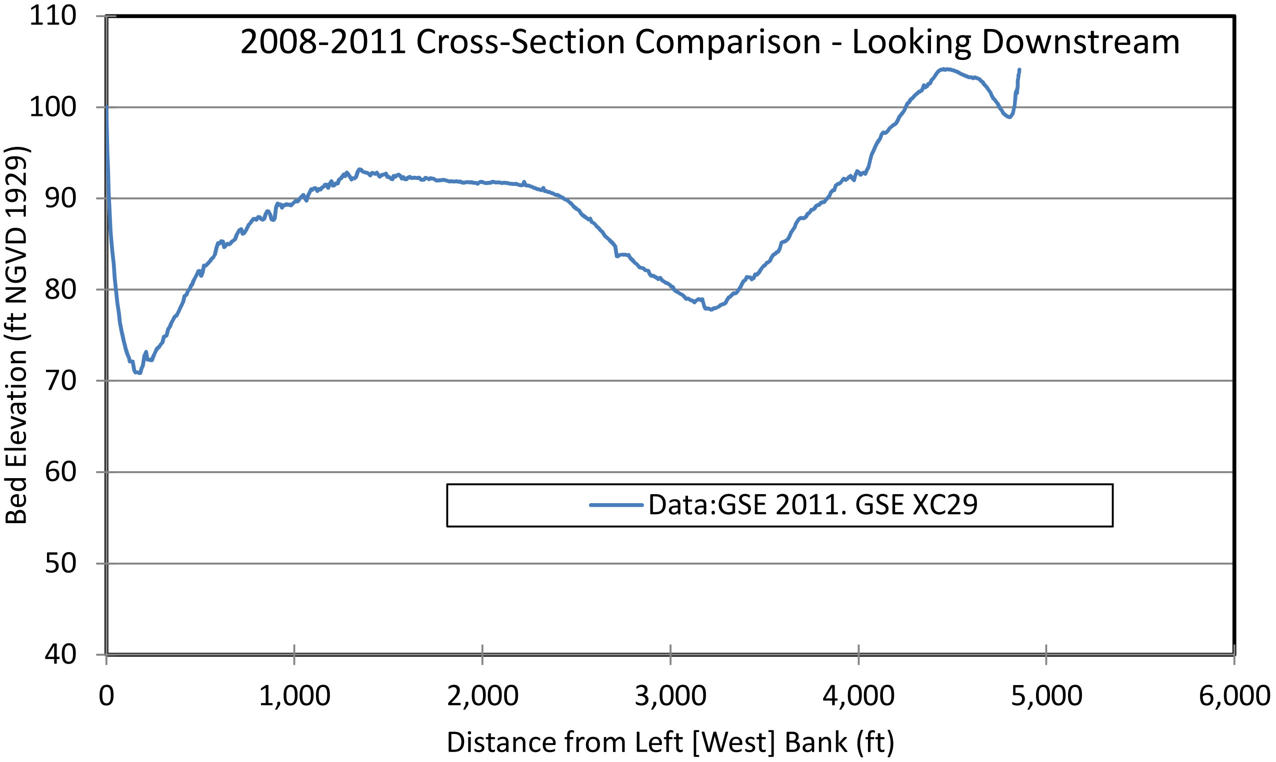
2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC25,USGS XC13

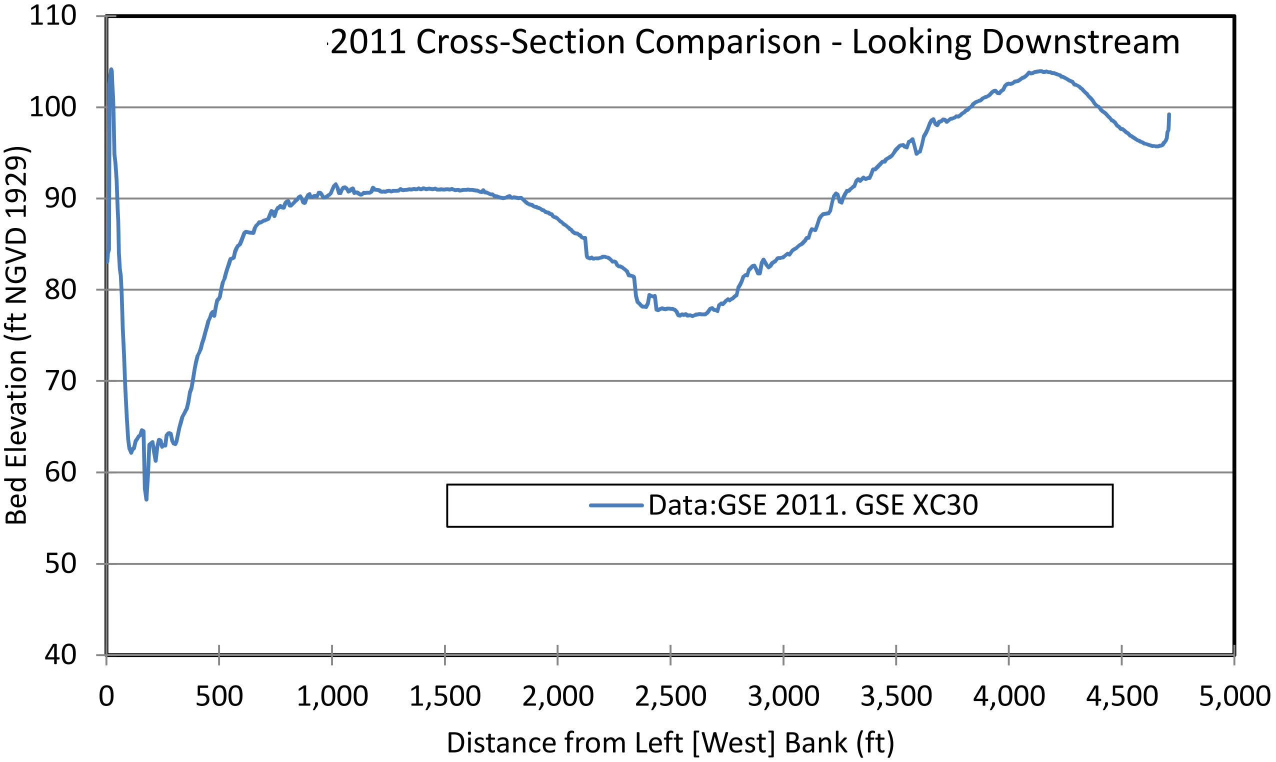


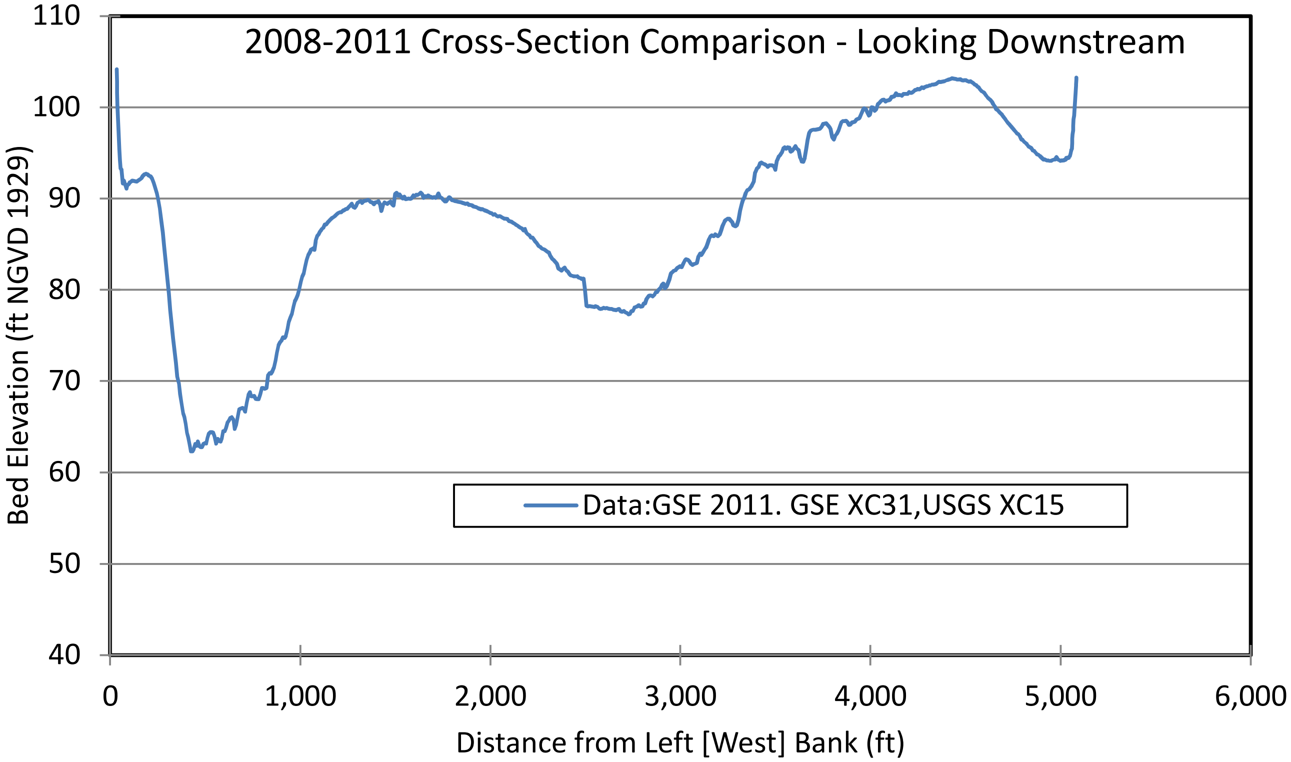
2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC26

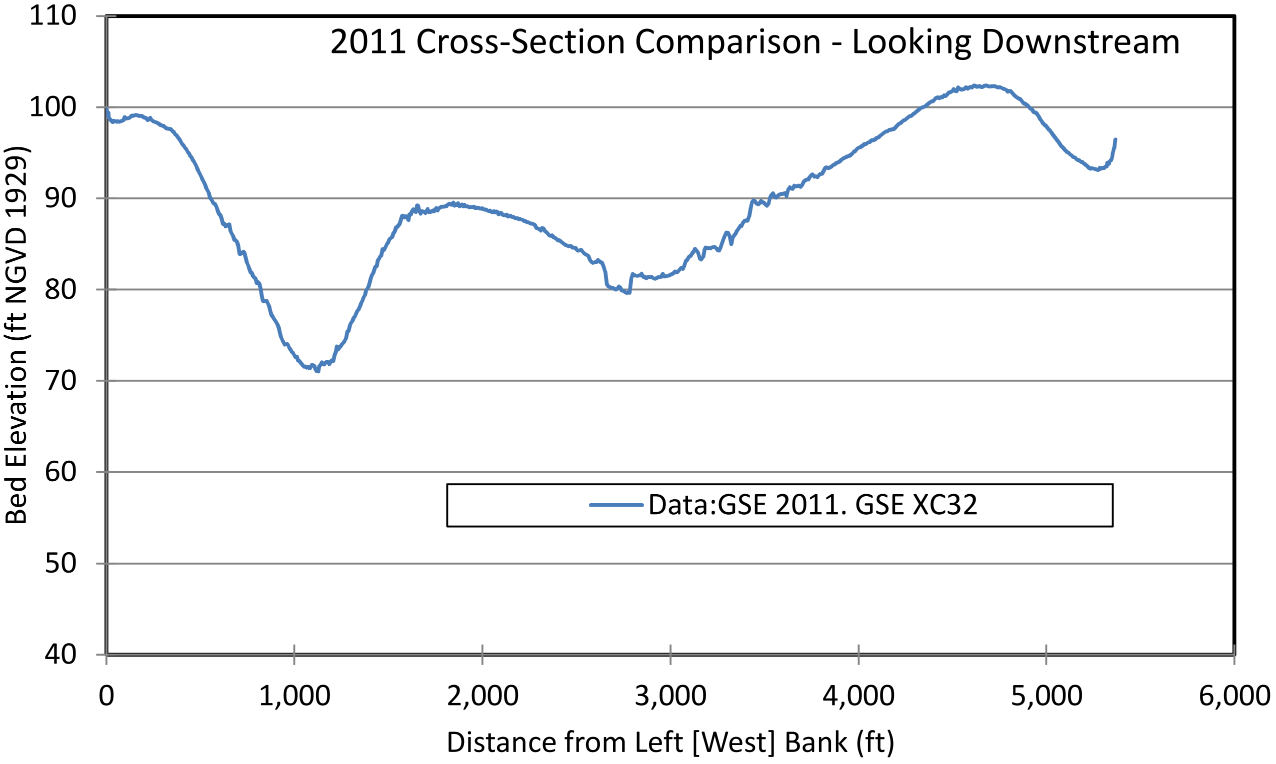

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC27

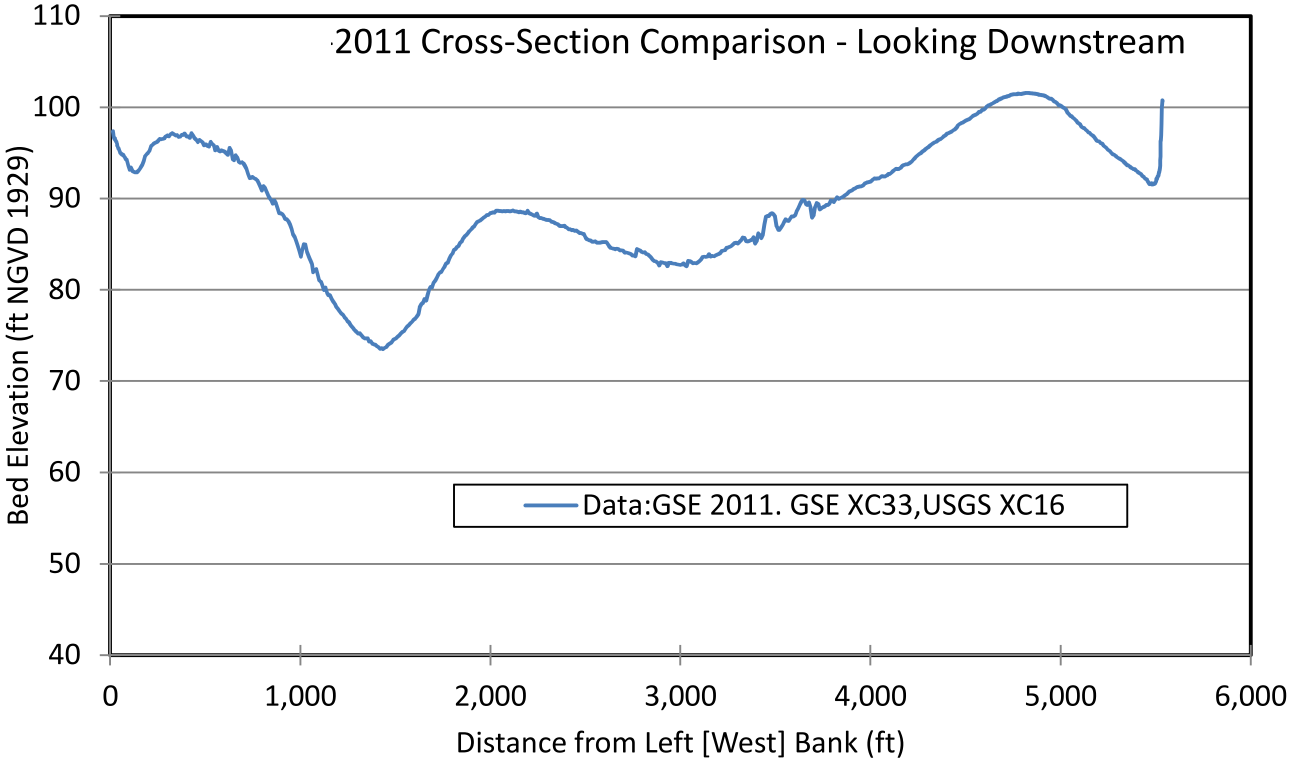

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC28,USGS XC14

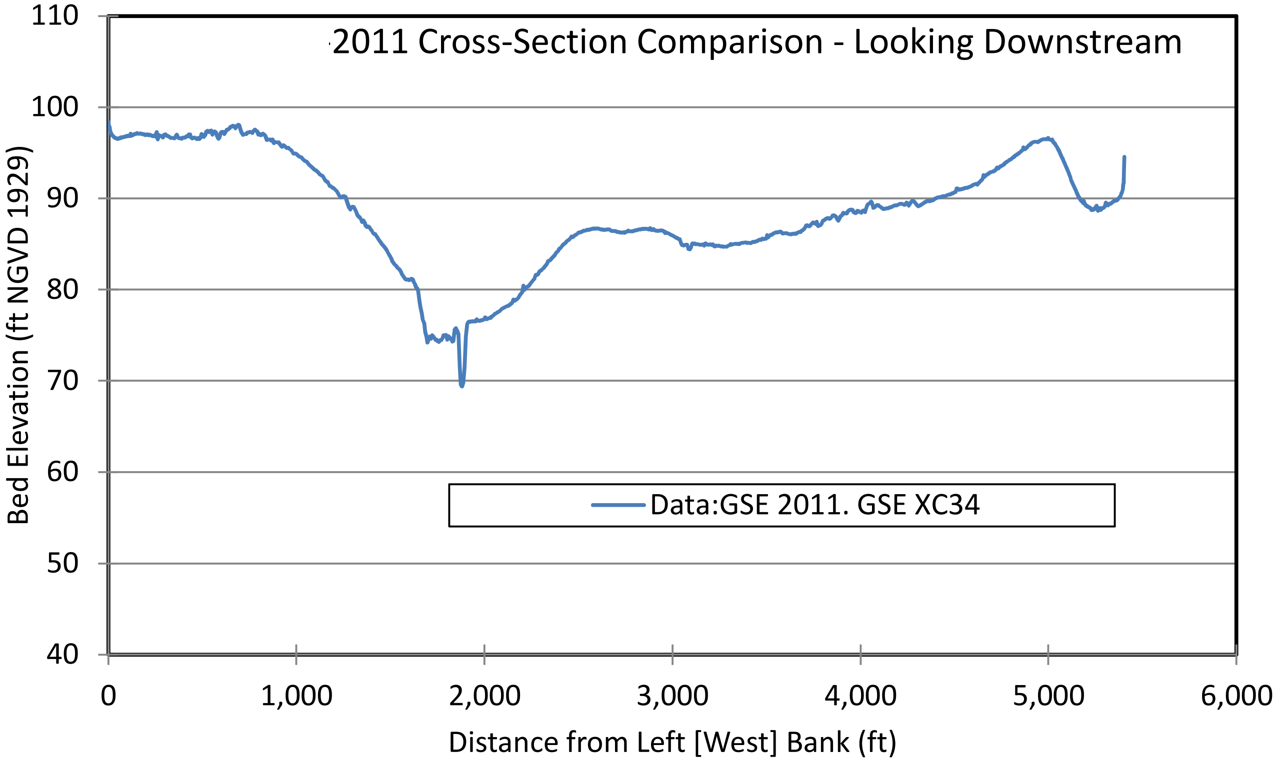

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC29

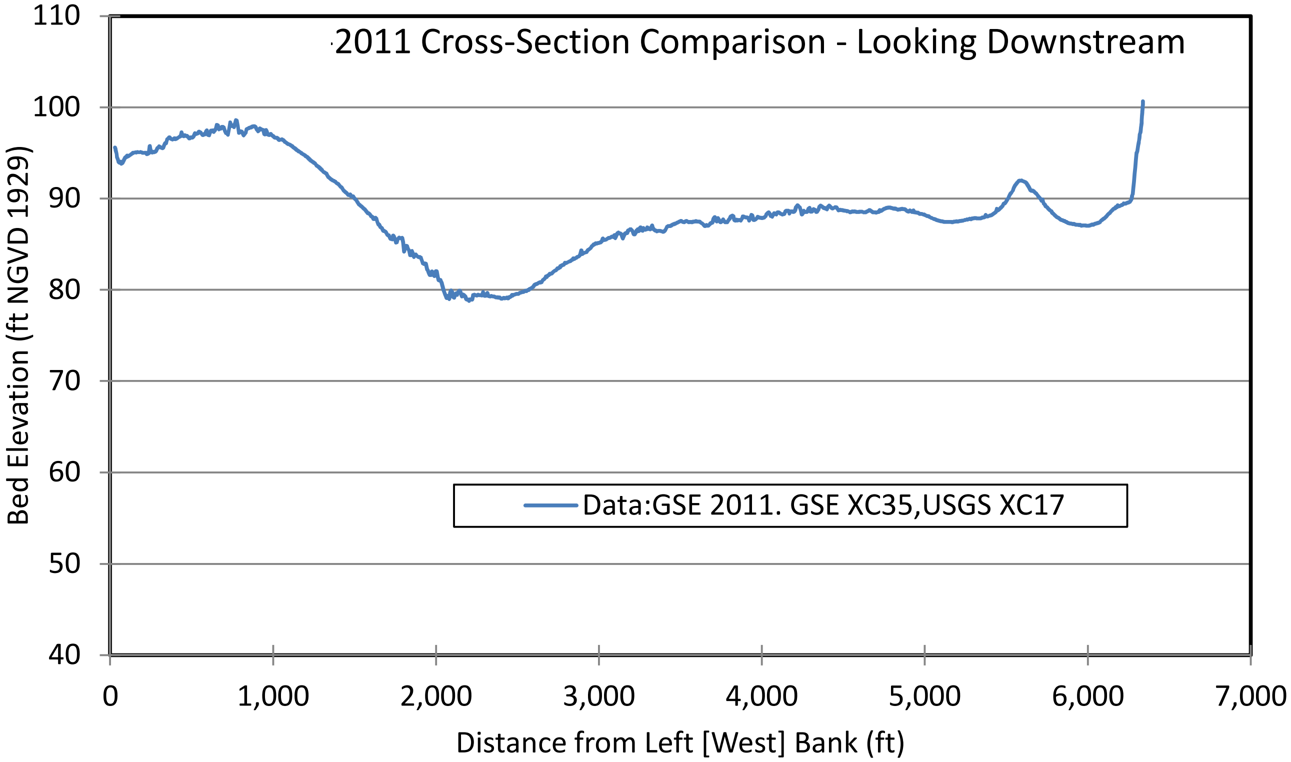

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC30

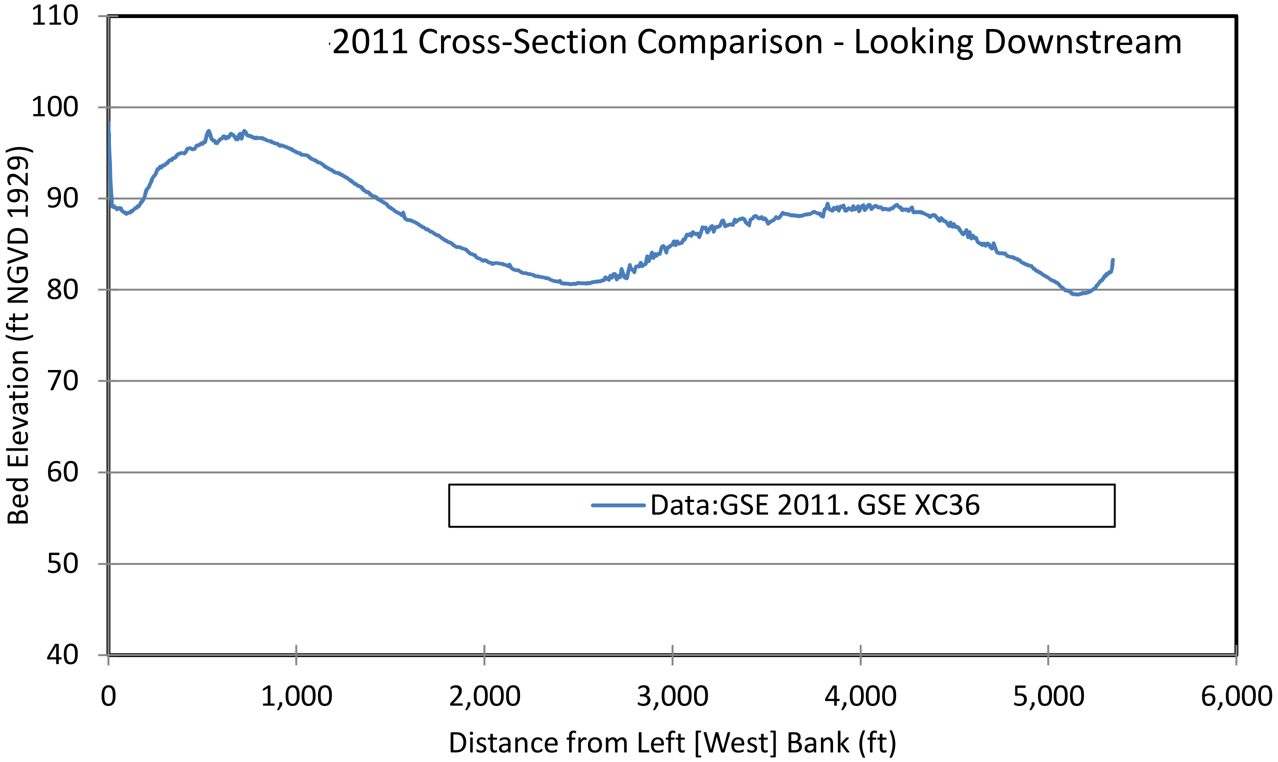

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC31,USGS XC15

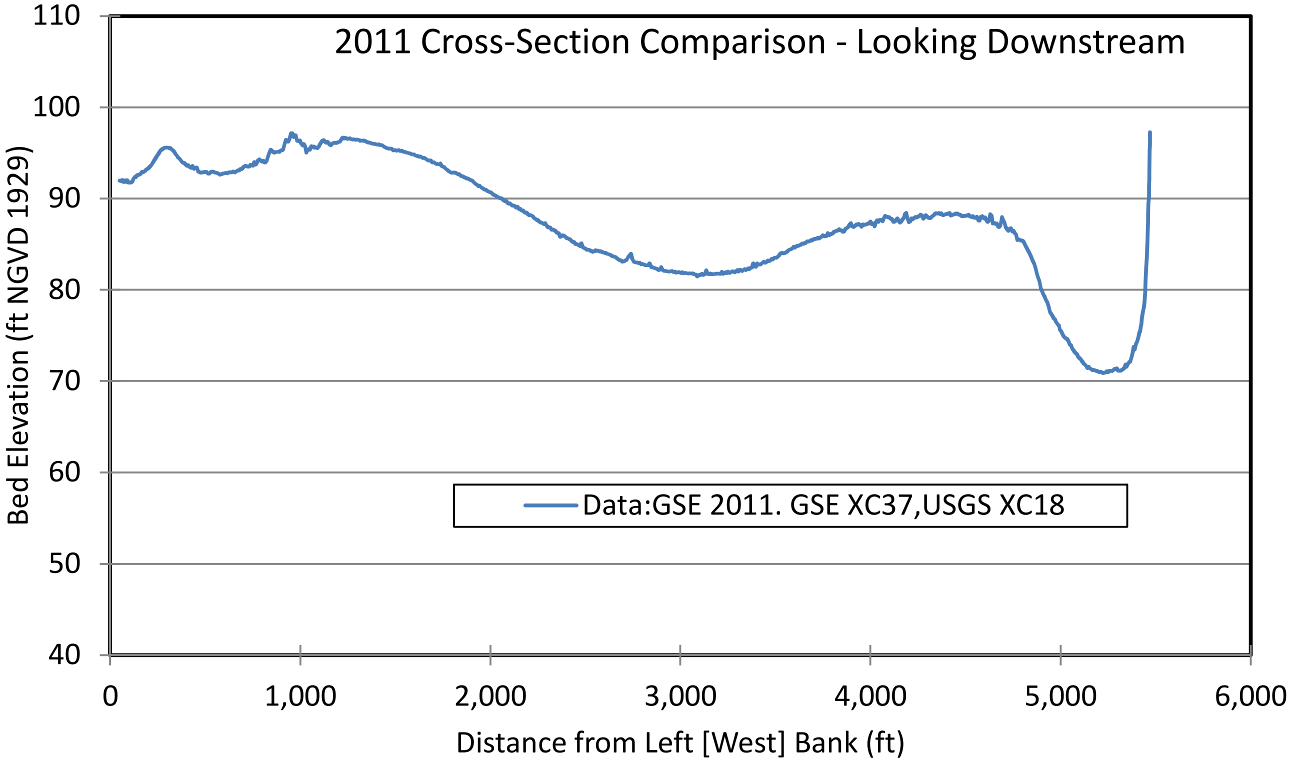

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC32

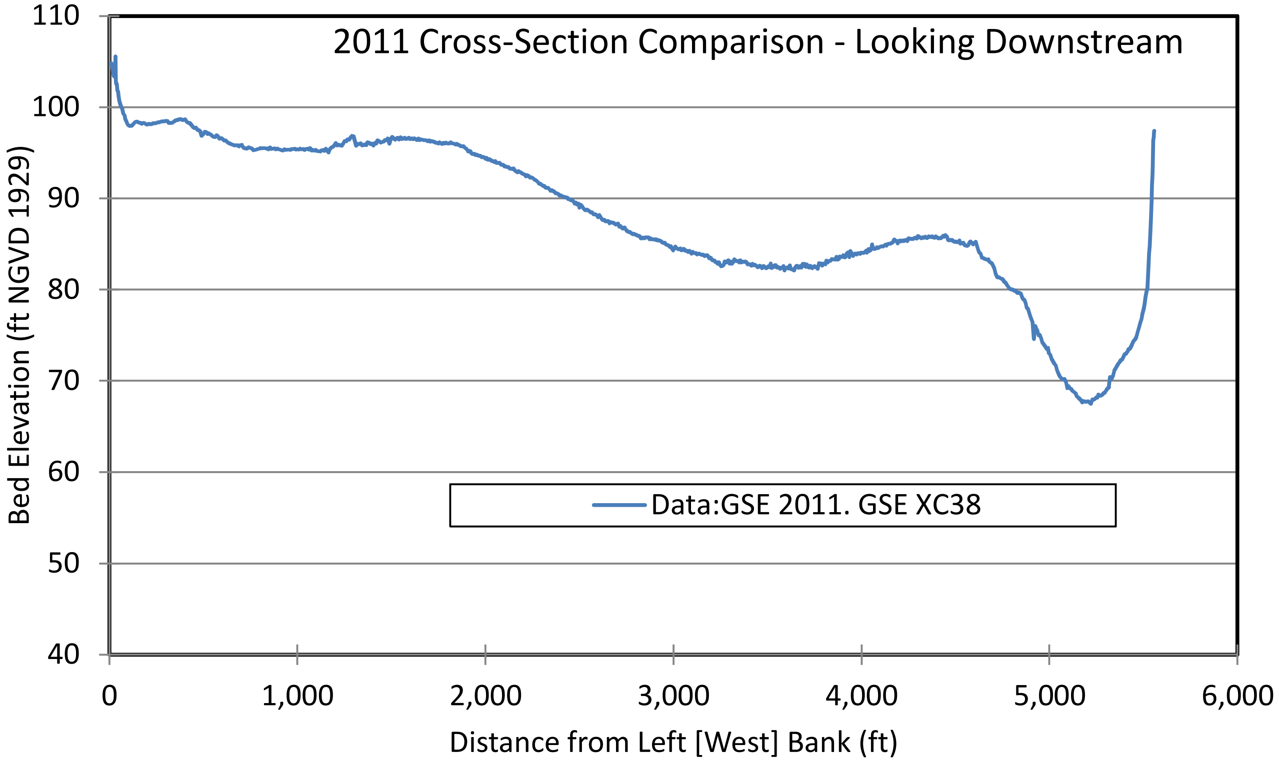

2011 Cross-Section Comparison - Looking Downstream
Data:GSE 2011. GSE XC33,USGS XC16
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)

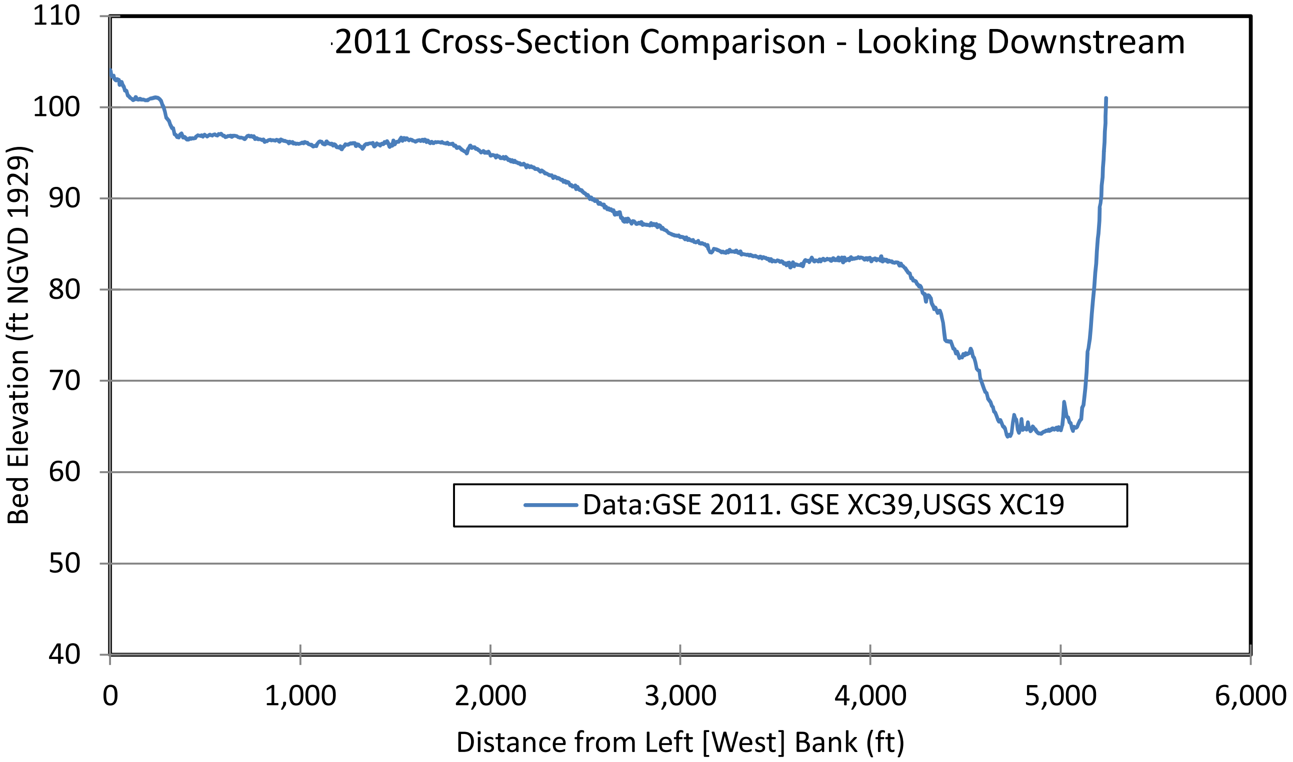

2011 Cross-Section Comparison - Looking Downstream
Data:GSE 2011. GSE XC34
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)

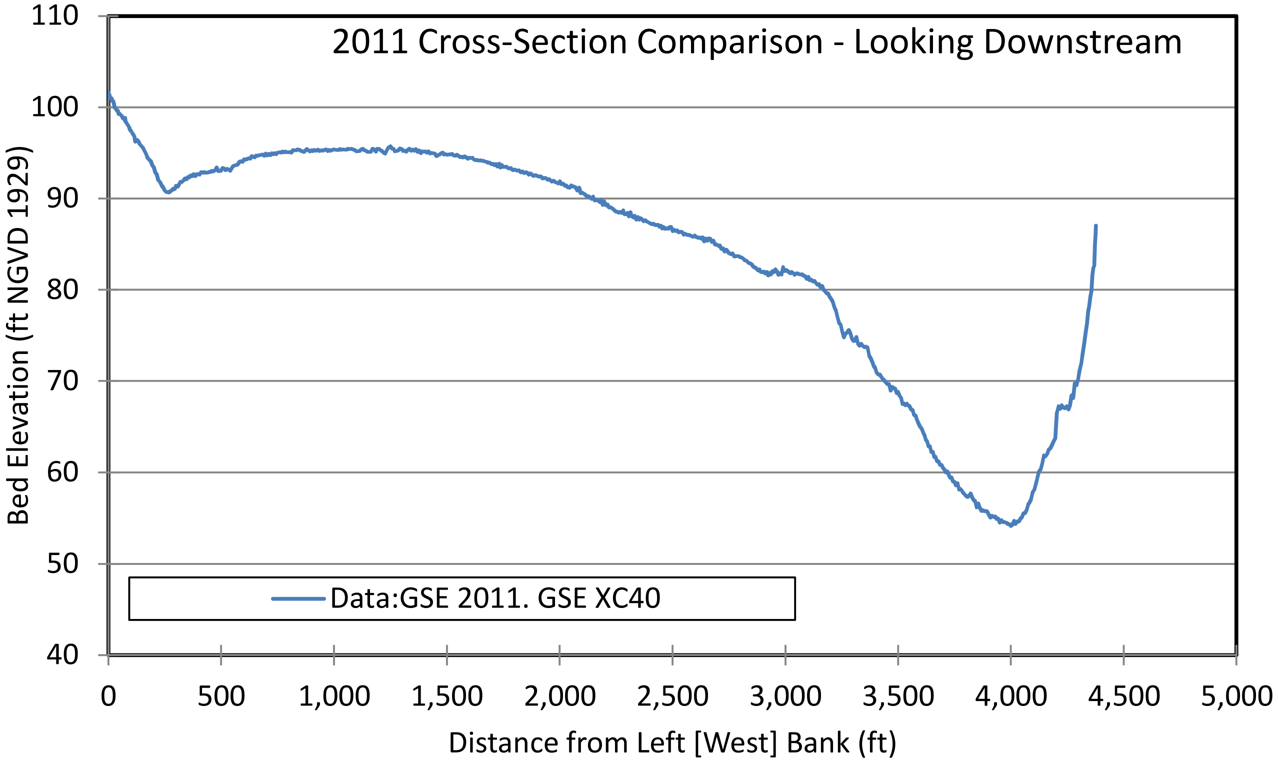

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC35,USGS XC17

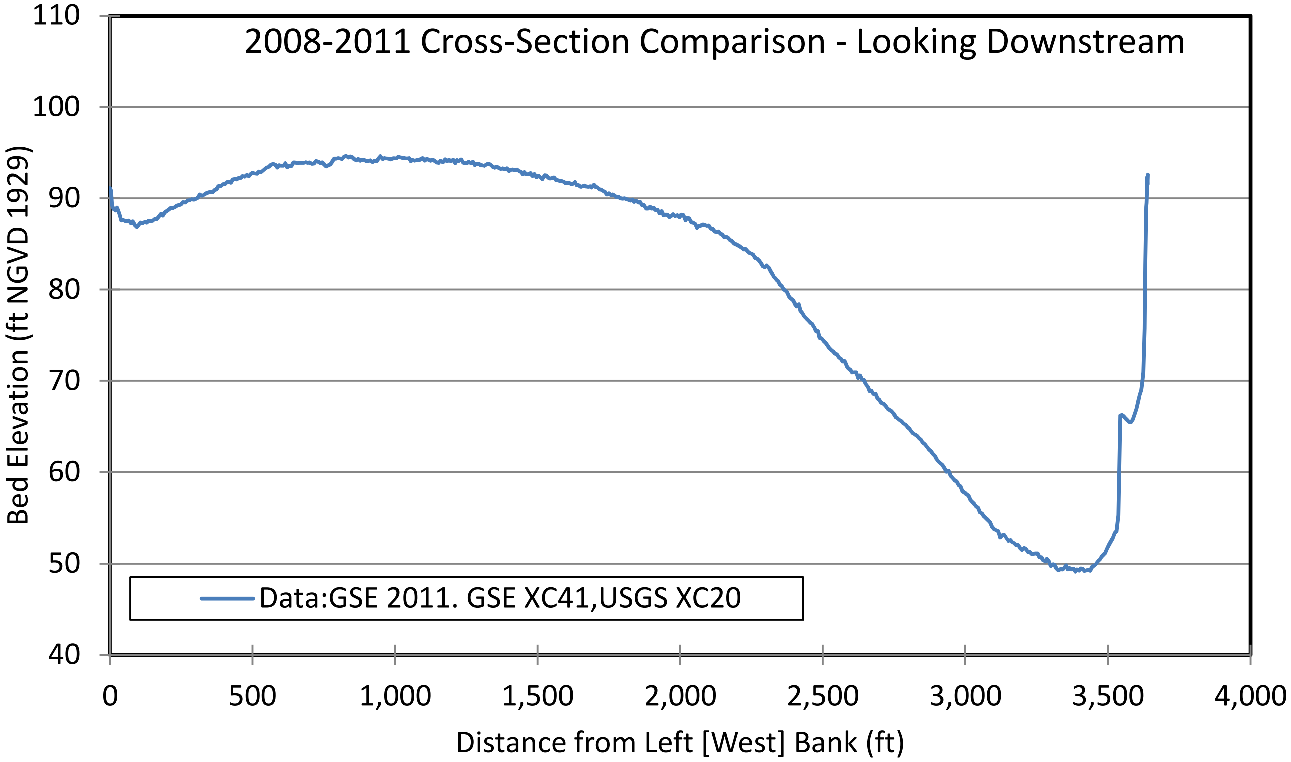

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC36

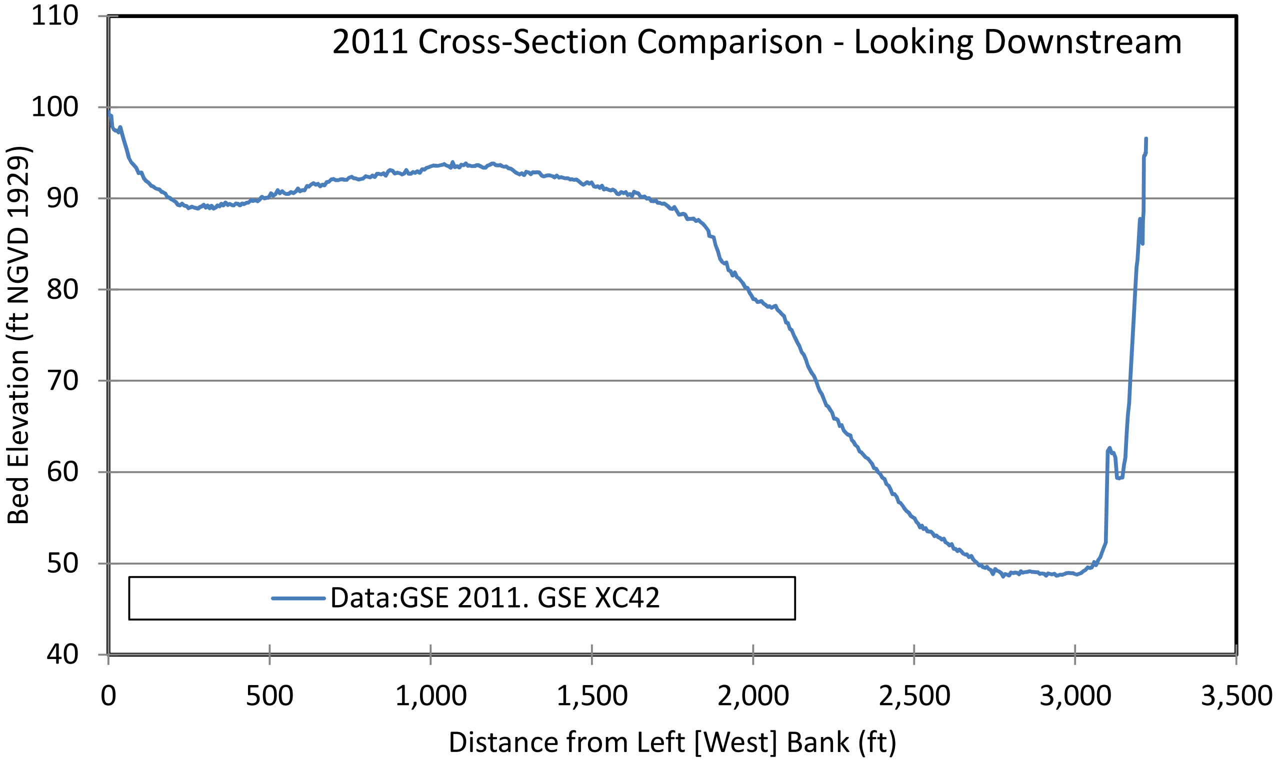

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC37,USGS XC18

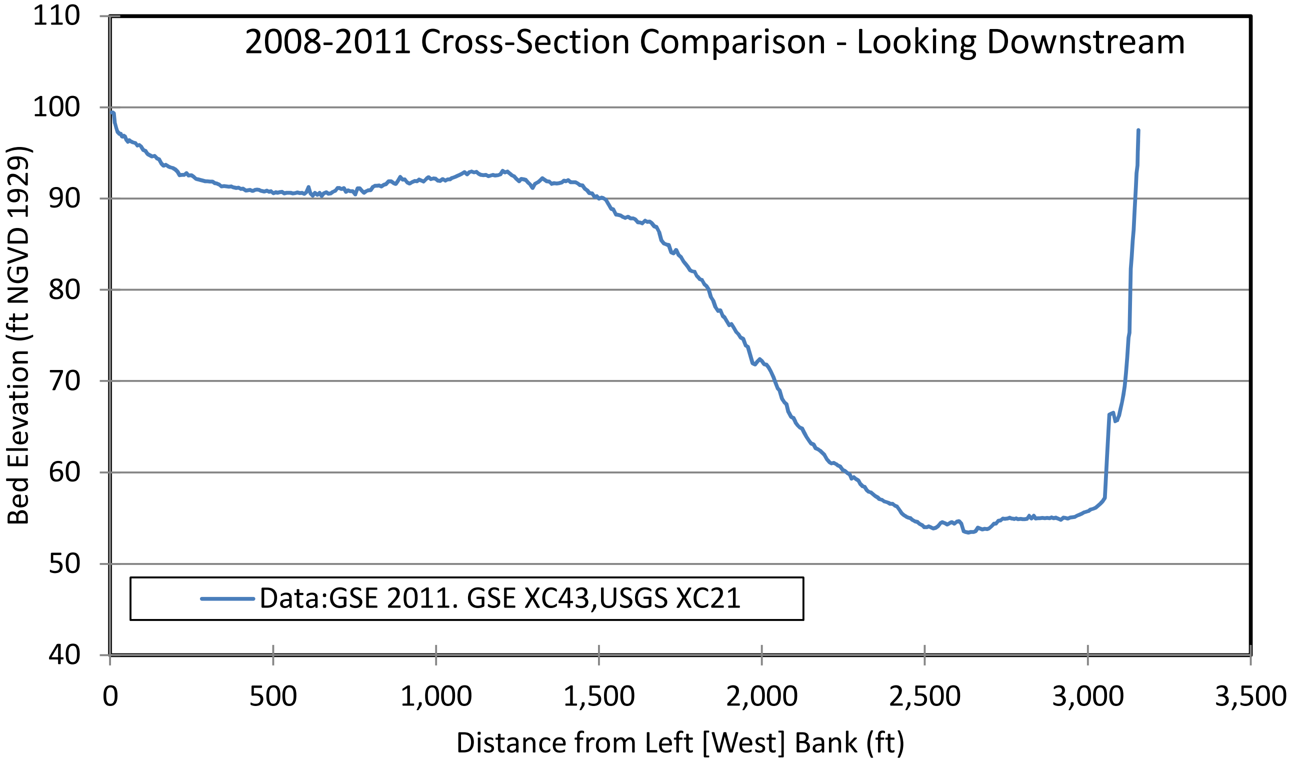

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC38

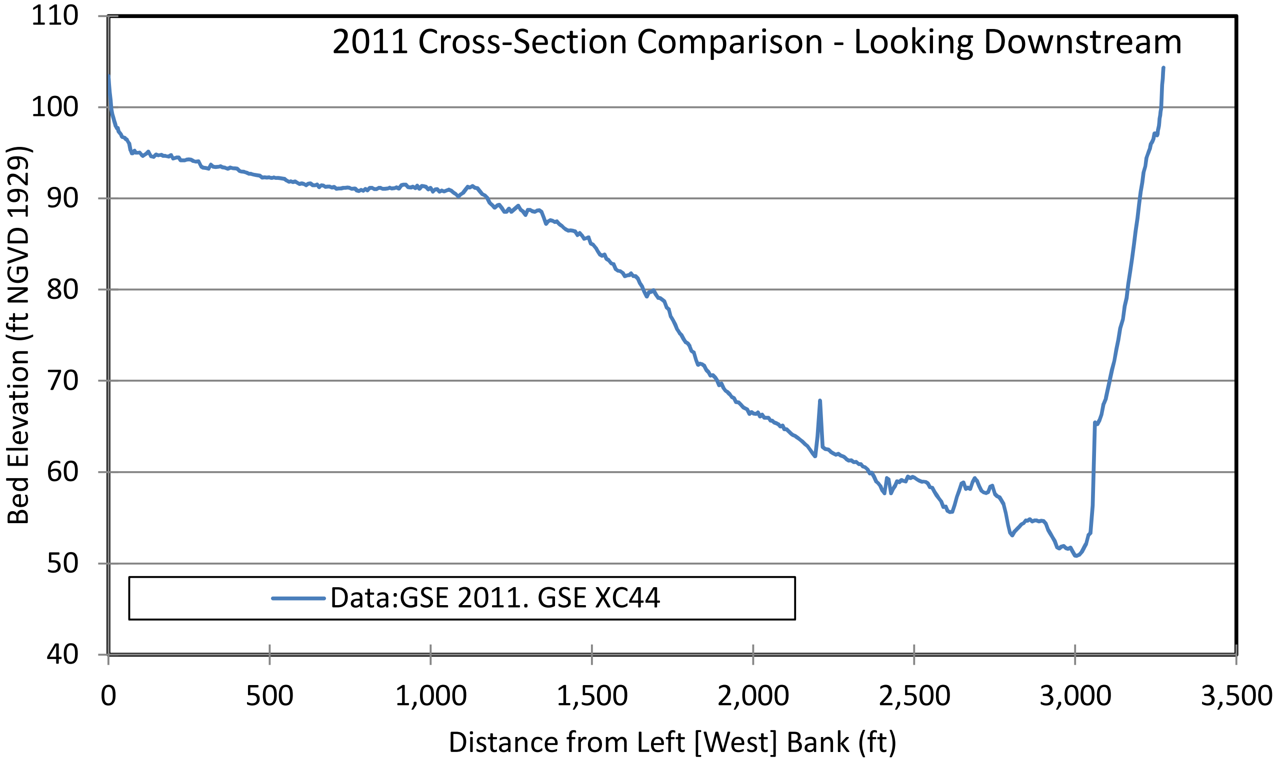

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC39,USGS XC19

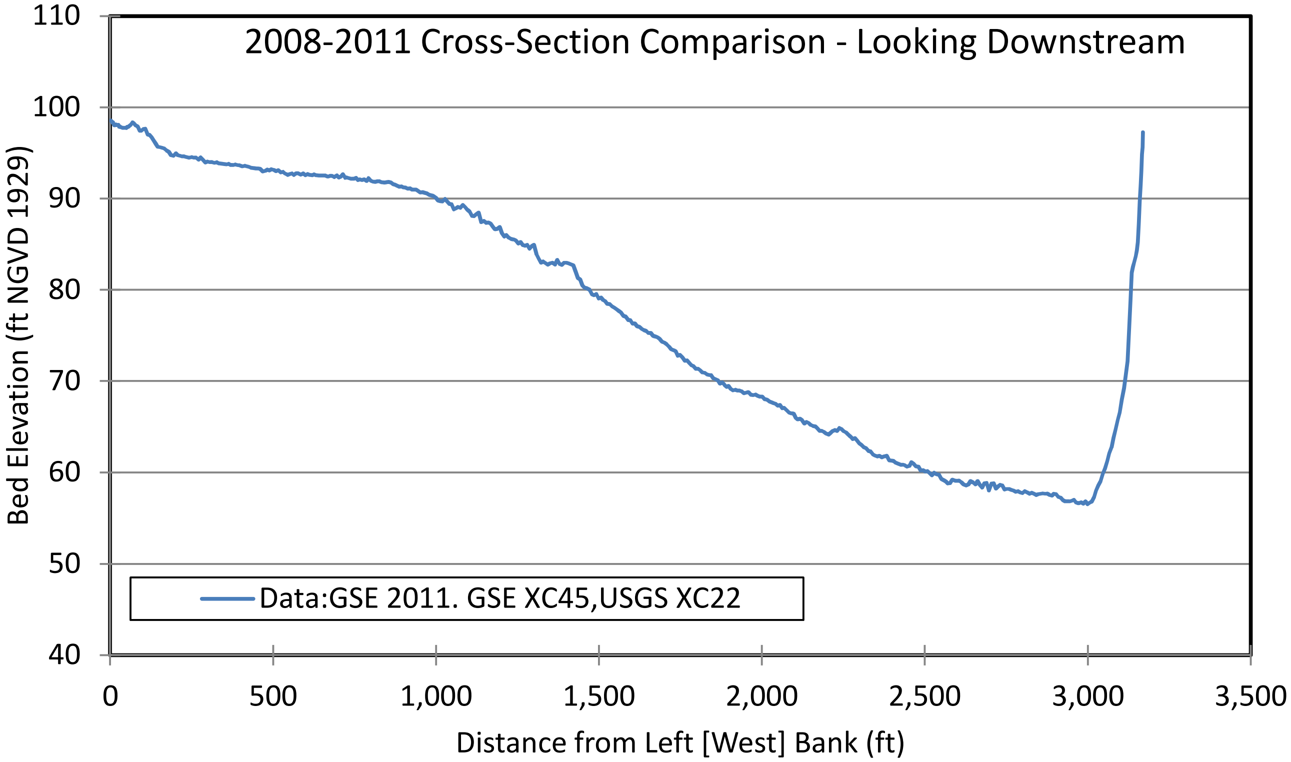

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC40

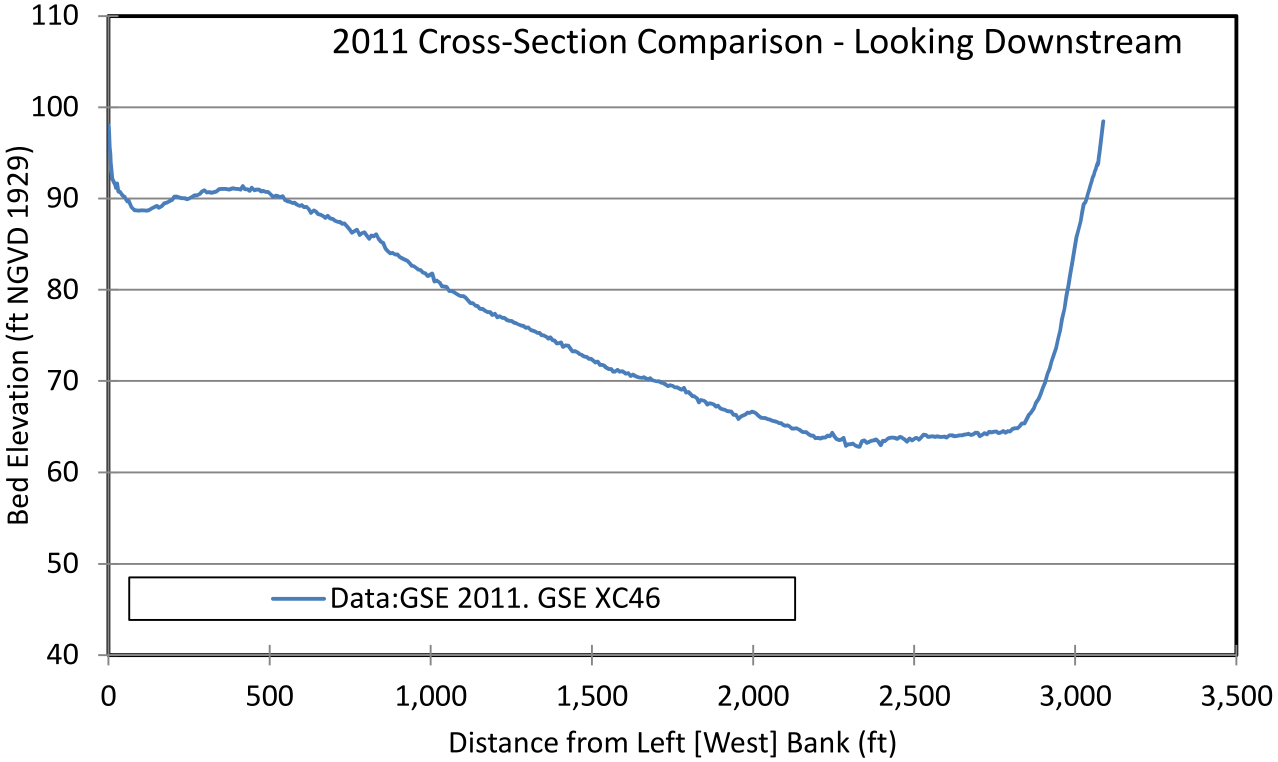

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
Data:GSE 2011. GSE XC41,USGS XC20
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
Distance from Left [West] Bank (ft)

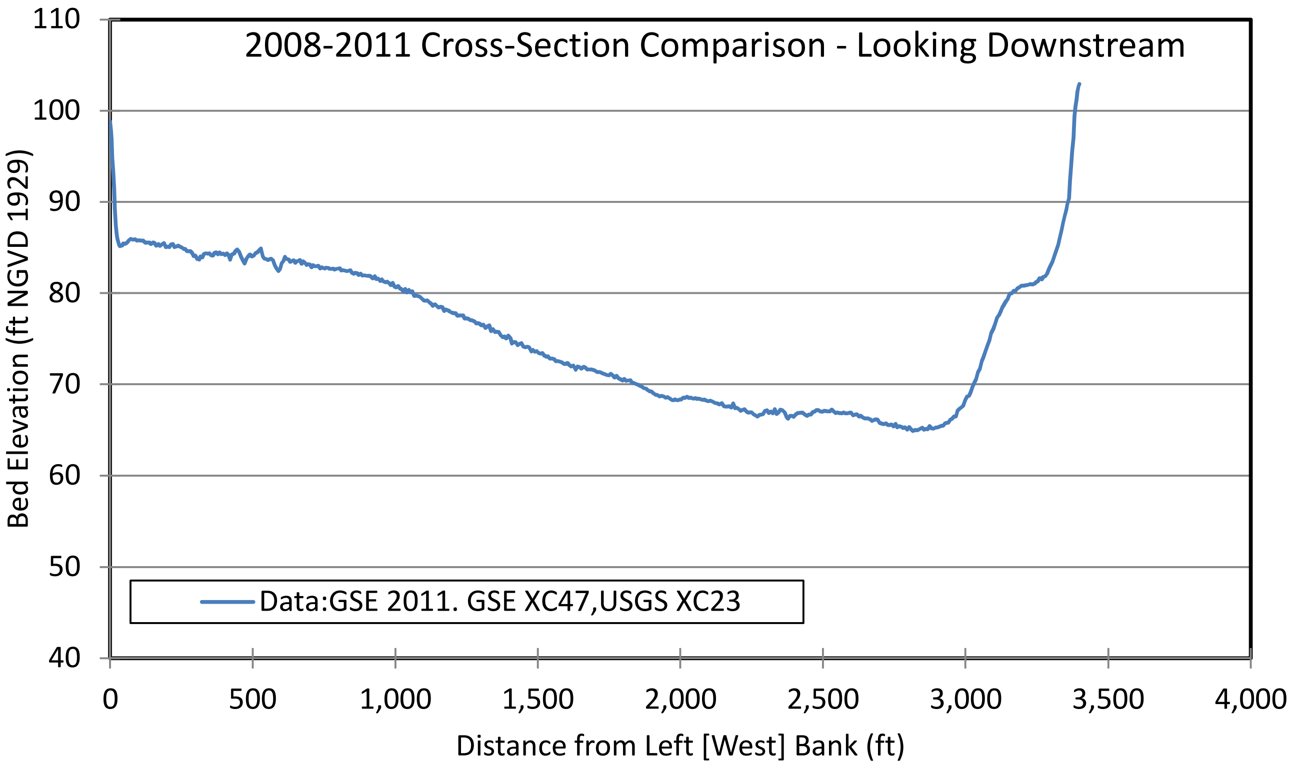

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
Data:GSE 2011. GSE XC42
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Distance from Left [West] Bank (ft)

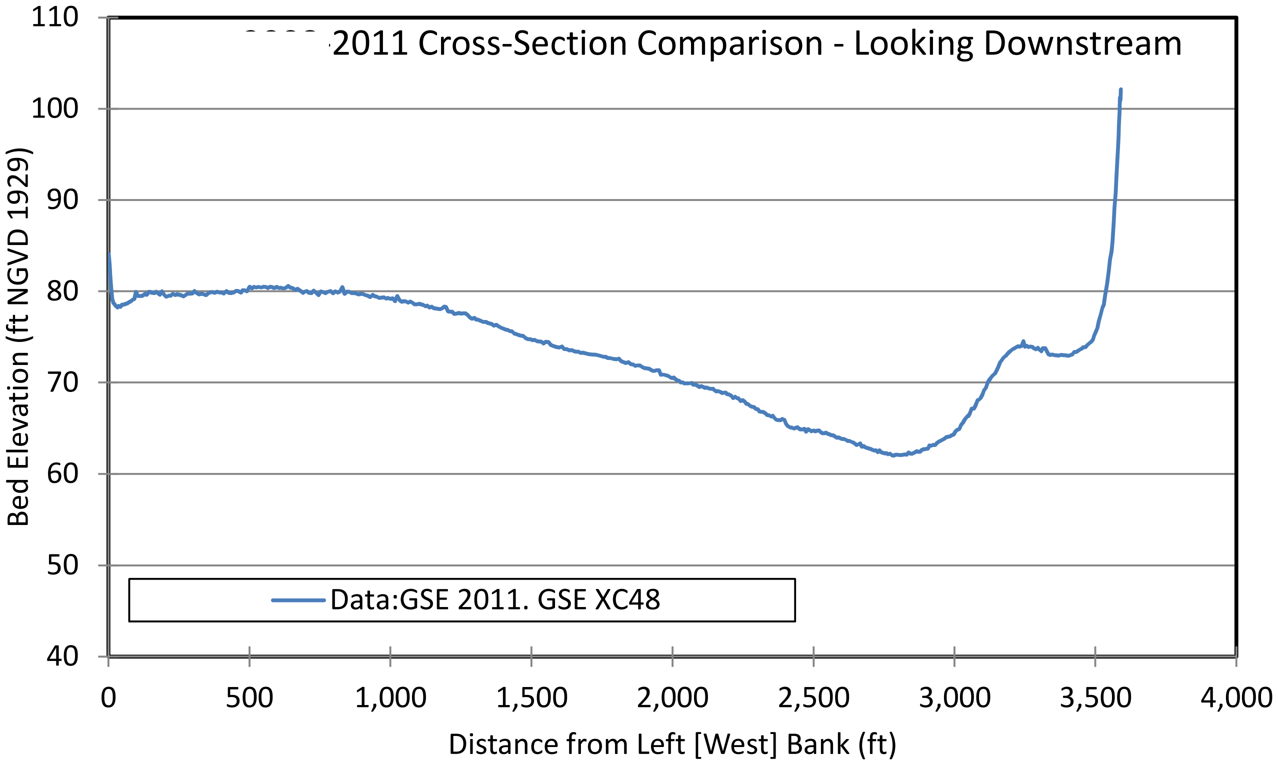

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC43,USGS XC21

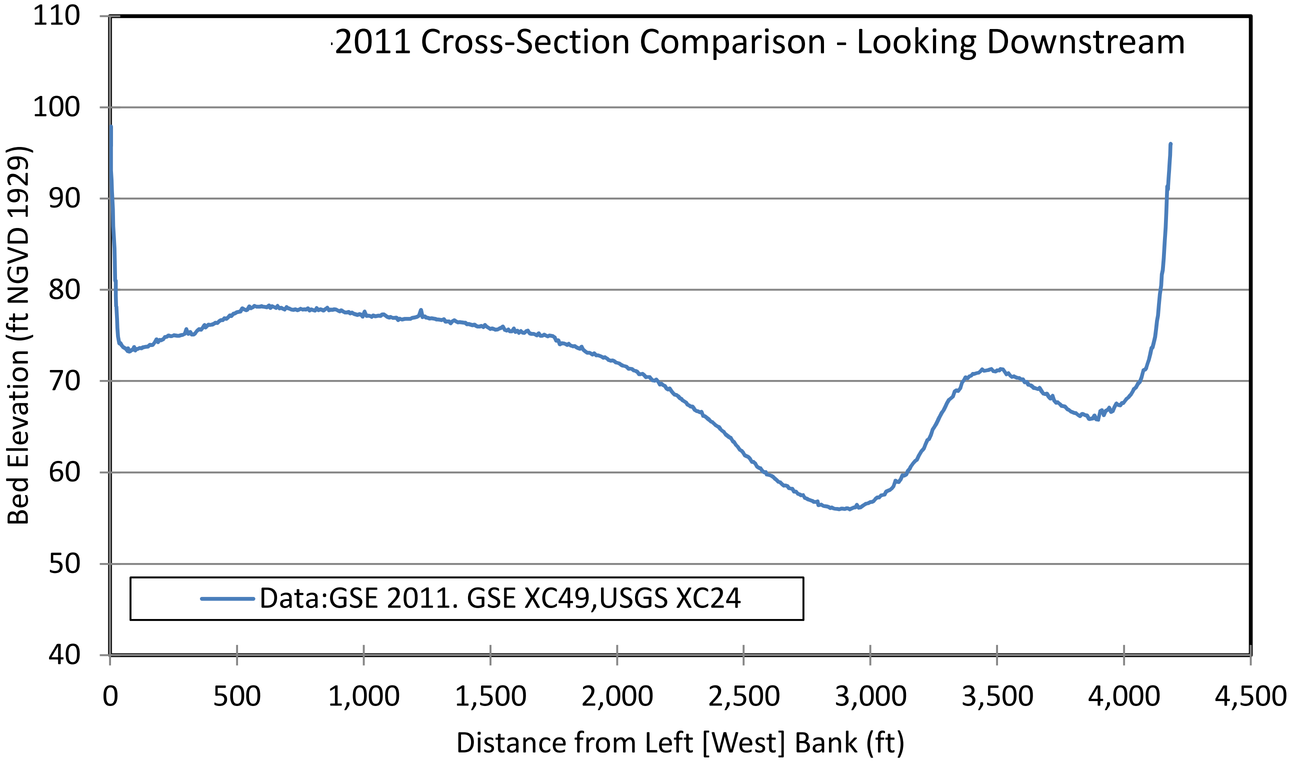

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC44

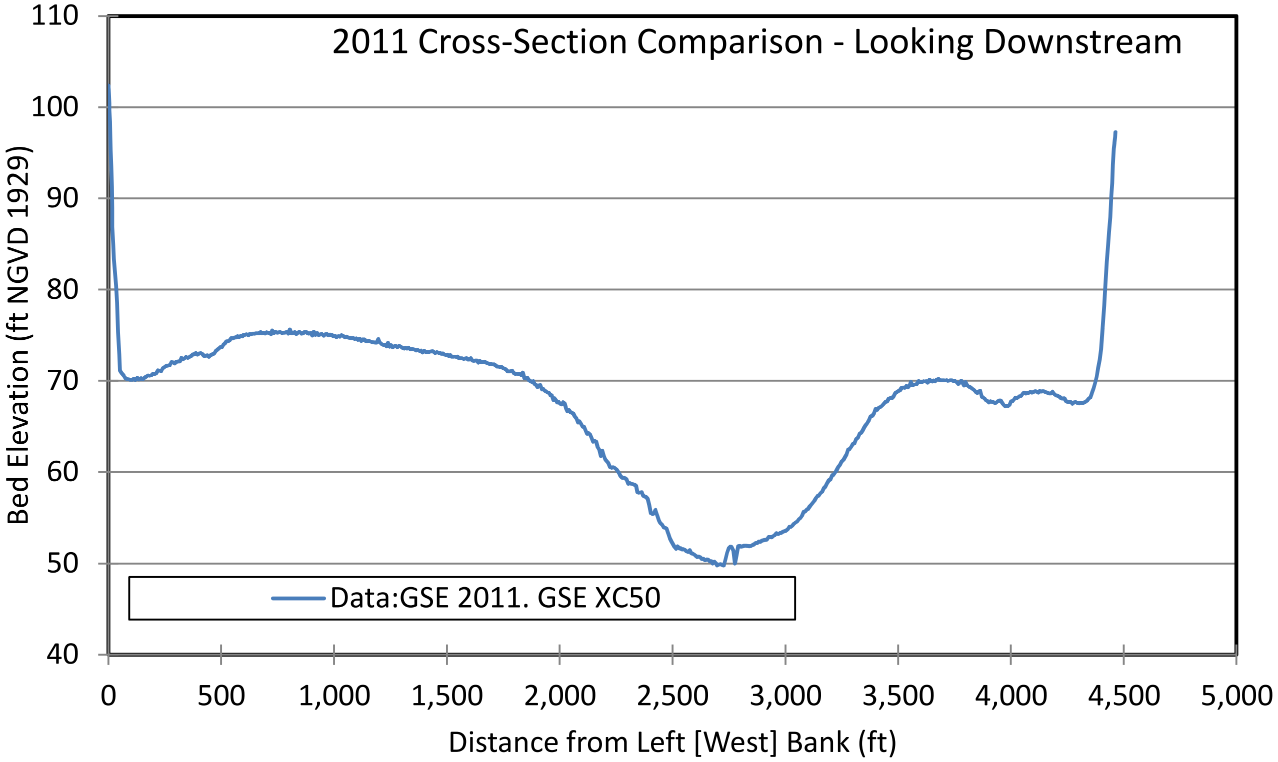

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC45,USGS XC22

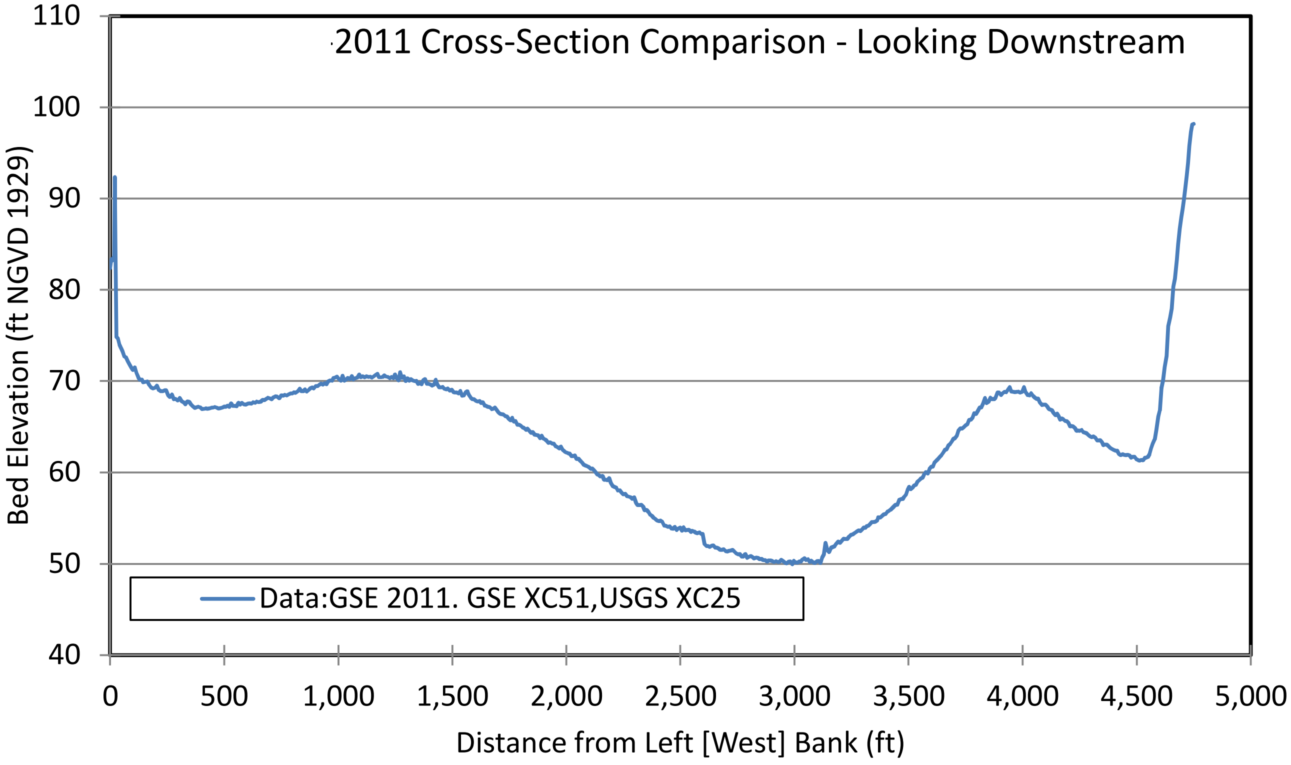

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC46

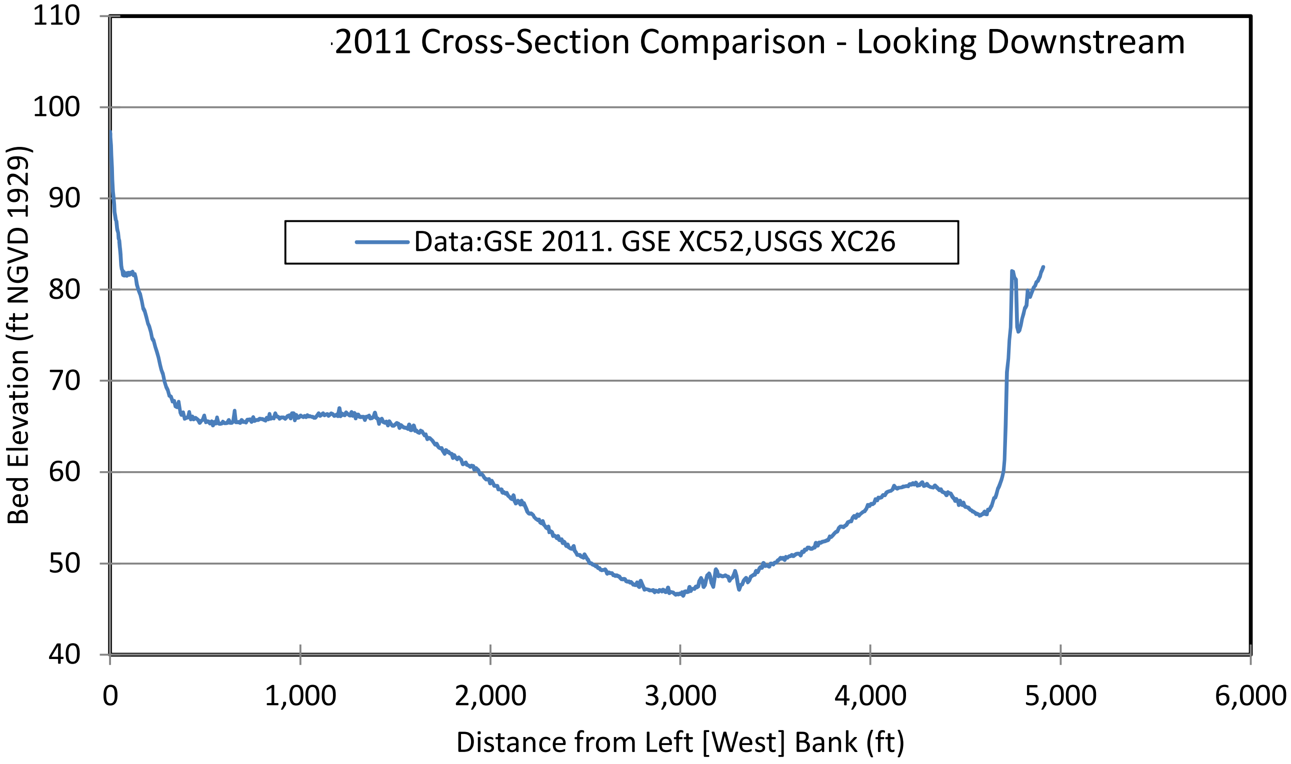

2008-2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
Data:GSE 2011. GSE XC47,USGS XC23
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
Distance from Left [West] Bank (ft)

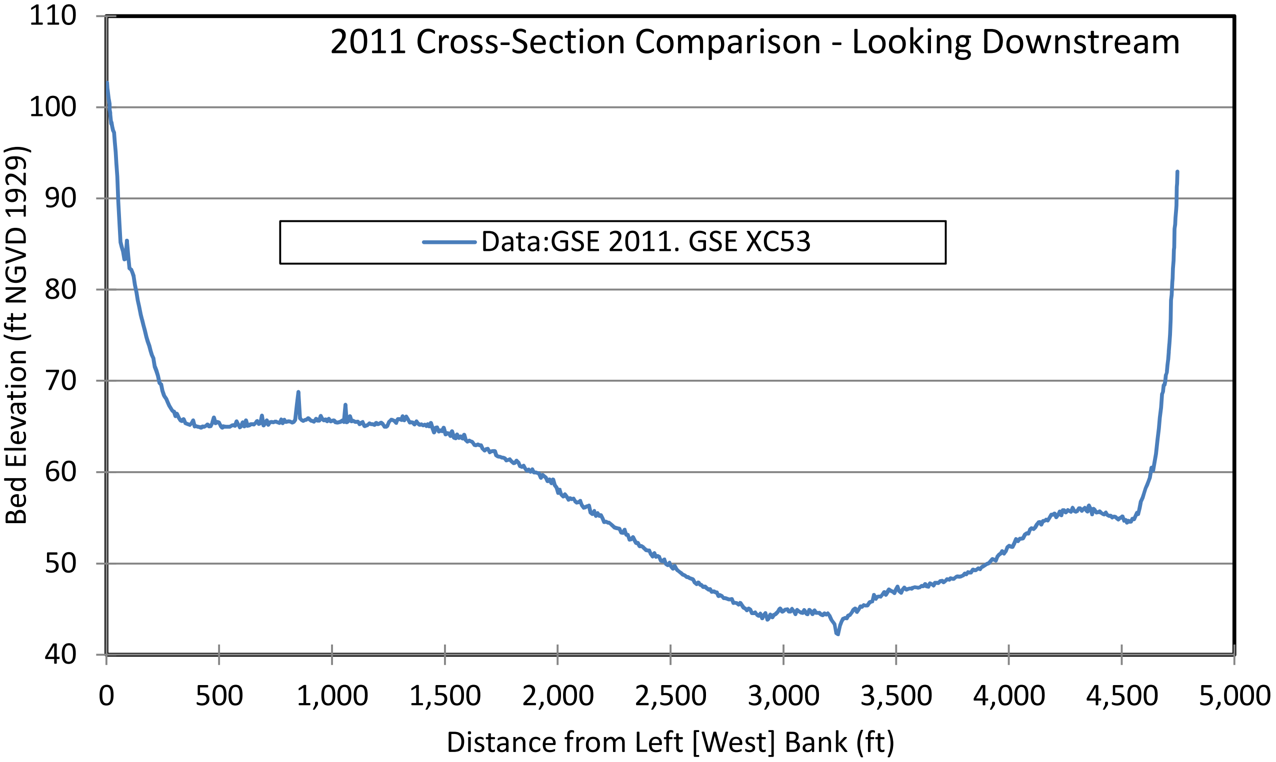

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
Data:GSE 2011. GSE XC48
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
Distance from Left [West] Bank (ft)

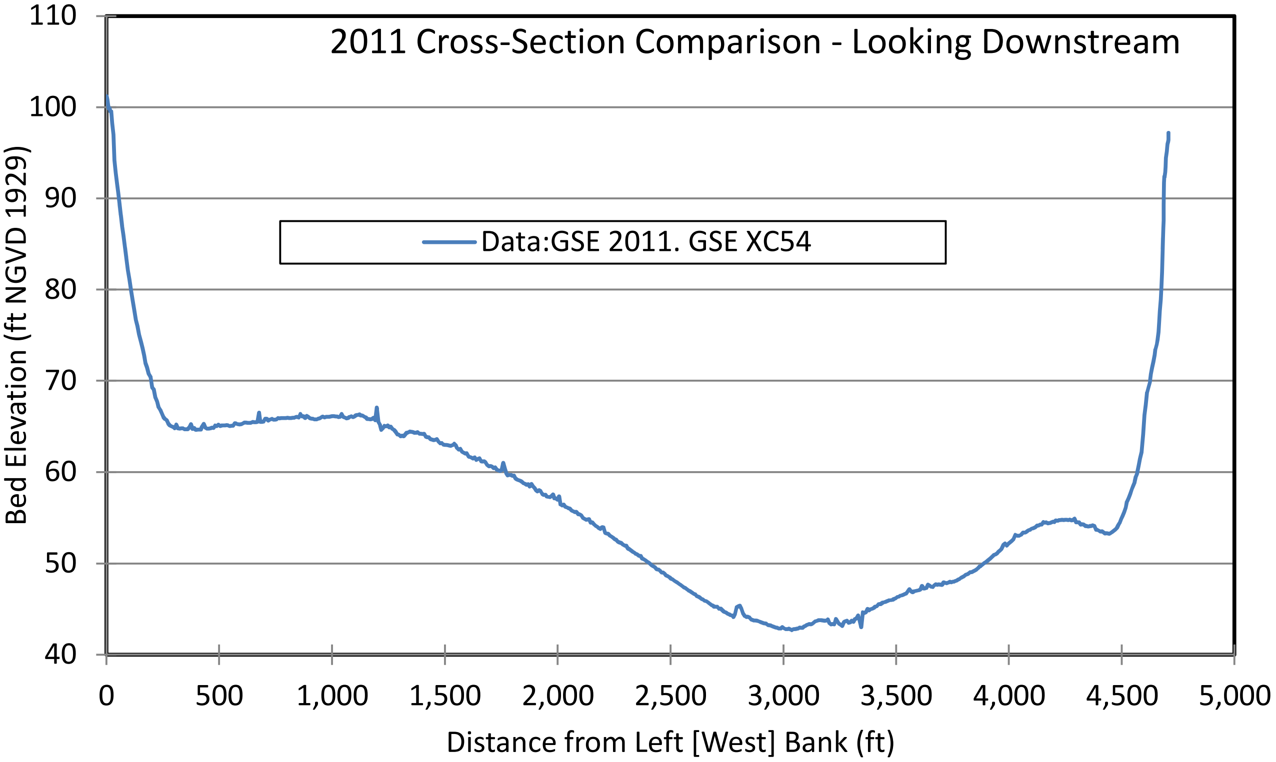

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC49,USGS XC24

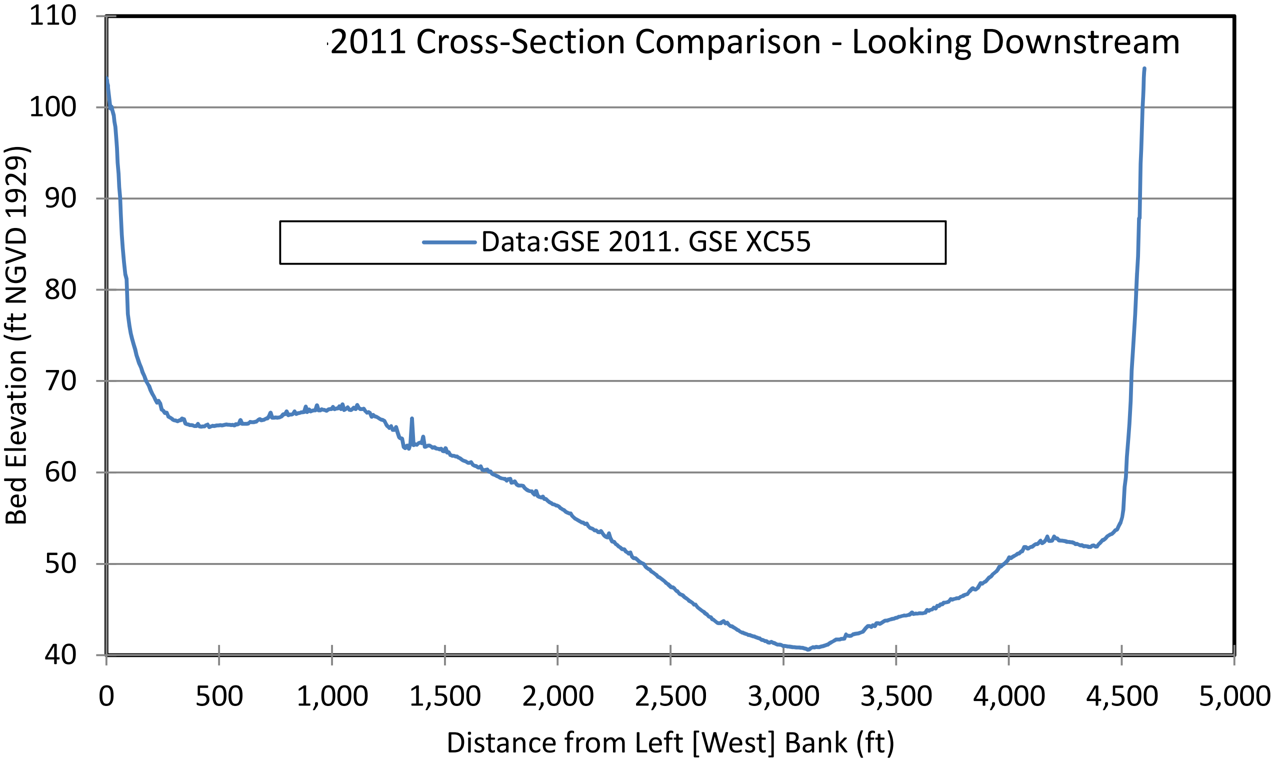

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)
Data:GSE 2011. GSE XC50

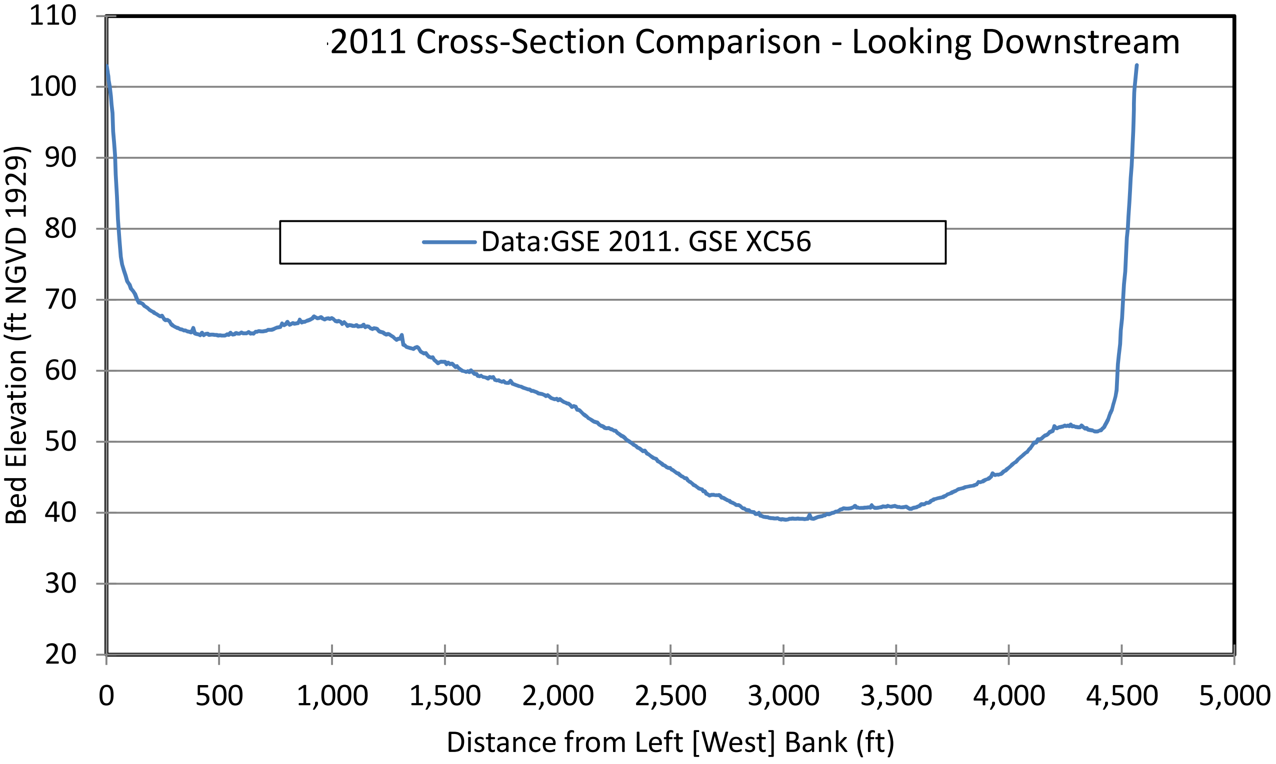

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
Data:GSE 2011. GSE XC51,USGS XC25
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)

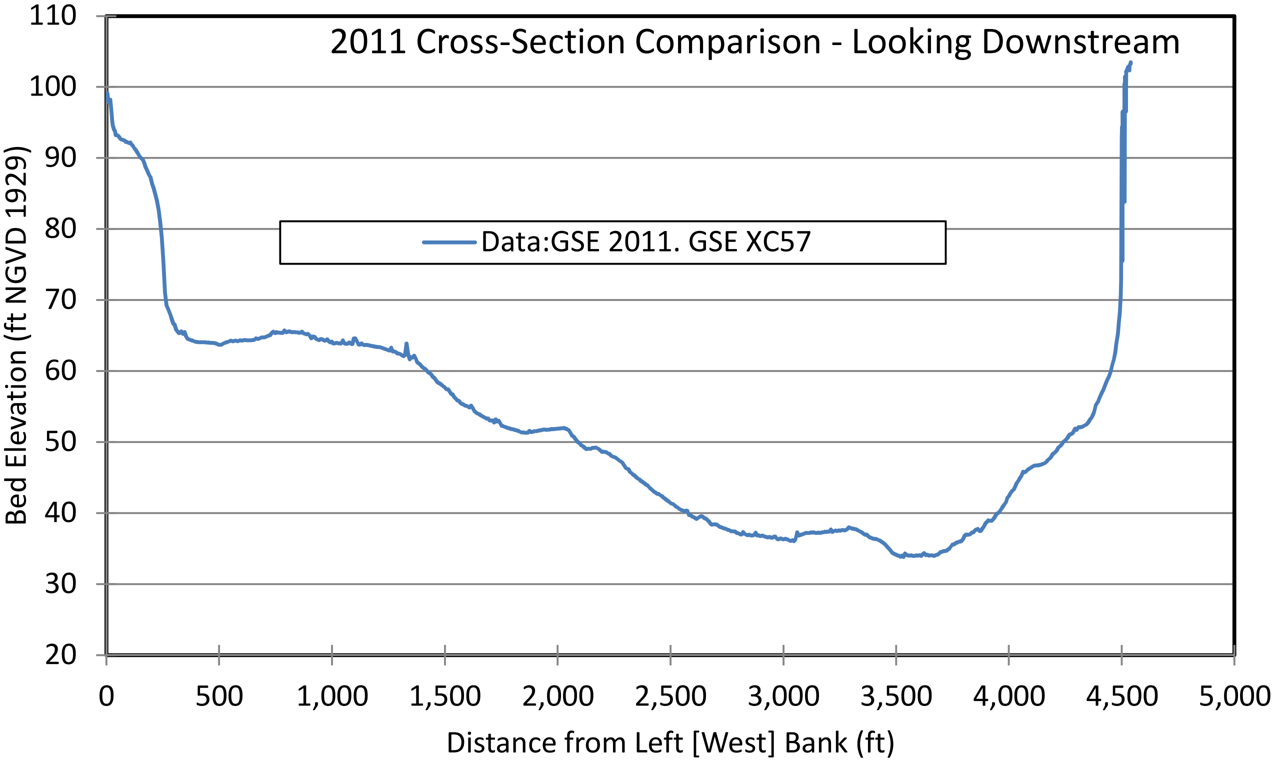

2011 Cross-Section Comparison - Looking Downstream
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
Data:GSE 2011. GSE XC52,USGS XC26
0
1,000
2,000
3,000
4,000
5,000
6,000
Distance from Left [West] Bank (ft)

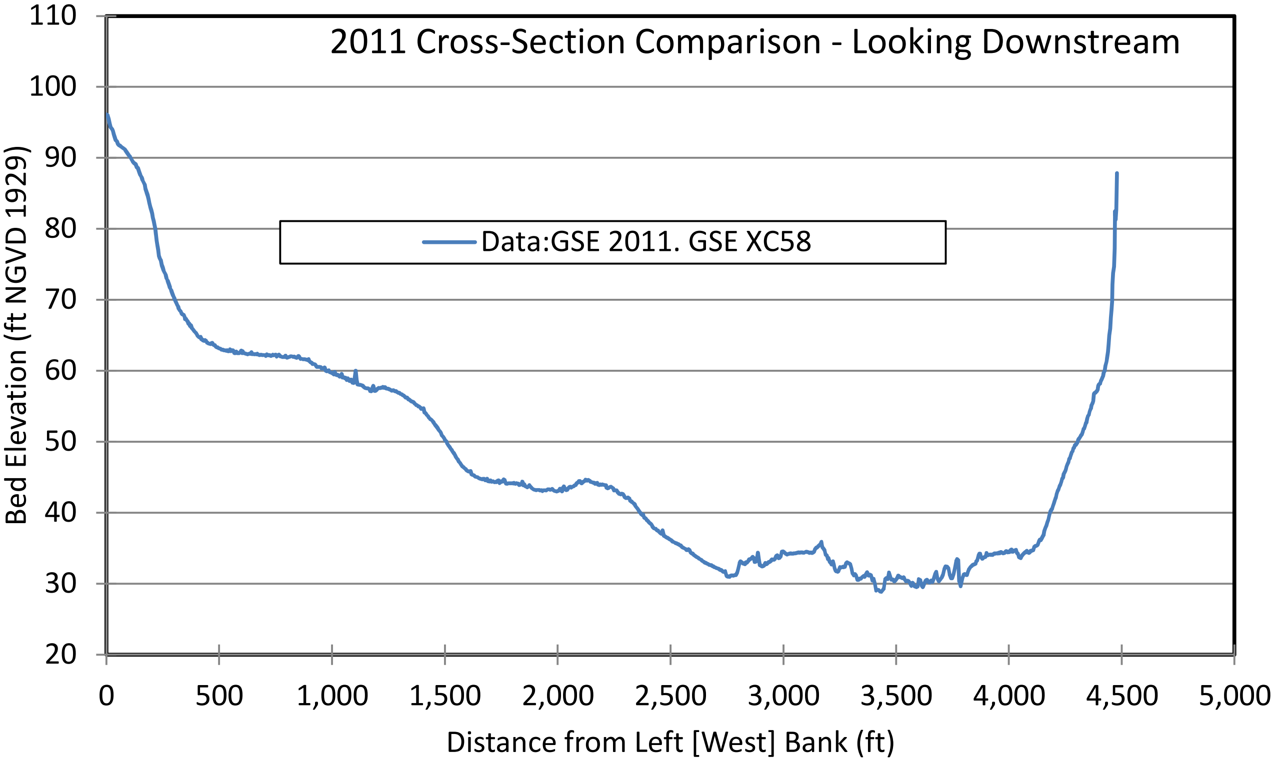

2011 Cross-Section Comparison - Looking Downstream
Data:GSE 2011. GSE XC53
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)

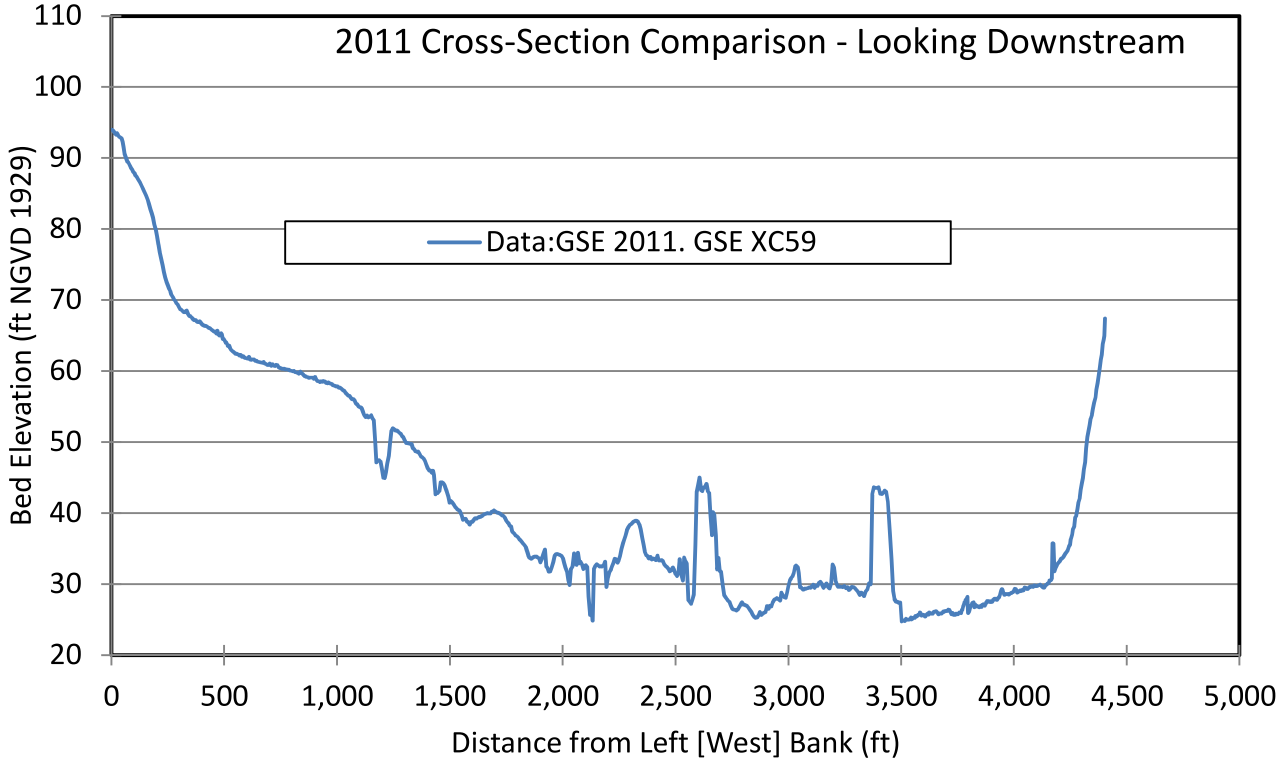

2011 Cross-Section Comparison - Looking Downstream
Data:GSE 2011. GSE XC54
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)


2011 Cross-Section Comparison - Looking Downstream
Data:GSE 2011. GSE XC55
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)


2011 Cross-Section Comparison - Looking Downstream
Data:GSE 2011. GSE XC56
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
30
20
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)


2011 Cross-Section Comparison - Looking Downstream
Data:GSE 2011. GSE XC57
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
30
20
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)


2011 Cross-Section Comparison - Looking Downstream
Data:GSE 2011. GSE XC58
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
30
20
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)


2011 Cross-Section Comparison - Looking Downstream
Data:GSE 2011. GSE XC59
Bed Elevation (ft NGVD 1929)
110
100
90
80
70
60
50
40
30
20
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
Distance from Left [West] Bank (ft)