Investigation of Suitable Habitat for the Endangered Plant *Ptilimnium nodosum* (Rose) Mathias (Harperella) Using Remote Sensing and Field Analysis—Documentation of Methods and Results

Open-File Report 2020–1088

U.S. Department of the Interior
U.S. Geological Survey

Cover. Mid-channel bar, composed of sand-, gravel-, and cobble-size materials, showing emergent vegetation during low-flow conditions on June 7, 2019, Chesapeake and Ohio Canal Lock 52. Photograph by Jessica DeWitt, U.S. Geological Survey.

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Abstract

Ptilimnium nodosum (Rose) Mathias (harperella) is an endangered plant species found in Maryland, Virginia, and West Virginia, as well as in other locations throughout the southeastern United States. The narrow range of habitat characteristics for areas in which harperella has been found makes locating potential occurrence sites difficult and attempts at reintroduction of the plant relatively unsuccessful. Sightings of harperella have been made along the banks and in-channel bars of the Potomac River, along the Chesapeake and Ohio Canal National Historic Park, and within the Sideling Hill Wildlife Refuge near Hancock, Md. The large area covered by these sightings presents logistical challenges for repeat studies of harperella growth within the Park and in nearby areas. This study developed a geospatial method for characterizing harperella habitat through remote sensing, geospatial analysis, and field investigation. A geospatial prediction model (GPM) was developed to model the habitat characteristics discussed in literature and found at harperella field observation sites in order to narrow the potential area for observation of the plant and its habitat. Analysis of historical aerial imagery was conducted within the space of the Potomac River to observe the persistence and flooding conditions of in-channel bars. The products of the GPM and the historical aerial image analysis are a geospatial description of where harperella habitat is most likely to be found, as well as a map of in-channel bar locations and their persistence through time. From these two analyses, areas were identified that merited detailed observation. Very high resolution, unmanned aerial systems (UAS) imagery was collected for 10 sites within this area in the Potomac River in June 2019. UAS imagery has the potential to greatly improve detailed study of the harperella plant, as it provides the spatial resolution necessary to catalog detailed vegetation conditions (and potentially species identification). More importantly, the timing of imagery collection can be aligned carefully with the plant's phenological patterns and local weather conditions to maximize cost-effectiveness of repeated imaging for specific areas.

Introduction

Ptilimnium nodosum (Rose) Mathias (harperella) is a federally listed endangered plant species that has been known to grow on flood-prone in-channel gravel and cobble bars and islands of the Potomac River and its tributaries. Efforts to re-introduce this species within the Chesapeake and Ohio Canal National Historical Park have met with little success, primarily owing to grazing by animals and the unanticipated effects of site hydrology (Wells, 2012a). Because it is 1 of only 2 federally listed endangered plant species in the Ridge and Valley and the Blue Ridge ecoregions of Maryland, and 1 of only 4 federally listed endangered plant species in West Virginia (Environmental Conservation Online System, 2017; West Virginia Division of Natural Resources, 2017; Maryland Natural Heritage Program, 2019; U.S. Fish and Wildlife Service, 2020a), dedicated efforts have been undertaken to record the presence of this plant in the Chesapeake and Ohio Canal National Historical Park and to identify appropriate habitat conditions that could support plant growth. The expansive area where the plant has been observed in the past provides a challenge for observation, monitoring, and conservation efforts of harperella. Individual plant counts for this large area are labor and time intensive (Smith and others, 2015). The cost and substantial data volumes associated with very high resolution imaging for digital plant counts are also limiting.

Prioritization of specific areas exhibiting the necessary environmental conditions for harperella can be accomplished through geospatial prediction modeling using remote sensing and geographic information systems. Analysis of historical aerial imagery can provide additional information regarding the presence and persistence of in-channel bars and other habitat characteristics. Together, geospatial modeling and historical image analysis can be used to isolate specific areas for detailed field observation and very high resolution imaging using unmanned aerial systems (UAS). The large file sizes and substantial data volumes generated by UAS imaging limit the collection of such imagery to specific small areas and prohibit collection of data from the entire Chesapeake and Ohio

Canal National Historical Park and Potomac River corridor. However, the potential benefits of the fine spatial resolution and repeat imaging that can be achieved from UAS could greatly improve the ability to monitor and study harperella. Owing to specific habitat conditions of the harperella species, large sections of the Chesapeake and Ohio Canal National Historical Park area are not suitable for its growth and thus do not require detailed scrutiny.

In lieu of a uniform mapping of the Chesapeake and Ohio Canal National Historical Park corridor at very high resolution using UAS, this study was developed as a multi-scale workflow, where geospatial modeling methods and historical image analysis were used to constrain the areal extent of detailed field and UAS observation. Harperella habitat characteristics reported in the literature and corroborated by extremely limited harperella occurrence data (in the form of Global Positioning System [GPS] locations) were compiled into a geospatial prediction model (GPM) to characterize the extent of harperella habitat for the region between Sideling Hill Wildlife Management Area and Harpers Ferry National Park in Maryland and West Virginia (hereafter, geospatial prediction model area). Most harperella occurrence data points are in the Potomac River corridor or its large tributaries between Sideling Hill Wildlife Management Area, W. Va., and Williamsport, Md. (hereafter, historical image analysis area). Historical aerial imagery was used to analyze in-channel bars within this smaller area. The extents of the study areas are shown in figure 1. Together the GPM and historical image analysis were used to isolate and identify specific small areas of interest (AOIs) with high potential for harperella habitat. Very high resolution imaging via UAS was acquired for these smaller areas, and field observation was conducted to evaluate habitat conditions.

This report describes and documents the multi-scale geospatial methods developed for this study to map harperella habitat within the Chesapeake and Ohio Canal National Historical Park and the Potomac River. Specific objectives of the study include

1. Development of a geospatial prediction model (GPM) containing potential harperella habitat locations;
2. Historical image analysis for the identification of persistent in-channel bars likely to support harperella habitat, specifically
   a. islands and large in-channel bars within the Potomac River and
   b. areas in tributary streams adjacent to the Potomac River;
3. Selection of small AOIs based on information developed in steps 1 and 2;
4. Completion of reconnaissance fieldwork to observe in-channel bar characteristics and conditions; and
5. Acquisition of very high resolution imagery using a UAS to produce a current orthophoto and digital terrain model for the AOI identified in step 1.

History of the Study

This study of harperella habitat near the Chesapeake and Ohio Canal National Historical Park was developed by the U.S. Geological Survey (USGS) as a Natural Resources Preservation Project (NRPP) in response to a National Park Service (NPS) National Capital Region (NCR) Park Science Needs Statement issued for fiscal year 2017 (FY 2017). The proposal was submitted in November and accepted in December 2017. Funding for the NRPP project was not approved until June 2018, at which time a study plan for the Chesapeake and Ohio Canal National Historical Park harperella project was developed to provide additional methodological and planning details beyond those discussed in the project proposal. This study plan was submitted to the NPS for approval in late June 2018. NPS requested substantial changes and edits to the plan. The updated study plan was signed, and work began in August 2018. Work on the study was delayed owing to unusually wet weather conditions from August 2018 through April 2019. Precipitation recorded in the study area in August and September 2018 totaled 17.2 inches, which is 10.4 inches greater than the average total precipitation for these months (National Oceanic and Atmospheric Administration [2019]). Total precipitation for the year in Williamsport, Maryland (Md.), was 64.1 inches, 16.4 inches greater than the average (National Oceanic and Atmospheric Administration [2019]). These unusually wet conditions continued until late spring 2019, delaying certain parts of the study, including field observation and unmanned aerial systems (UAS) imagery collection. The Federal Government shutdown and furlough that occurred from December 2018 until January 25, 2019, also delayed progress. Field observation and UAS imaging of selected sites occurred in June 2019, and work concluded in September 2019.

Habitat and Distribution of Harperella

Harperella is a small plant that generally inhabits the sunny margins of moderately flowing water bodies along silty, cobbly, and shallow substrates (Smith and others, 2015; NatureServe Explorer, 2019). The flowering organs are composed of multiple small, white flowers with five petals (fig. 2) that bloom from late June until frost and seed in September and October (U.S. Fish and Wildlife Service, 1990). Harperella is often harbored by the *Justicia americana* (American water willow) vegetation community type and is also found on the leeward side of large, stationary objects that buffer the plant from the erosive effects of strong water currents (U.S. Fish and Wildlife Service, 1990). Harperella is

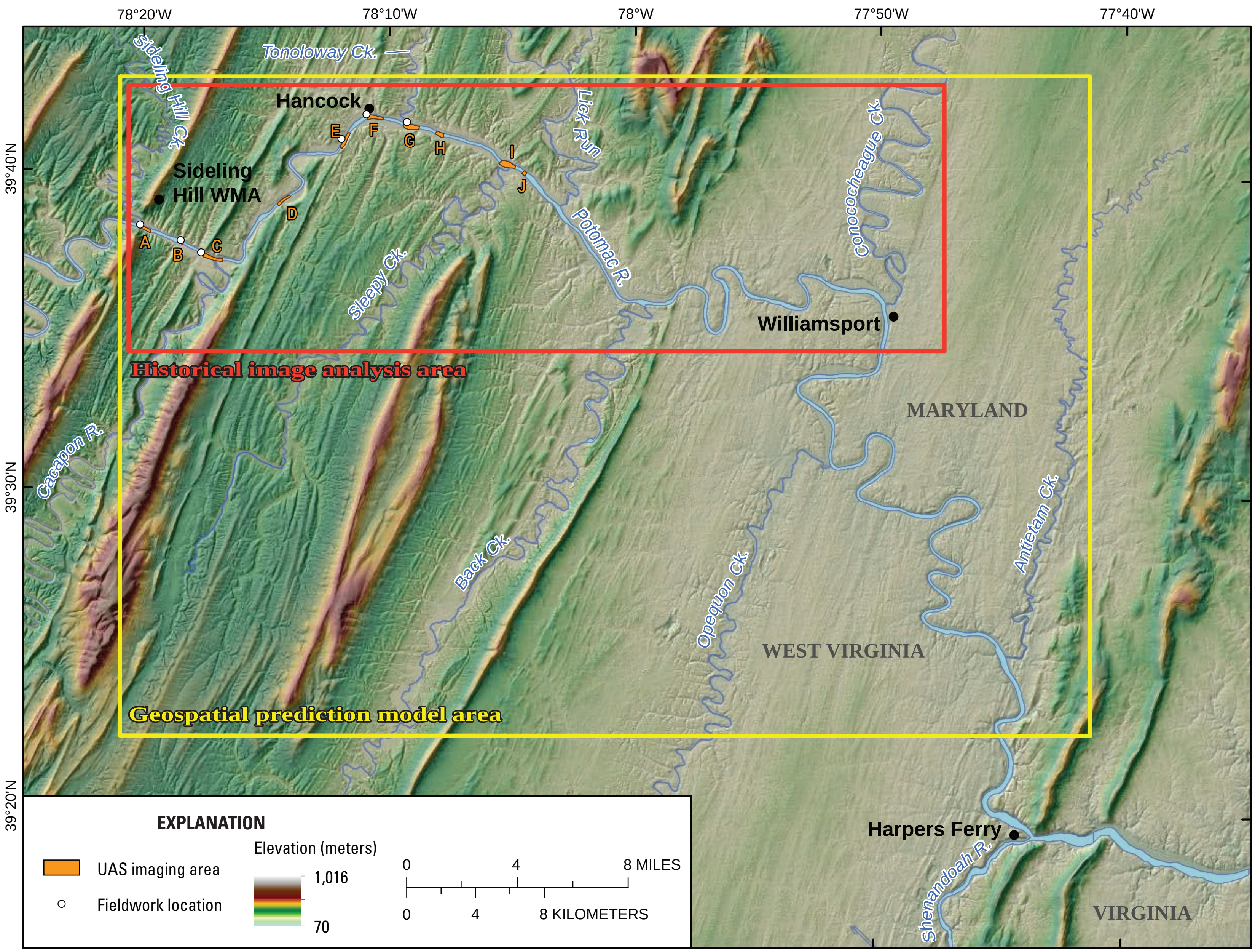

Figure 1. Map of the study areas—historical image analysis area and geospatial prediction model area—Maryland and West Virginia. The geospatial prediction model covers a large area surrounding the Potomac River from just north of Harpers Ferry upstream to the Sideling Hill Wildlife Management Area, Maryland and West Virginia. The historical imagery analysis covers a smaller area from Williamsport upstream to Sideling Hill. UAS, unmanned aerial systems; WMA, Wildlife Management Area.

a semi-aquatic plant that has reproductive strategies adapted to dynamic riparian zones and timed to seasonal hydrologic cycles. It tends to flower and set seed during low-water periods but can also reproduce asexually during high-water years through self-germination and dispersal of ramets that can root when transported downstream (Wells, 2012b). Owing to its propensity for clonal reproduction, stalks rather than individuals are counted in censuses because there is no visible difference between new seed sprouts and new offshoots (Wells, 2012a). During the 1980s and early 1990s, extensive surveys for harperella were completed along most of the Potomac River and its tributary streams. The plant was found to be extant in only 5 of the approximately 40 watersheds (hydrologic unit code 8 or 10) that were surveyed, including Sideling Hill Creek and Fifteen Mile Creek in western Maryland, Cacapon River and Sleepy Creek in West Virginia, and sites along the mainstem Potomac in Maryland (Bartgis, 1997). Harperella purportedly has been found at various times along the mainstem of the Potomac River as far downstream as Antietam Creek (Andrew Landsman, Chesapeake and Ohio Canal National Historical Park, written commun., 2019); however, previously noted mainstem Potomac populations were not persistent (Bartgis, 1997). Because of these dynamic habitat conditions, harperella populations are challenging to locate, map, and monitor. The observed populations may be ephemeral in many locations along the mainstem Potomac River, which are subject to repeat, large-scale flood disturbances. Moreover, not all areas of potentially suitable habitat will be occupied in any given year (Bartgis 1997; Frye and Tessel, 2012).

The endangered and transient nature of harperella has stymied the definition of ideal habitat characteristics, which is often variable depending on population location and physiology. Table 1 lists several habitat descriptors of the harperella plant. The information was acquired through review of available literature discussing the plant's behaviors and preferences; however, there are differences between details reported. These differences have historically prompted an argument that the *Ptilimnium nodosum* species should be separated into three subparts: *P. fluviatile* (river form, no asexual buds, found in Arkansas and Alabama), *P. viviparum* (river form, asexual buds, found in Maryland, West Virginia, Virginia, and North Carolina), and *P. nodosum* sensu stricto (pond form, found in Georgia and South Carolina) (Kress and others, 1994; Smith and others, 2015). The Harperella Recovery Plan, established by the Maryland Natural Heritage Program for the U.S. Fish and Wildlife Service in 1990, details the taxonomic history of the species, noting that the observed genetic variability in the *P. nodosum* populations does not warrant a species rank (Kress and others, 1994). As of 2019, no steps have been taken to formally separate the species.

Figure 2. Image of *Ptilimnium nodosum* (harperella plant). From the U.S. Fish and Wildlife Service (2020b).

Table 1. Harperella habitat characteristics as noted in existing literature studies, based on harperella growth requirements; for example, an inability to withstand long periods of both inundation and drought.

[Literature source is listed at the top of the column, the characteristic being discussed is listed in the left column, and a brief description extracted from the literature source is below each source. Different studies have reported different requirements for the various parameters. ND, not discussed]

Habitat features	Literature source					Summary
	NatureServe Explorer (2019)	Wells (2012a)	U.S. Fish and Wildlife Service (2020b)	Smith and others (2015)	U.S. Fish and Wildlife Service (1990)	
Flow	Swift-flowing streams (usually in microsites that are sheltered from rapidly moving water)	ND	Clear, swift-flowing	ND	Quickly moving	Proximal to quickly moving flow but protected
Flooding	Periodic, moderate	Moderate	ND	Periodic	Seasonally flooded	Seasonally or periodically flooded
Moisture	Intolerant of conditions that are too dry, saturated substrates	Damp	ND	Semi-aquatic	ND	Moist
Light	ND	Full sun	ND	ND	Sunny	Sunny
Water depth	Intolerant of deep water	Shallow	Margins	ND	Protected banks	Proximal to water's edge
Soil	ND	ND	Sandbars	Shale, silt, and fine-sand substrate	Rarely, on muddy banks	Shoals, sandy, bedrock outcrops, rarely on muddy banks
Grain	Rocky or gravelly shoals or cracks in bedrock outcrops beneath the water surface	Cobbles	Rocky or gravelly shoals	Rocky shoals and bedrock	Shoals, bedrock outcrops	Rocky, cobbly, or gravelly shoals

Geospatial Prediction Model

A traditional species distribution model (SDM) relies on an abundance of recorded sightings to assess the significance of environmental variables in order to establish statistically relevant characteristics that create an ideal habitat for a specific species. The strength of statistical relation is driven largely by repeated associations between occurrences and narrow ranges of environmental factors, necessitating a large number of occurrences from which to build models. This is rarely feasible when modeling for endangered species, as scarcity of observation data inhibits reliable outputs. Several modeling methods have historically been used to compensate for this lack of data, among them the Maxent technique (Phillips and others, 2006; Elith and others, 2006; Merow and others, 2013), which develops predictive statistical relations between known occurrence sites, known non-occurrence sites, and environmental attributes to statistically weigh the significance of a feature and extrapolate probable habitat suitability across the landscape.

In this study, the creation of an SDM for Potomac River harperella was not possible owing to several distinct challenges. The most important of these was the severely limited availability of sufficient harperella plant occurrence data. Online species data portals (for example, USGS BISON, https://bison.usgs.gov/#home; and VegBank, http://vegbank.org/vegbank/index.jsp) were searched for records. Data were also requested from several conservation and government agencies, including the Nature Conservancy, National Park Service (NPS), the Maryland Department of Natural Resources (MD DNR), and the National Resources Conservation Service (NRCS). Although detailed data locations were available for a small and heavily studied watershed in one part of the study area (Sideling Hill Creek, Md./Pennsylvania), records for much of the study area along the Potomac River were either not spatially referenced (VegBank) or numbered too few to conduct traditional SDM modeling. The available spatially referenced data were generally located (imprecise geospatial coordinate locations) and thus difficult to incorporate into geospatial modeling. Additional information about available occurrence data and the limitations of its use in this study can be found in appendix 1.

The utility of available harperella occurrence data in geospatial modeling was investigated by comparison with modeled environmental characteristics. Results of this comparison are found in appendix 2. Additional difficulties arose in describing habitat characteristics at the detailed, micro-site scale necessary to describe the nuanced habitat of this harperella population. Most importantly, the potential for differing habitat characteristics between each informal species subpart of harperella (river and pond) complicated the transposition of environmental variables between subparts. The use of environmental characteristics known to support foreign harperella populations as habitat conditions for the Potomac River population may also introduce inaccuracies, as the two populations (river and pond) can contain disparate features that support both harperella occurrence types.

Modeling Methods

Because this study lacked the quantity and quality of occurrence and detailed environmental data that are required by an SDM, a GPM was derived using a mixture of inductive and deductive practices (Whigham and others, 1992). Environmental characteristics indicative of harperella habitat as documented by the literature were developed as parameters for the GPM. In total, six parameters were used—soil type, soil slope, soil moisture, geomorphic terrain, solar radiation, and land cover. Since direct observation or geospatial data for several of these parameters did not exist at the scale necessary for the GPM, these parameters were developed in proxy from a digital elevation model (DEM). Table 2 shows each of the GPM parameters, the proxy used to characterize it, and the source data used to create the proxy.

Despite the uncertainty associated with the available spatially referenced harperella occurrence points, it was assumed that the occurrence points were collected in some proximity to a harperella plant. In order to characterize harperella habitat at the local scale, the general location of each point was used to determine an appropriate range of values for each model parameter. This evaluation of parameter values in the vicinity of occurrence points was generally confined to the local drainage area within which the point was located.

For each of these parameters, the conditions existing at limited occurrence points were evaluated together with information from the literature to determine the range of values appropriate for characterizing harperella habitat near the Potomac River. Statistical analysis of each model parameter was conducted within local drainage basins (considered to be first-order watersheds containing the harperella occurrence locations). The results of this analysis are shown in table 3.

Each environmental characteristic was then re-mapped as a binary dataset. Areas supporting harperella habitat were indicated by a new value of “1,” and all other areas were indicated by a value of “0.” The six parameters were then integrated into a GPM by adding them together. In the resultant model, areas where all parameters were present, indicating very favorable environmental conditions to support harperella habitat, were given a value of “6.” Areas where no parameters were present, suggesting that environmental characteristics are not favorable for harperella habitat, were given a value of “0.”

The GPM created by this method is useful because it is distributed beyond known occurrence sites to show the suitability of all parts of the study area to support harperella habitat. Note that modeling from limited presence-only data can introduce bias to a spatial analysis, so this study was meant only to develop a method to locate potential habitat locations and eliminate unlikely habitat locations.

GPM Parameter Development

The following sections provide detailed guidance on the data and methods used by this study to develop each parameter in this GPM analysis.

Table 2. Geospatial prediction model parameters with proxy and source data information.

[NA, not applicable; gSSURGO, geospatial database containing information about soil as collected by the National Cooperative Soil Survey]

Parameter	Proxy	Source data
Soil type	NA	gSSURGO data
Soil slope	Slope	Digital elevation model (lidar source data)
Soil moisture	Compound Topographic Index	Digital elevation model (lidar source data)
Terrain	Geomorphic model (Chirico, 2011)	Digital elevation model (lidar source data)
Solar radiation	Direct radiation analysis	Digital elevation model (lidar source data)
Land cover	NA	2016 National Land Cover Dataset (Homer and others, 2020)

Table 3. Results of statistical analysis of environmental parameters in the vicinity (local drainage basin) of harperella occurrence points.

[CTI, Compound Topographic Index; WH/m², watt-hour per square meter; NLCD, National Land Cover Database; gSSURGO, Gridded Soil Survey; muname, gSSURGO map unit name field indicating soil map unit name and prime farmland designation]

		Soil type (gSSURGO muname)	Soil slope (degrees)	Soil moisture (CTI)	Fluvial/alluvial terrain	Solar radiation (WH/m²)	Land cover class
Statistics for local drainage basin	Minimum		0.1	5.2		836,467.1	
	Maximum		44.7	18.0		988,314.9	
	Range		44.6	12.8		151,847.8	
	Mean		5.2	8.7		927,584.9	
	Standard deviation		3.8	3.4		35,468.2	
Most common parameter value near occurrences		Silt-loam, gravelly, rocky outcrops	Low to moderate slopes that promote soil development	Moderate to moist soil	In-channel or frequently flooded alluvial floodplain	Moderately sunny	Mixed forest (NLCD class 43)

Data Required for Analysis

- NRCS Gridded Soil Survey (gSSURGO) data for Virginia, West Virginia, and Maryland: downloaded from the U.S. Department of Agriculture (USDA) NRCS data portal, containing polygons of classified surficial soil types.
- Federal Emergency Management Administration (FEMA) 2012 LiDAR digital elevation model (DEM) from National Map Viewer for Virginia, West Virginia, and Maryland: downloaded from USGS EarthExplorer data portal and resampled to 30 meters (m) to reduce data processing time and reduce noise in the model parameters. Additional datasets were derived from the DEM, including stream lines with Strahler stream order codes (Strahler, 1952) and watersheds. Seven processing steps were included in the DEM.

1. The DEM was filled to eliminate sink points.
2. Flow direction and accumulation were calculated using geographic information system (GIS) software tools.
3. The flow accumulation raster was reclassified so that streams had a value of “1,” whereas “0” and empty data values were “NoData.”
4. A stream order raster was created using flow direction and reclassified flow accumulation rasters as inputs in the Stream Order tool with Strahler classification.
5. A stream network line shapefile was established using the Stream Link tool. The “Input stream raster” was the Flow Accumulation raster, and the “Input flow direction raster” was the Flow Direction raster.
6. Watersheds were delineated by processing the stream network through the Watershed tool as “pour point data,” with the “Input flow direction raster” being the Flow Direction raster.
7. This raster was then exported as a polygonal shapefile to be used in statistical analyses.

Soil Type

Maryland and West Virginia soil data were downloaded from the USDA Natural Resources Conservation Service site and compared to existing harperella sightings. Soil maps (commonly referred to as gSSURGO data) were downloaded as separate files for Maryland, Pennsylvania, Virginia, and West Virginia. The different attribute tables of the separate files were analyzed and combined by redefining and re-attributing relevant soil types, and finally separating all soil types into family categories. In total, 582 soil polygon features cover the study area. Soil types found within local drainage areas near harperella occurrence points were recorded, and general characteristics were observed. Examples of soil type, as recorded in the gSSURGO data, are shown in table 4. Silt-loam and gravelly soils, water, and rocky outcrops are the relevant classes found to have a connection with harperella habitat, which are similar to findings in existing literature. Thus, any soil type that listed silt-loam and gravelly soils,

Table 4. Examples of soil types found in the gSSURGO tables.

Soil type example	Relevancy
Combs fine sandy loam, 0 to 3 percent slopes, occasionally flooded	3
Covegap cobbly sandy loam, 3 to 8 percent slopes	2
Dekalb and Hazleton soils, 3 to 25 percent slopes, rubbly	0
Comus silt loam, 0 to 2 percent slopes, occasionally flooded	3

rocky-outcrops, or water as a main component was included in the geospatial prediction model as potential harperella habitat. However, all soil types were assessed for relevancy. Polygonal features within the soil dataset containing these soil types were identified and given a relevancy score from “0” to “3,” where “0” indicated no appropriate soil characteristics for harperella habitat, and “3” indicated multiple relevant characteristics. These polygons were converted to a 30-m binary raster, where the soils most indicative of harperella growth were indicated by a “1,” and all other areas were given a “0.” An example of the resultant soil relevancy classification used in the model is shown in figure 3.

Soil Slope

The gSSURGO soil types tend to broadly define categories and areal extents of soil. Additional detail was necessary to differentiate soils located in different parts of the terrain and landscape. In soil modeling literature, the catena concept indicates that soil differences result from different drainage conditions, and transport and redeposition of eroded material and its chemical constituents (Milne, 1936). These factors can be mapped and modeled through several different methods (Gessler and others, 1995), but the most basic factor affecting the rate and lateral development of soil is slope (Hall and Olson, 1991). Slope is also related to erosion rates and depth of the soil column (Hall and Olson, 1991; Jungerius, 1985), which have substantial implications for harperella habitat depending on certain vegetation and soil types.

Slope was calculated (in degrees) using a 3x3 cell moving window to evaluate the values in an input DEM. Analysis of slope in the vicinity of available harperella occurrence data indicates that a large variation of slope occurs (up to 44.6 degrees) within the space that could constitute harperella habitat. Analysis of the points themselves indicates that 16 of 17 points in the Potomac River and 31 of 44 points along Sideling Hill Creek have a slope of less than 15 degrees. According to the principles of the catena concept, soils on these moderate to low slopes typically have slower drainage and slower rates of lateral erosion than steep slope areas (Milne, 1936) and are thus considered favorable for harperella habitat. Areas of 15-degree slope or less were prioritized by reclassifying the slope raster as a value of “1” (shown in fig. 4). All higher slope values were reclassed to a value of “0.”

Soil Moisture

Soil moisture was integrated into the GPM to improve characterization of soil development based on the catena concept (Milne, 1936) and to better model harperella habitat. The Compound Topographic Index (CTI) is a method of quantifying soil wetness that simulates three-dimensional moisture movement through geomorphic modeling. The result of this analysis is a two-dimensional map describing where soil moisture is concentrated and how persistent this moisture is likely to be over time. Because this analysis is derived from slope values, flat areas with a slope of “0” will result in unusable numbers. This means that areas covered by water in the DEM must be disregarded, and above-water habitat will be prioritized by the model. High values from the resultant CTI analysis represent convex areas that maintain high amounts of moisture. Low values represent steep slopes and concave areas where water runs off quickly.

1. The filled DEM and flow accumulation raster files created in the watershed analysis were set aside for later use.

2. Note: If the raster is too detailed, the CTI will become unrealistically complex, so the DEM may need to be resampled to a coarser resolution. If this is the case, the filled DEM and flow accumulation files are recreated using the resampled DEM.

3. A Realistic Flow Accumulation (RFA) raster was created to account for the appropriate DEM resolution by using the following equation in the Raster Calculator: [(“flow accumulation” + 1) * “cell size”].

5. Slope degree was calculated via the Slope tool.

6. The slope raster was converted to radians through the following raster calculator expression, where the value 1.570796 comes from (pi/2): [(“Slope” * 1.570796)/90].

7. The Raster Calculator was then used to generate the complete wetness index, or CTI: [Ln (“RFA” /tan “slope in radians”)]. If this output has “NoData” holes, add 0.01 to both the RFA and slope radian files, then step 4 is repeated.

Harperella requires moist soils and frequent inundation, so the mean value for local drainage areas was used as a threshold for reclassification of the output. The analysis used values extracted from local drainage basins in the vicinity of harperella sightings where soil moisture values ranged from 2.2 to 26.9, with a mean of 6.6. The value range used in this classification is 6.6–26.9. All CTI values equal to or greater

Figure 3. Relevant soil classes, including those that contained silt-loam and gravelly soils, water, and rocky outcrops, are shown in orange for the extent of the historical image analysis area, Maryland and West Virginia. GPM, geospatial prediction model.

Figure 4. Soil slope favorable for harperella habitat, shown for the extent of the historical image analysis area, Maryland and West Virginia. Favorable areas, shown in orange, include those with gentle slopes of less than 15 degrees. GMP, geospatial prediction model.

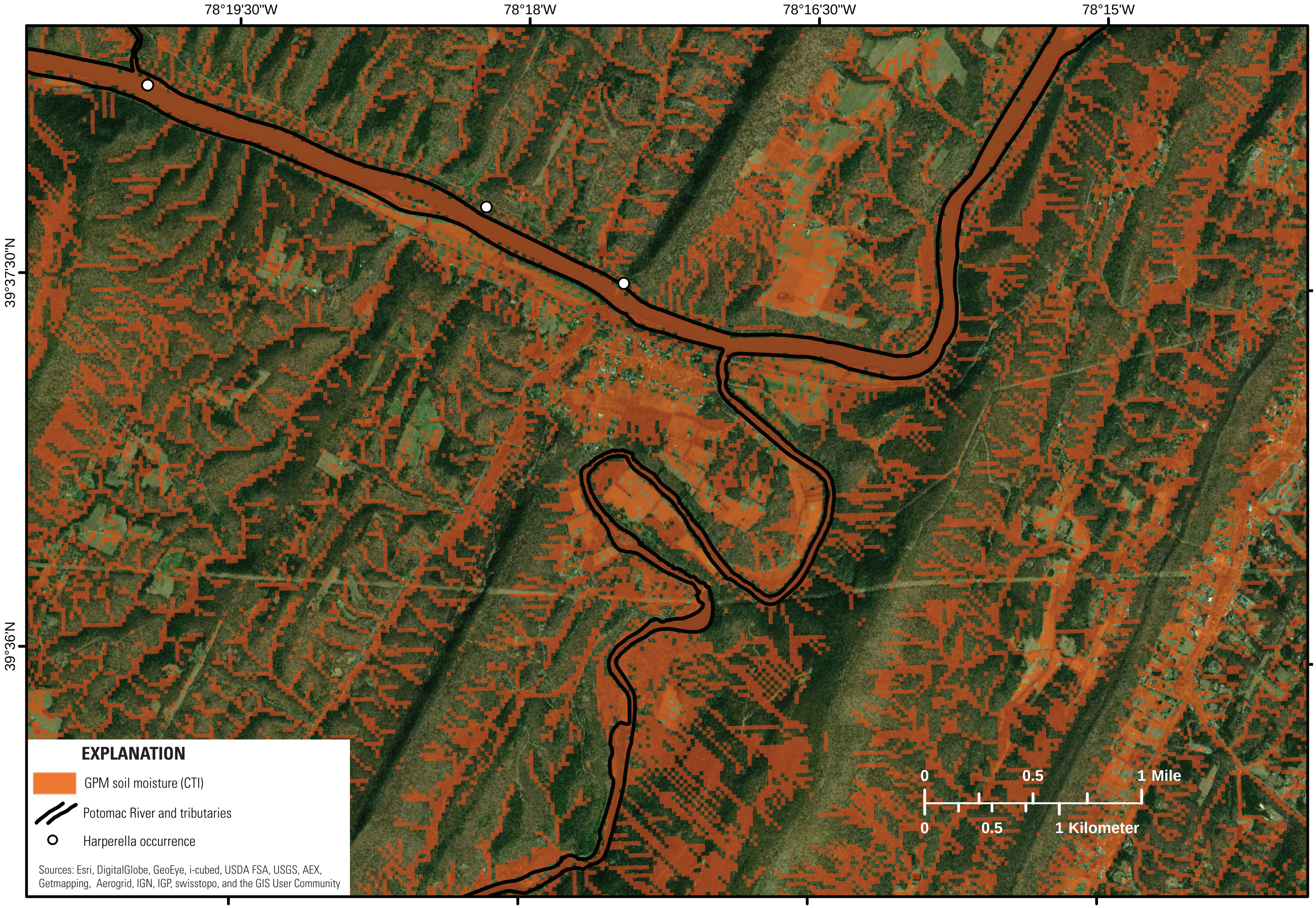

Figure 5. Classified soil moisture favorable for harperella habitat, shown for the historical image analysis area. Favorable areas, shown in orange, include those with CTI values between 6.6 and 26.9. GPM, geospatial prediction model; CTI, Compound Topographic Index.

than this average were reclassified to 1, and all others to 0. Figure 5 shows an example of the resultant soil moisture parameter used in the GPM.

Fluvial/Alluvial Terrain

Geomorphic zones provide detailed and distributed characterization of the erosive and depositional processes that occur in fluvial systems in alluvial terrain. In this study, geomorphic zones were modeled through the combination of a relative elevation analysis with a path-distance analysis, following the methods suggested by Chirico (2011). Such distributed modeling typically provides substantially more mapped detail than the best-available Quaternary surficial geology map units shown on geologic maps of the area (Southworth and others, 2000; Southworth and others, 2001). In the first part of the model, elevation of non-stream areas is compared to elevation of the closest stream path to quantify relative elevation. This characteristic describes the complexity and patterns of elevation variation at the local scale. The procedures for this model included nine steps.

Relative Elevation Analysis

1. The filled DEM was used to calculate flow direction and flow accumulation.
2. Flow accumulation was classified into major streams, where stream areas were reclassified as "1" and everything else was classified as "0." The result is a raster, called StreamsRaster, where pixels indicate the presence of a stream.
3. Elevation at each stream pixel was derived using the following equation in the raster calculator: ["Streams-Raster" * "Filled DEM"].
4. Because stream values were all reclassified to "1," this equation results in a new raster where the value of each pixel equals the stream elevation at that pixel. This is called Stream_Elevation.
5. Stream_Elevation was exported as a point shapefile using the Value field.
6. A triangular irregular network (TIN) was created using the Create TIN tool. Input for the tool was the Stream_Elevation point shapefile. The Height_Field was set to GRIDCODE and the SF_TYPE was Masspoints.
7. The TIN was converted to a raster using the Tin to Raster tool; the Output Data Type was "float," the Method was "Linear," and the Sampling distance was "Cellsize," which was set to 30 m. The output raster was called Base_Elevation.
8. Relative elevation was calculated using the Raster calculator as Filled DEM - Base Elevation.
9. The resultant relative elevation model was segmented into classes that characterize different geomorphic units in the terrain, such as the active channel, flood plain alluvium, terraces, high terraces, and upland areas. The values used to segment this model may differ by study area or extent of the model; the values used in this analysis are listed in table 5.

In the second part of the model, path-distance is used to quantify the cost of travel from each grid cell, where "cost" is equal to slope, which indicates the relative erosivity of surficial materials. The procedures for this model include Path-Distance analysis.

Path-Distance Analysis

1. The Path-Distance tool within the Spatial Analyst toolbox is utilized to model potential flow paths. The input raster or feature source data is the StreamsRaster generated in step 2 of the relative elevation section. Output raster is referred to as "PathDistance." Input cost is the Slope raster generated for the previous GPM parameter. Input surface raster is the "Filled DEM."
2. Reclassify the Path-Distance result into classes that indicate the extent of low-order alluvium. Similar to the Relative Elevation, the exact value used to segment the output can vary. In this study, values of 0–15 were found to indicate low-order alluvium.
3. To integrate the result of Path-Distance analysis with the Relative Elevation analysis, add the two segmented results using the raster calculator.

Combined, these two factors spatially model alluvial deposition and erosion in the form of specific geomorphic zones. Segmentation of the model into specific zones must be done through visual analysis of the model and ancillary data,

Table 5. Categories used to segment the relative elevation model. Each category represents a different geomorphic unit in the terrain.

Relative elevation	Geomorphic or terrain unit
−108 to −25	Quarry, mine, or other substantial topographic depression
−24.9 to −5	Primary river or stream channel
−4.9 to 0	Stream channel or active flood plain
0 to 2	In-channel cobble bar or flood plain
2.1 to 5	In-channel cobble bar or low terrace
5.1 to 10	Upper terrace, or mid-slope area
10.1 to 277	Upland area

such as stream extent, high-resolution imagery, and geologic data. The analysis used features extracted from local drainage basins in the vicinity of harperella sightings. After manual observation, low-order alluvium, in-channel or frequently flooded, and low terrace were used in this classification. Figure 6 shows an example of the resultant fluvial/alluvial terrain parameter used in the GPM.

Solar Radiation Analysis

Analysis of solar radiation was done to characterize areas with sufficient direct sunlight to support harperella habitat throughout the study area. In this region, the mountainous topography combined with the sun's zenith angle can be an important factor in the amount of sunlight received by stream areas. According to literature sources, harperella requires sunny conditions but not excessive heat. There is, however, a substantial range as to what constitutes sunny between the tributary and small-stream locations near Sideling Hill where harperella has been observed and the broad, flat Potomac River locations. For a large part of each day in the summer and fall, in-channel bars of the Potomac River typically experience direct sunlight and subsequently high temperatures. The narrow valley areas of tributary streams experience substantially less direct sunshine and for a shorter duration each day.

The area solar radiation tool was used to calculate insolation across the landscape. This tool quantifies global solar radiation received by each grid cell in the raster through computation of direct solar radiation and diffuse radiation received during the 12 months of the year. Direct solar radiation is calculated from the solar constant, the average transmissivity of the atmosphere in each month of the year, the insolation path length in each month of the year, daylight duration, and the angle of incidence. Diffuse radiation was calculated from the global normal radiation and a factor accounting for the proportional diffusion of different sky conditions, as well as the time interval for analysis, proportion of the visible sky, and the angle of incidence. In addition to the global solar radiation raster generated by the analysis in watt-hour per square meter (WH/m^2), the tool may also be set to generate outputs of direct solar radiation (in WH/m^2), diffuse radiation (in WH/m^2), and direct duration of radiation (in hours).

The area solar radiation tool requires a filled DEM as input, the specification of latitude, the specification of the resolution or sky size for the viewshed (with a default of 200 m), and a specification for the time configuration. The time configuration for this analysis was set to whole year with monthly interval, and an hourly interval was used to calculate sky sectors each day. Slope and aspect were calculated by the tool to compute the effect of surface orientation, which is used in various equation elements such as the surface zenith and azimuth angles (Fu and Rich, 2002; Fu, 2000; Rich and others, 1994). The direct solar radiation raster output was used to determine areas with sufficient insolation to support harperella growth. Analysis of this result, together with point locations in the Potomac River and along Sideling Hill Creek, indicated that areas with enough, but not too much, direct sunlight to support harperella growth were 0.5 to 2.5 standard deviations from the average direct solar radiation for the study area, or approximately 930,000–1,000,000 WH/m^2. Figure 7 shows an example of the resultant solar radiation parameter used in the GPM.

Land Cover

Although land cover is not directly referred to as a constraining factor on habitat conditions in literature studies of the harperella plant, the characteristics of specific land cover classes either prohibit harperella growth (for example, medium- or high-density development) or are highly unlikely to support other specific conditions of harperella habitat. The 2016 National Land Cover Dataset (NLCD; https://www.mrlc.gov/data) characterizes land cover at 30-m resolution using 16 different classes that are based on the Anderson Level II classification system (Homer and others, 2020); the dataset was used to integrate land cover into the GPM. NLCD products are developed from a multi-source decision-tree-based land cover classification of Landsat imagery and ancillary geospatial datasets (Homer and others, 2020). All classes of land cover except perennial ice/snow are found in the study area. Of these various land covers, analysis of local drainage basins and areas in the vicinity of harperella occurrences determined that only deciduous forest, evergreen forest, mixed forest, shrub/scrub, grassland/herbaceous, woody wetlands, and emergent herbaceous wetlands potentially support harperella habitat. These seven classes of land cover were used in the GPM. Figure 8 shows the NLCD 2016 classes found in the study area. Figure 9 shows an example of the resultant land cover parameter used in the GPM.

GPM Results

The GPM created by this analysis integrated the parameters of soil type, soil moisture, soil slope, fluvial/alluvial terrain, solar radiation, and land cover to determine the extent and distribution of areas potentially supporting harperella habitat in the study area. This integration was accomplished by adding the six parameters using the raster calculator. As a binary dataset, each parameter has values of "1" or "0," where areas with value "1" indicate locations that could support harperella habitat, and areas with value "0" indicate locations that likely do not support harperella habitat. When added together, the parameters produced a new raster where each pixel value indicates the count of the number of parameters with value "1." The likelihood of an area containing harperella habitat increases as values approach 6. Figure 10 demonstrates this concept.

The results identify low-lying areas that are connected to the Potomac River and its tributaries as being potential harperella habitat. Figures 11 and 12 show these results.

Figure 6. Terrain analysis results favorable for harperella habitat, shown for the historical image analysis area, Maryland and West Virginia. Favorable areas, shown in orange, include those where low-order alluvium, in-channel or frequently flooded, and low terrace classes were present.

Figure 7. Direct solar radiation classification conditions favorable for harperella habitat, shown for the historical image analysis area, Maryland and Virginia. Favorable areas, shown in orange, include those where the duration of sunlight exposure is approximately 930,000–1,000,000 watt-hours per square meter. GPM, geospatial prediction model.

Figure 8. Land cover classes from the National Land Cover Database 2016 that were found in the geospatial prediction model study area. Land covers found in the vicinity of harperella occurrences and used in the geospatial prediction model are indicated by an asterisk (*).

The areas indicated by the GPM exhibit environmental conditions either noted in the literature or observed through harperella observations as supporting harperella growth. The resulting areas of potential habitat cover a broad region of the study area and include many areas beyond the Potomac River and its main tributaries (fig. 12). Although harperella has not been extensively documented in these areas, there are minimal occurrences (U.S. Department of Agriculture, National Resources Conservation Service, 2020) outside river and large creek environments. Thus, harperella could potentially grow in these non-stream areas. However, it is likely that additional factors both contribute to and constrain suitable habitat for harperella growth. Additional research into the biology of the plant species (and its subparts) would be necessary to further develop the GPM and isolate specific areas of potential harperella habitat.

The objectives of this study were to focus on identifying harperella habitat in the Chesapeake and Ohio Canal National Historical Park and Potomac River area. Results of the GPM analysis were combined with historical image analysis to provide more detail regarding habitat conditions on the in-channel bars and other areas of possible habitat within the Potomac River. The following section discusses the methods used to improve understanding of the persistence of in-channel bars in the Potomac River and their viability as potential habitat for harperella growth.

High-Resolution Historical Image Analysis

Analysis of high-resolution historical aerial imagery was conducted to investigate parts of the Potomac River channel and flood plain that might support conditions favorable for harperella growth. Since the plant has been documented as occurring on in-channel bars of the Potomac River, these areas are of primary interest. According to literature documenting harperella habitat, plant growth occurs on the leeward side of cobble bars and other in-channel areas that are partially sheltered from the full strength of the river's current (NatureServe Explorer, 2019). The downstream sides of persistent in-channel bars thus have a higher chance of supporting harperella habitat than other locations in the channel. To determine the extent of this potential habitat area within the Potomac River, it becomes necessary to assess where cobble bars are the most prominent during moderate- or low-flow conditions, as well as their persistence over time.

The historical image analysis consisted of visual examination and manual delineation of in-channel bars within the Potomac River and its larger tributaries, including the Cacapon River, lower Tonoloway Creek, Sleepy Creek, lower Lick Run, and Back Creek (fig. 1). This manual delineation was conducted for several dates of historical aerial imagery, including 2009, 2011, 2013, 2016, and 2017. The persistence of different parts of the in-channel bars over time was mapped by intersecting the 5 years of interpretations. The following sections explain the methods of this analysis in detail.

Methods

The USGS has a rich and diverse archive of aerial photography, including more than one million frames collected by government mapping and resource management agencies. A list of available imagery datasets for the study area was compiled using the USGS EarthExplorer data portal (https://earthexplorer.usgs.gov/). To determine river conditions captured by each image, river discharge (cubic feet per second [ft^3/s]) and streamgage height (feet [ft]) as reported on the USGS National Water Information System for the Hancock, Md., streamgage (USGS 01613000) (U.S. Geological Survey, 2017) were noted for each date of image acquisition (table 6). Imagery dates with the lowest streamgage heights were selected because a greater extent of in-channel cobble bars would be visible for analysis. No single acquisition date

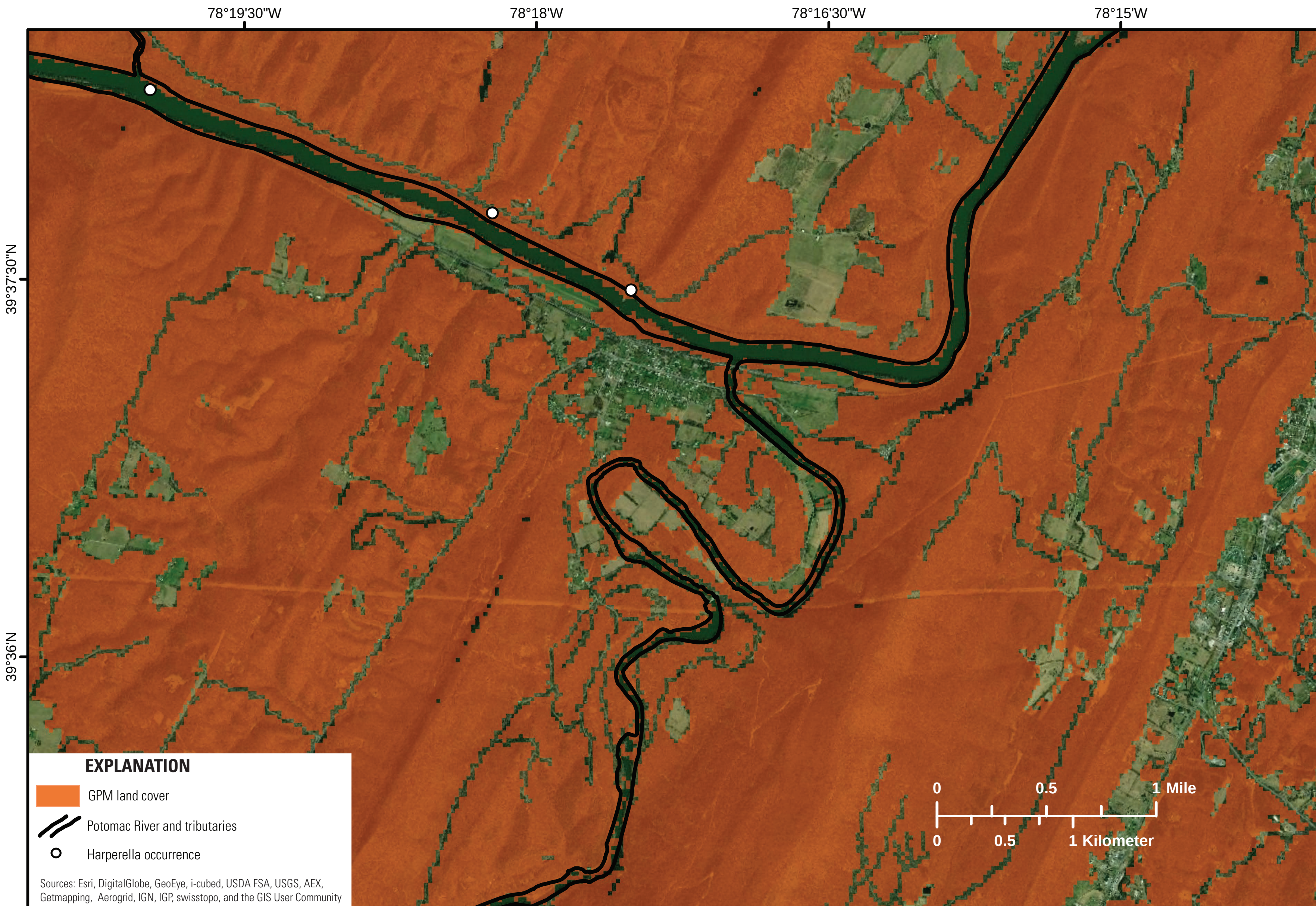

Figure 9. Land cover classes favorable for harperella habitat, shown for the historical image analysis area, Maryland and West Virginia. Favorable areas, shown in orange include those where deciduous forest, evergreen forest, mixed forest, shrub/scrub, grassland/ herbaceous, woody wetlands, or emergent herbaceous wetlands were present. GPM, geospatial prediction model.

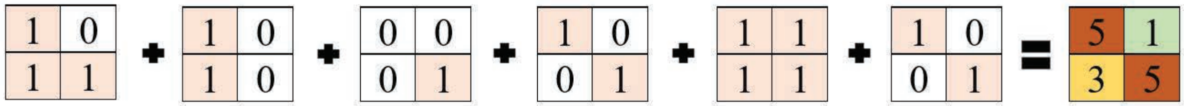

Figure 10. Hypothetical example of input variables added together using a raster calculator. Each quadrant box indicates the same pixels for the evaluated variables, including soil type, soil slope, soil moisture, terrain, solar radiation, and land cover. The summation of the same quadrant pixel from each variable results in the value in the quadrant box on the right.

covers the entire study area; therefore, analysis for each year was composed of multiple imagery dates. Water data records for these multiple dates were averaged per year. An analysis interval of 1–3 years was selected to optimize the duration of analysis from available datasets.

Within the historical image analysis study area, which extends from Sideling Hill to Williamsport (shown in fig. 1), all in-channel bars within the Potomac River and its tributaries were manually interpreted and delineated for each year of imagery. Any land mass partially or wholly surrounded by water that contained visible signs of sedimentary deposits was classified as an in-channel bar. Note that image coverage varies between image collection dates, and the boundaries of available imagery for each year of analysis do not always coincide. This difference in the dates of image acquisition complicates direct comparison between years because river conditions and in-channel bar areas may vary within a year. This complication was mitigated by constraining the study area to specific years of aerial imagery and by focusing analysis on areas of potential habitat found in the GPM.

The in-channel bar areas, delineated as polygons from aerial imagery, were converted into rasters where each pixel was given a value of "1." All other pixels were given a value of "0." Multi-year image analysis was performed by adding these rasters together using the Cell Statistics tool. This resulted in a new raster with pixel values between "1" and "5," where "1" indicates the presence of an in-channel bar in only 1 year of imagery, and "5" indicates the presence of an in-channel bar in all 5 years of imagery. Pixels with high values (4 or 5) indicate in-channel bar areas that are most persistent through the years of observation.

Results

The results of the historical image analysis are shown in figure 13 for part of the historical image analysis area and in figure 14 for the full extent of the historical image analysis area. Figure 15 shows an example of the multi-year delineation of in-channel bar extent at the confluence of Sideling Hill Creek and the Potomac River. In general, these results show that the extent of in-channel bar areas—and thus the potential extent of harperella habitat in the Potomac River—changes substantially between years. While this change is partially explained by differences in river conditions during each imaging, the amount of fluctuation of in-channel bar extent during low-flow seasonal periods is still substantial. Table 7 lists river conditions (discharge and streamgage height) recorded at the Hancock, Md., streamgage for each date of imagery included in the study, as well as the area of in-channel bars quantified by each year of image analysis. Although the imagery dates selected for this study had similar gage heights, relatively small differences in gage height can substantially affect the area of in-channel bars quantified by the analysis. A gage height increase of several inches may partially or entirely submerge an in-channel bar, obscuring it from analysis.

The in-channel bar area results for 2017 are a great example of this effect, where the area of in-channel bars quantified was approximately one-half of that observed in the other years of study because discharge and streamgage height were 2–3 times higher. A similar but less substantial difference was noted between the 2011 and 2013 observations, which have comparable discharge and streamgage height but a reduction of in-channel bar area of 0.13 km^2.

In-channel bar areas can change as a result of changing river conditions; therefore, the amount of area visible during key parts of the harperella growing cycle is important in determining the viability of these in-channel bars as habitat. Although it is true that the plant thrives in moist, occasionally inundated soil, it is important that these areas also be intermittently above water and dry. The selection of imagery taken during the late summer and early fall is relevant to the phenological cycle of the plant as the delineated in-channel bar areas potentially support harperella growth at a time when the plant is known to flower and re-seed. Image analysis was thus conducted using imagery acquired during the summer or early fall months. The area of in-channel bars mapped for the analysis represents the approximate maximum extent of potential habitat in the Potomac River.

The results of the analysis (fig. 14) indicate that, although the margins of the in-channel bars seem to vary greatly, the general locations appear to remain relatively static. In almost all areas, a central "core" of the in-channel bar persists for all years in the analysis. This area of high persistence can be seen in the multi-year analysis results (figs. 15–19) and demonstrates the overall stationary nature of the in-channel bars along the Potomac River. It is likely that the presence of in-channel bars in the Potomac River is closely related to the influx of sediments and runoff from tributary streams, such

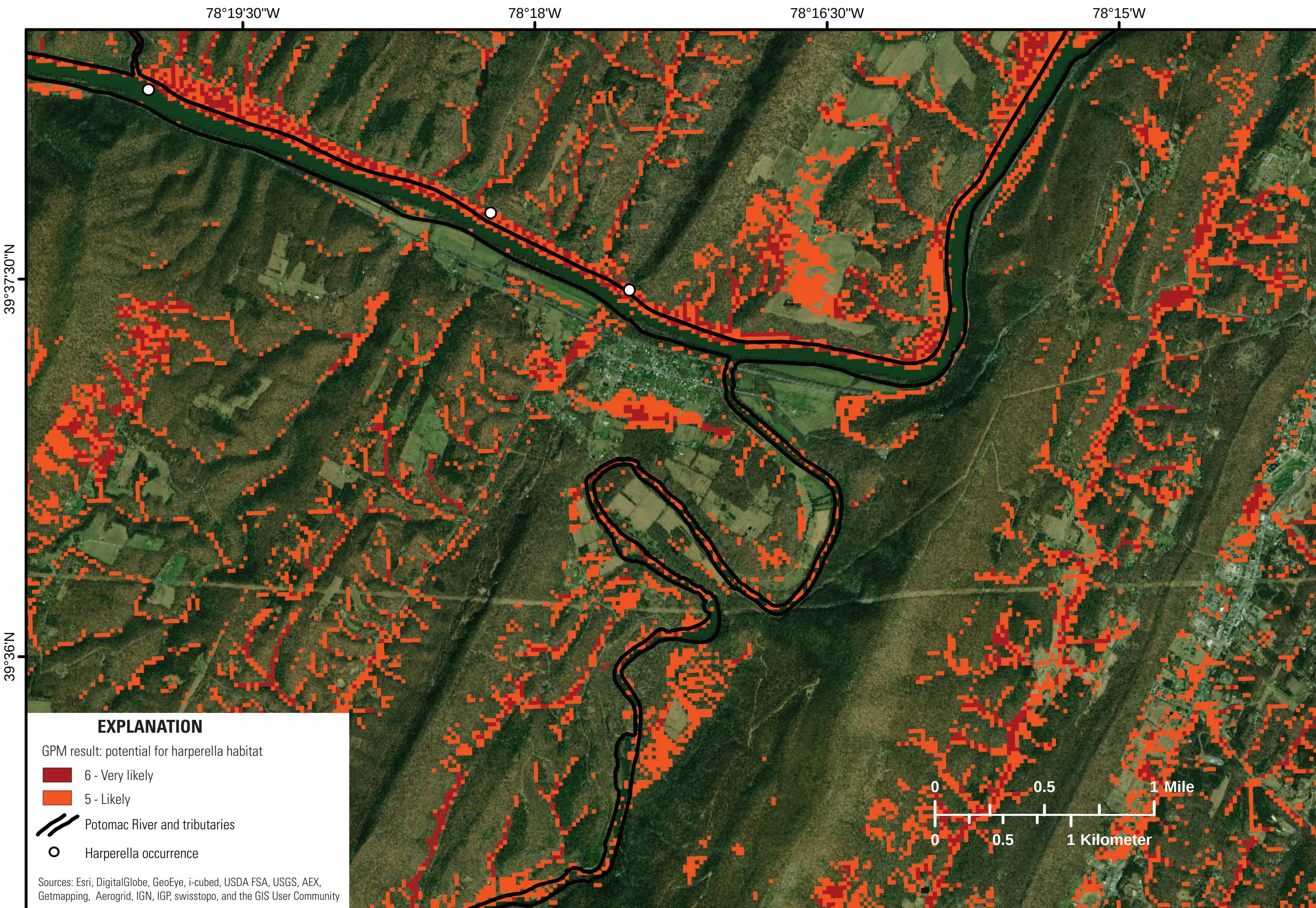

Figure 11. Integration of the six geospatial prediction model parameters for the historical image analysis area, Maryland and West Virginia. This geospatial prediction model maps areas most likely to support harperella habitat indicated by a value of 5 or 6.

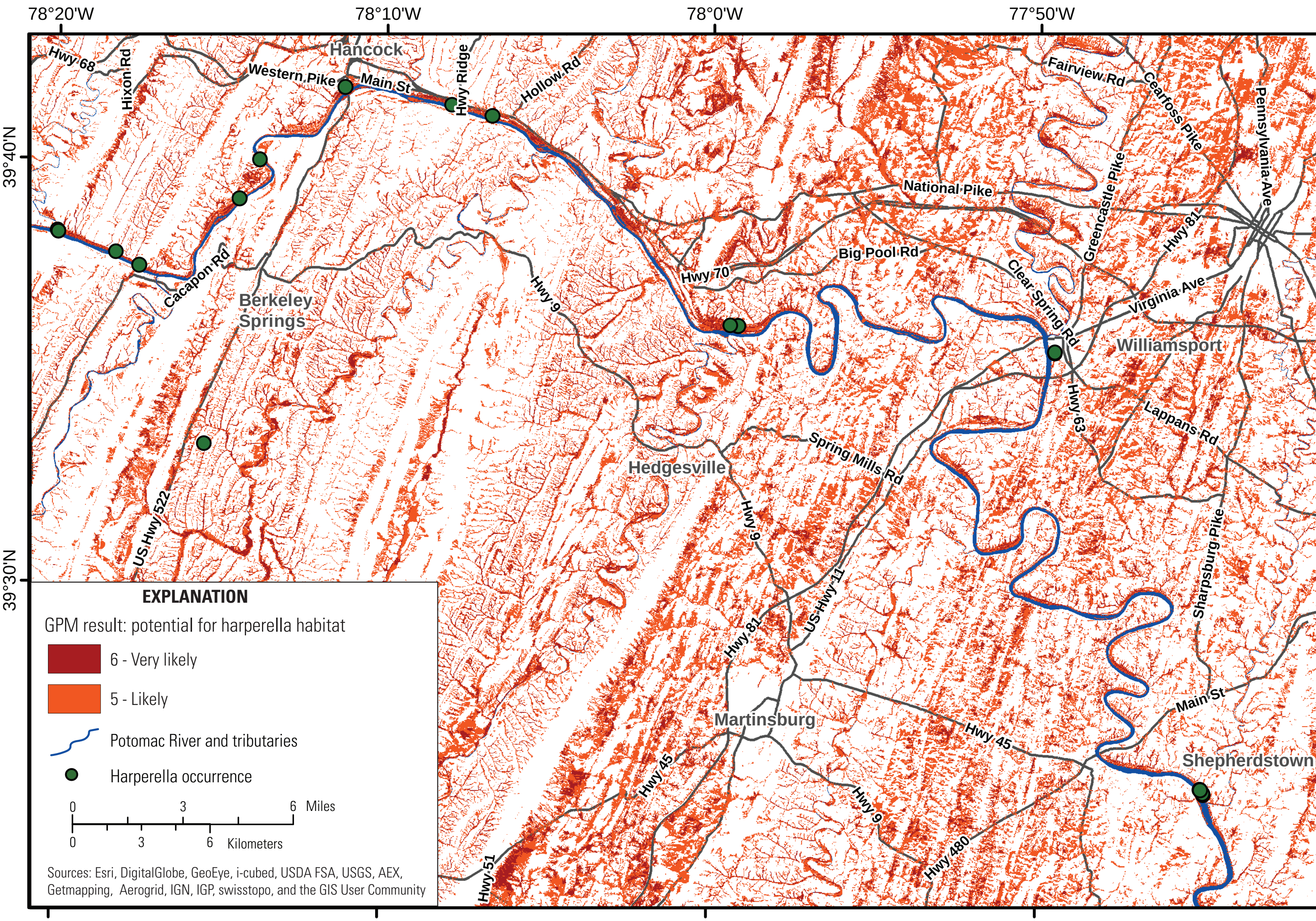

Figure 12. Integration of the six geospatial prediction model parameters for the entire study area, Maryland and West Virginia. This geospatial prediction model maps areas most likely to support harperella habitat, indicated by a value of 5 or 6.

Table 6. Discharge rate and streamgage height from the U.S. Geological Survey National Water Information System for the Hancock, Md., streamgage (01613000). Data were downloaded and analyzed for the dates of available aerial imagery. Data in green were collected during low-flow conditions and selected for use in the historical image analysis.

[ft^3/s, cubic foot per second; ft, foot; Min, minimum; Max, maximum; NA, not available]

Date	Image type	Discharge (ft^3/s)		Streamgage height (ft)	
		Min	Max	Min	Max
05/??/1983	Aerial Photo Singleframes	NA	NA	NA	NA
2/24/1984	Aerial Photo Singleframes	8,730	8,730	NA	NA
2/26/1984	Aerial Photo Singleframes	15,700	15,700	NA	NA
6/29/1989	GeoEye	3,730	3,730	NA	NA
Beginning of discharge records—10/1/1990					
4/18/1996	Digital Orthometric Quadrangle	3,970	4,080	NA	NA
4/1/1997	Aerial Photo Singleframes	5,410	5,630	NA	NA
12/31/2002	GoogleEarth	3,870	3,920	NA	NA
3/10/2003	High-resolution orthoimage	26,300	33,500	NA	NA
05/??/2003	Aerial Photo Singleframes	NA	NA	NA	NA
6/6/2003	National Agriculture Imagery Program	12,400	16,900	NA	NA
6/24/2003	National Agriculture Imagery Program	8,700	11,400	NA	NA
9/16/2003	National Agriculture Imagery Program	2,630	2,790	NA	NA
8/29/2004	National Agriculture Imagery Program	697	725	NA	NA
9/23/2004	National Agriculture Imagery Program	3,610	4,400	NA	NA
10/3/2004	National Agriculture Imagery Program	4,960	6,090	NA	NA
10/4/2003	National Agriculture Imagery Program	3,360	3,730	NA	NA
11/10/2004	National Agriculture Imagery Program	3,600	3,970	NA	NA
6/7/2005	GoogleEarth	2,020	2,050	NA	NA
6/8/2005	National Agriculture Imagery Program	1,890	2,050	NA	NA
6/21/2005	National Agriculture Imagery Program	1,130	1,180	NA	NA
9/8/2005	National Agriculture Imagery Program	706	734	NA	NA
8/24/2007	GoogleEarth	2,200	3,020	NA	NA
Beginning of streamgage height records—10/1/2007					
5/29/2009	GoogleEarth	3,870	5,790	5.34	6.44
07/06/2009	National Agriculture Imagery Program	1,210	1,280	3.45	3.51
07/08/2009	National Agriculture Imagery Program	1,090	1,140	3.34	3.39
7/25/2009	National Agriculture Imagery Program	941	951	3.2	3.21
8/10/2009	National Agriculture Imagery Program	941	1,050	3.21	3.3
8/16/2009	National Agriculture Imagery Program	660	687	2.91	2.94
03/??/2011	Aerial Photo Singleframes	NA	NA	NA	NA
7/9/2011	GoogleEarth	1,100	2,930	3.34	4.74
5/31/2011	National Agriculture Imagery Program	6,150	8,120	6.63	7.62
6/29/2011	National Agriculture Imagery Program	1,430	1,480	3.64	3.68
7/14/2011	National Agriculture Imagery Program	1,020	1,180	3.27	3.41
8/15/2013	National Agriculture Imagery Program	2,090	2,600	4.21	4.56
8/24/2013	National Agriculture Imagery Program	1,400	1,600	3.44	3.83
9/23/2013	GoogleEarth	900	962	3.18	3.24
02/??/2014	Aerial Photo Singleframes	NA	NA	NA	NA
2/24/2014	High-resolution orthoimage	18,600	23,100	11.18	12.53

Table 6. Discharge rate and streamgage height from the U.S. Geological Survey National Water Information System for the Hancock, Md., streamgage (01613000). Data were downloaded and analyzed for the dates of available aerial imagery. Data in green were collected during low-flow conditions and selected for use in the historical image analysis.—Continued

[ft^3/s, cubic foot per second; ft, foot; Min, minimum; Max, maximum; NA, not available]

Date	Image type	Discharge (ft^3/s)		Streamgage height (ft)	
		Min	Max	Min	Max
1/3/2016	WorldView-3	5,060	5,870	6	6.42
2/5/2016	WorldView-3	21,400	30,700	11.97	14.6
3/7/2016	WorldView-3	3,950	4,340	5.34	5.55
4/14/2016	WorldView-3	2,670	3,080	4.58	4.84
5/16/2016	WorldView-3	5,770	6,410	6.28	6.58
6/29/2016	WorldView-3	3,130	3,950	4.92	5.41
9/5/2016	National Agriculture Imagery Program	455	500	2.66	2.72
9/14/2016	National Agriculture Imagery Program	434	500	2.63	2.72
9/22/2016	National Agriculture Imagery Program	441	470	2.64	2.68
9/26/2016	GoogleEarth	378	714	2.55	2.98
6/28/2017	National Agriculture Imagery Program	1,740	2,180	3.95	4.28
7/10/2017	National Agriculture Imagery Program	1,390	1,620	3.65	3.85
6/2/2017	National Agriculture Imagery Program	5,520	6,920	3.24	6.91
6/28/2017	National Agriculture Imagery Program	1,740	2,180	3.95	4.28
6/30/2017	National Agriculture Imagery Program	1,400	1,520	3.66	3.77
7/10/2017	National Agriculture Imagery Program	1,390	1,620	3.65	3.85
7/19/2017	National Agriculture Imagery Program	540	1,360	3.12	3.63

as Sideling Hill Creek (figs. 15 and 16). At these tributary confluences, the introduction of a new flow vector (from the tributary stream) and the suspended sediment load it carries, creates eddies and interrupts the rate of flow of the main stream (the Potomac River). The increased sediment load and the lower flow rate in the main stem Potomac River causes sediment carried in the Sidling Hill Creek flow to be deposited in the Potomac River. Over time these sediments accumulate as an in-channel bar. This depositional process may also have important implications for dispersal of harperella seedlings, which have been known to reproduce asexually. Persistence of in-stream bars near the confluence of tributaries in the Potomac River thus indicates a relation between sediment contributions of these tributaries, in-channel bar formation, and harperella occurrence.

Figures 16–20 show the results of multi-year image analysis at specific locations near tributary confluences or near harperella occurrences. Although the occurrences near site B (fig. 17) and site C (fig. 18) were derived from the imprecise locations of past sightings, they imply that harperella once grew on these in-channel bars. The occurrences located at site A (fig. 16) were observed during field surveys conducted in 2016 and 2019 by the National Park Service (National Park Service, written commun., 2019) and are geospatially

Table 7. In-channel bar area, maximum discharge, and maximum streamgage height recorded at the Hancock, Maryland, streamgage (01613000) in the historical image analysis area during the time of image collection, 2009–17.

[km², square kilometer; ft³, cubic foot; ft, feet]

Date of imagery	In-channel bar area (km²)	Maximum discharge (ft³)	Maximum streamgage height (ft)
2017-06-02	0.85	6,920	6.91
2016-09-22	1.34	470	2.68
2016-09-14		500	2.72
2016-09-05		500	2.72
2013-08-24	1.12	1,600	3.83
2013-08-15		2,600	4.56
2011-07-14	1.25	1,180	3.41
2011-06-29		1,480	3.68
2011-05-31		8,120	7.62
2009-08-16	1.24	687	2.94
2009-08-10		1,050	3.3
2009-07-25		951	3.21
2009-07-8		1,140	3.39
2009-07-6		1,280	3.51

accurate, although no other points were concurrently collected. Note that these two occurrences are found along the leeward margins of the most stable in-channel bar areas within site A, which substantiates habitat characteristics derived from literature studies.

In addition to river conditions at the time of imaging, an abnormally high-flow hydrological event can change the extent and location of in-channel bars during the duration of the analysis. Extreme weather events have substantial hydrological effect on this dynamic system. Historical image analysis is limited to observation of river conditions at the time of image acquisition, and despite inclusion of multiple imagery dates within a year, the temporal resolution of river observation in this analysis is low. This is a notable challenge associated with all historical image analyses, and in this case, the correlation of limited imagery observation dates to records of river conditions was particularly challenging. High-flow hydrological events between image acquisitions are unaccounted for in this analysis but could still affect the extent of the quantified in-channel bars. The advent of high-resolution aerial imaging via unmanned aerial systems (UAS) presents an opportunity to increase the temporal resolution of observation for in-channel bar areas in the Potomac River. For this study, UAS imagery was collected in July 2018 as a first step towards this goal and to demonstrate its technical feasibility. Additional information about UAS imaging of the in-channel cobble bar areas in the Potomac River is provided in the following section.

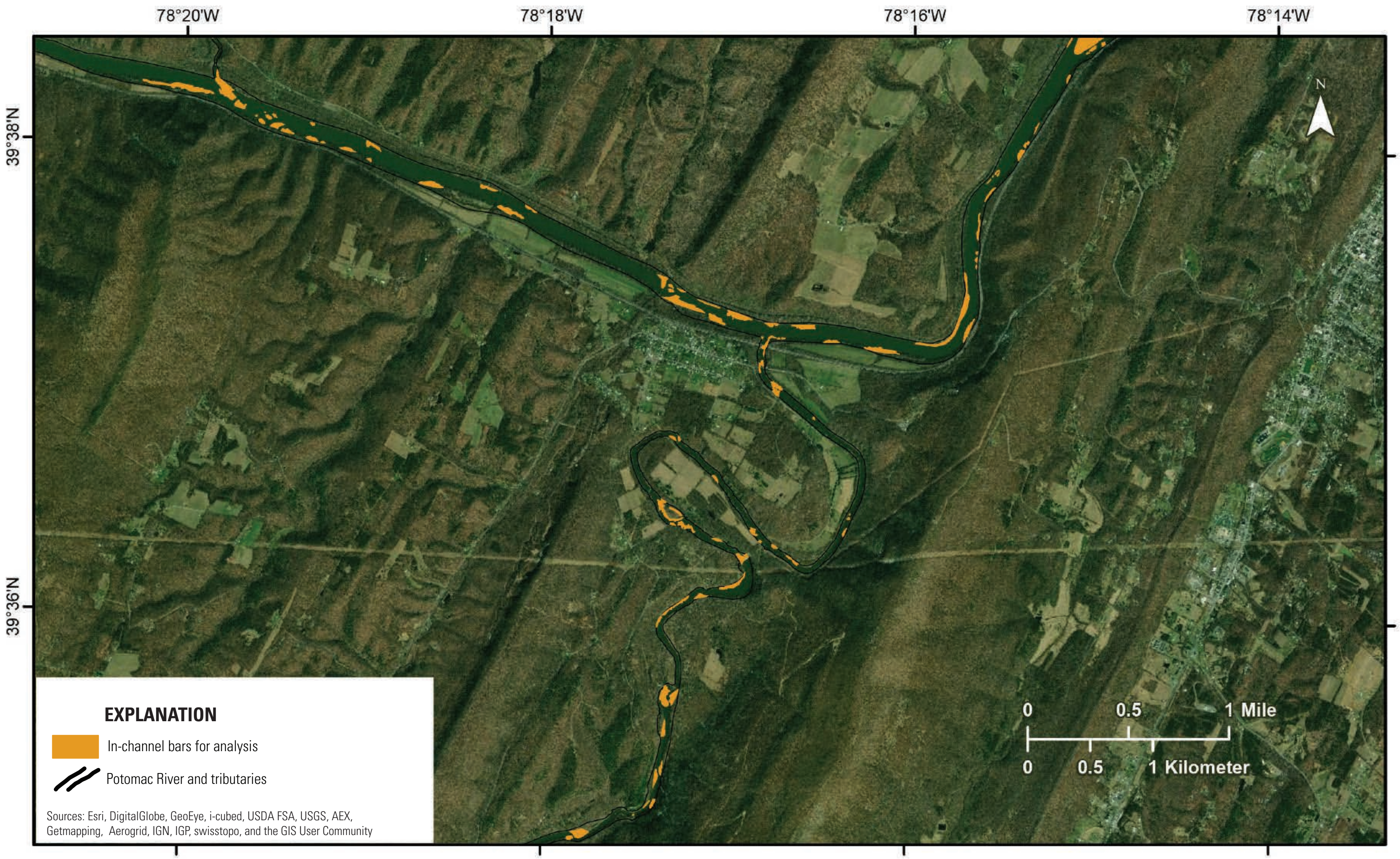

Figure 13. Results of historical image analysis for 2017 for part of the historical image analysis area, Maryland and West Virginia. Extent and locations of in-channel bars are indicated in orange.

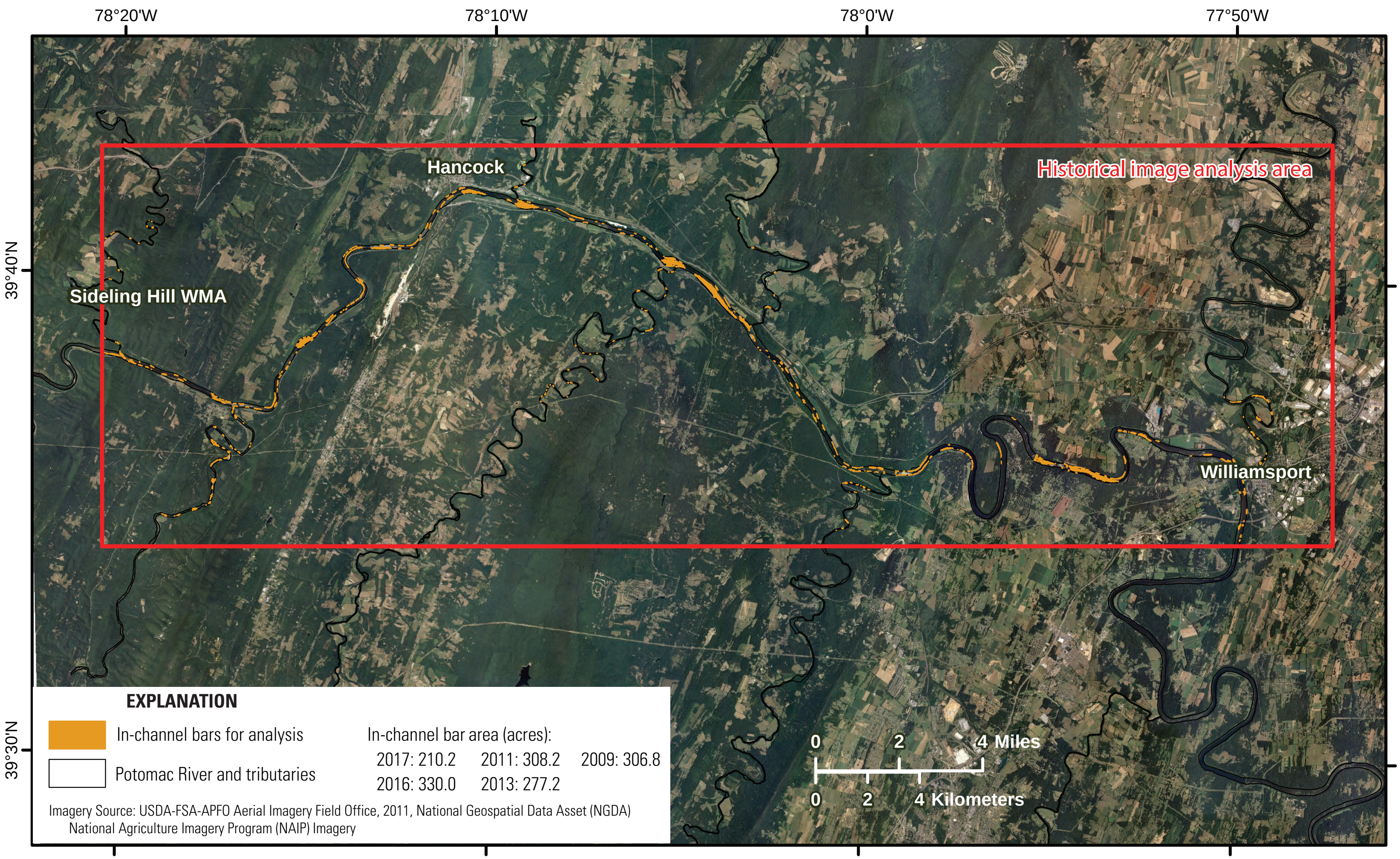

Figure 14. Results of historical image analysis for 2017 for the full extent of the historical image analysis area, Maryland and West Virginia. Extent and locations of in-channel bars are indicated in orange.

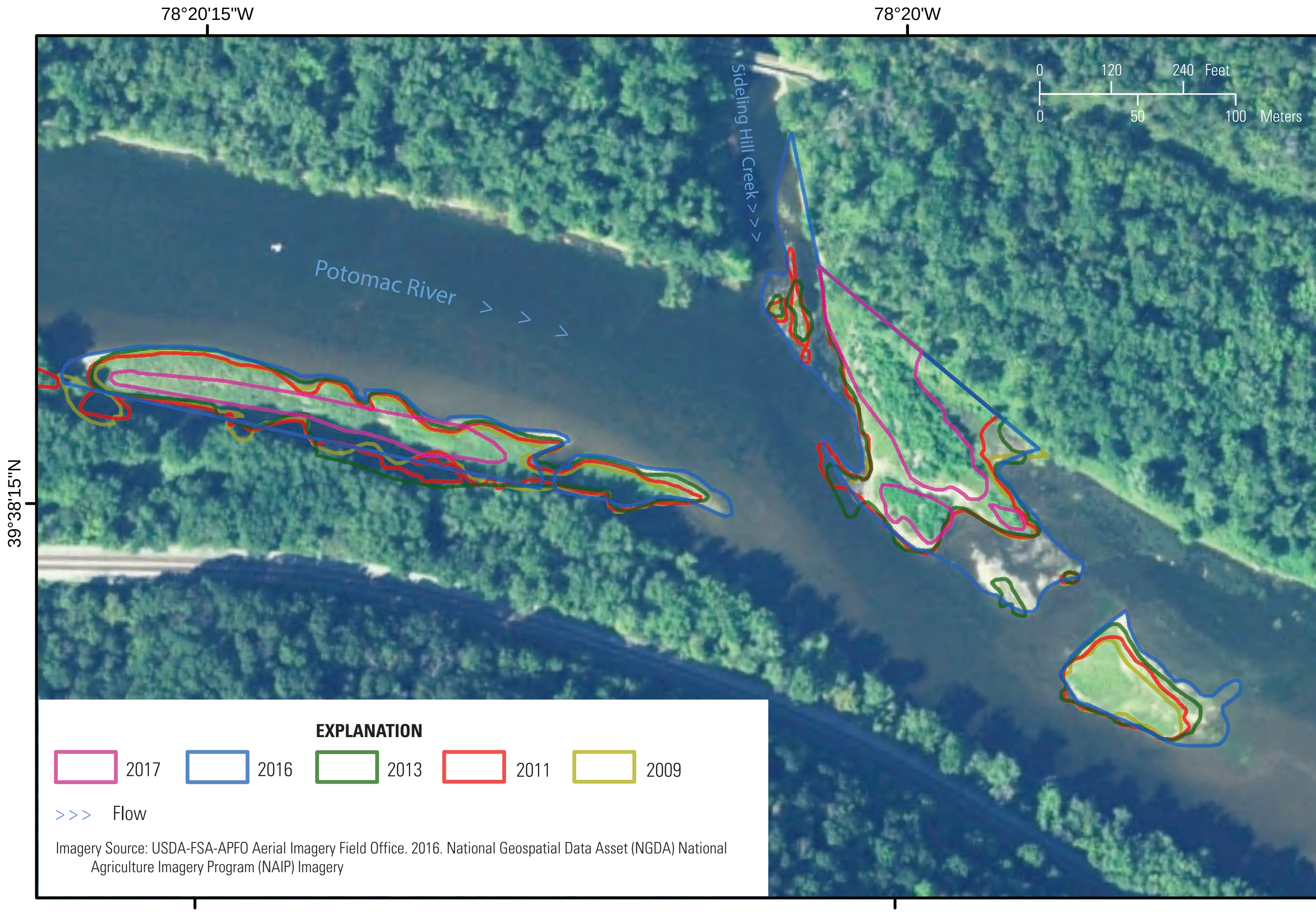

Figure 15. Delineated in-channel bars at the confluence of Sideling Hill Creek and the Potomac River, Maryland and West Virginia, using historical imagery for 2009, 2011, 2013, 2016, and 2017. Each year of delineated in-channel bars is shown with partially transparent fill so that all in-channel bars are visible. Areas where overlap occurs for multiple years appear darker.

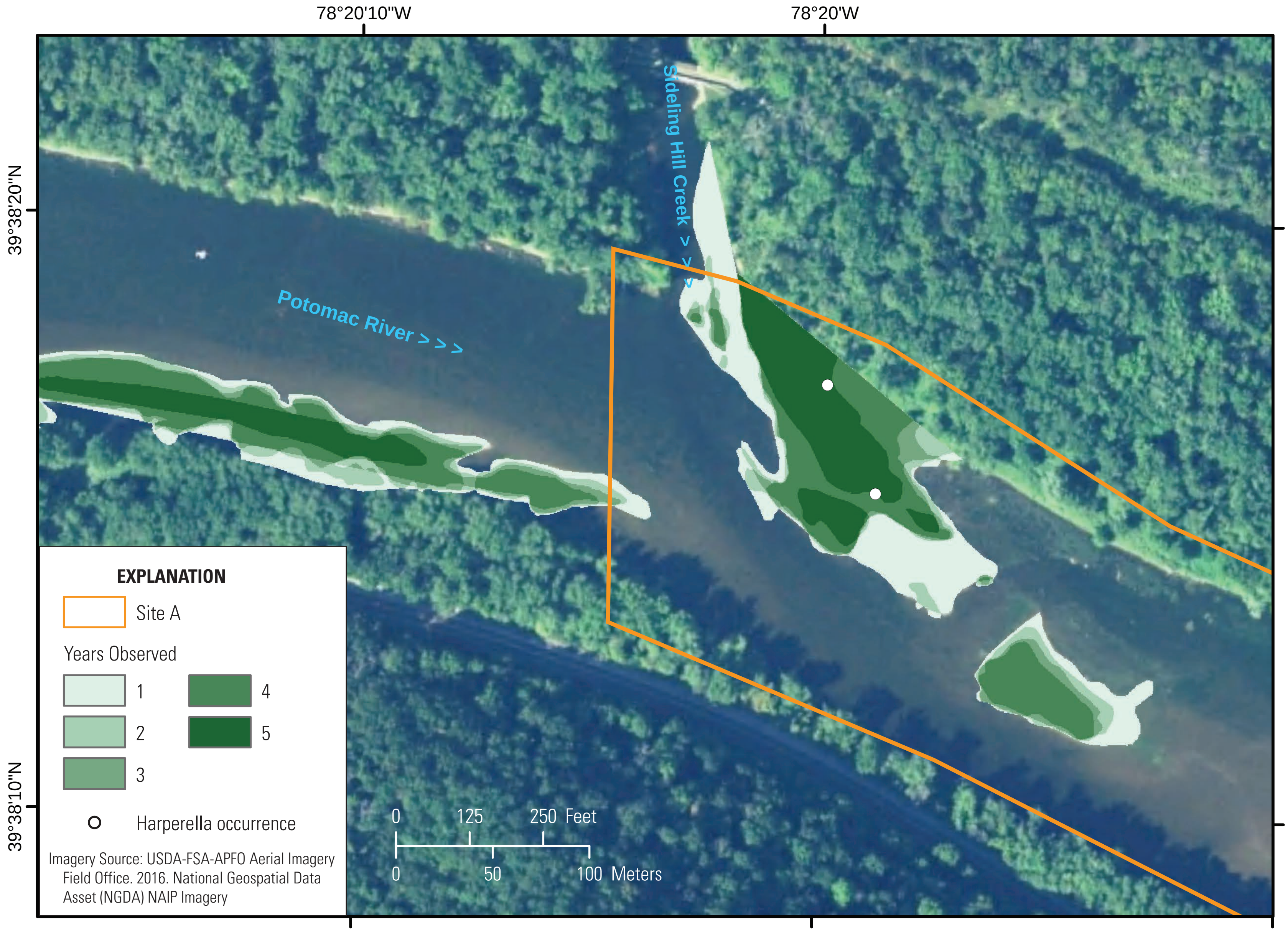

Figure 16. Result of multi-year analysis of in-channel bars at the confluence of Sideling Hill Creek and the Potomac River, site A, Maryland.

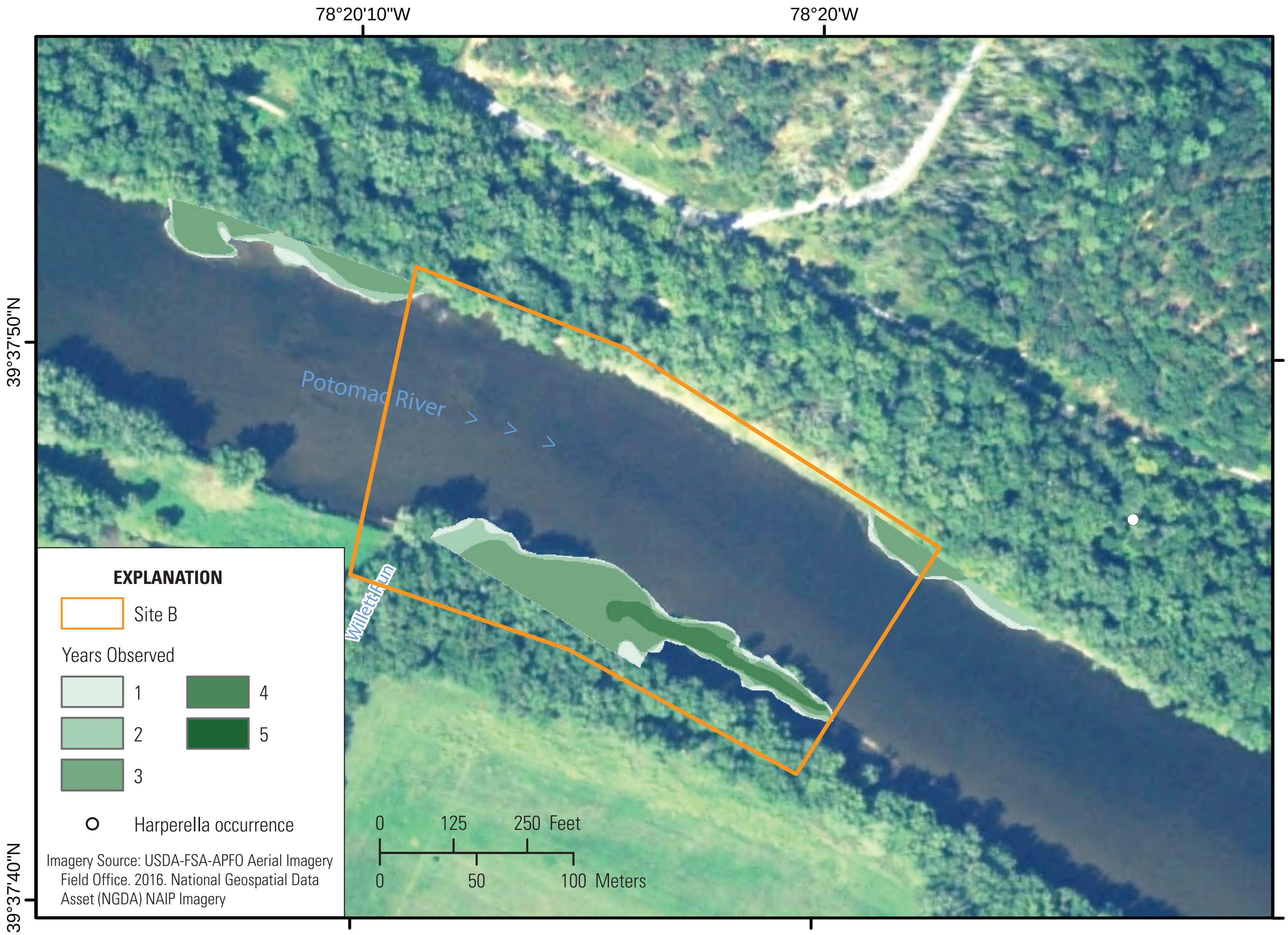

Figure 17. Result of multi-year analysis of in-channel bars just downstream from the confluence of Willett Run and the Potomac River, site B, Maryland.

Figure 18. Result of multi-year analysis of in-channel bars downstream from the confluence of Long Hollow Run and the Potomac River, site C, Maryland.

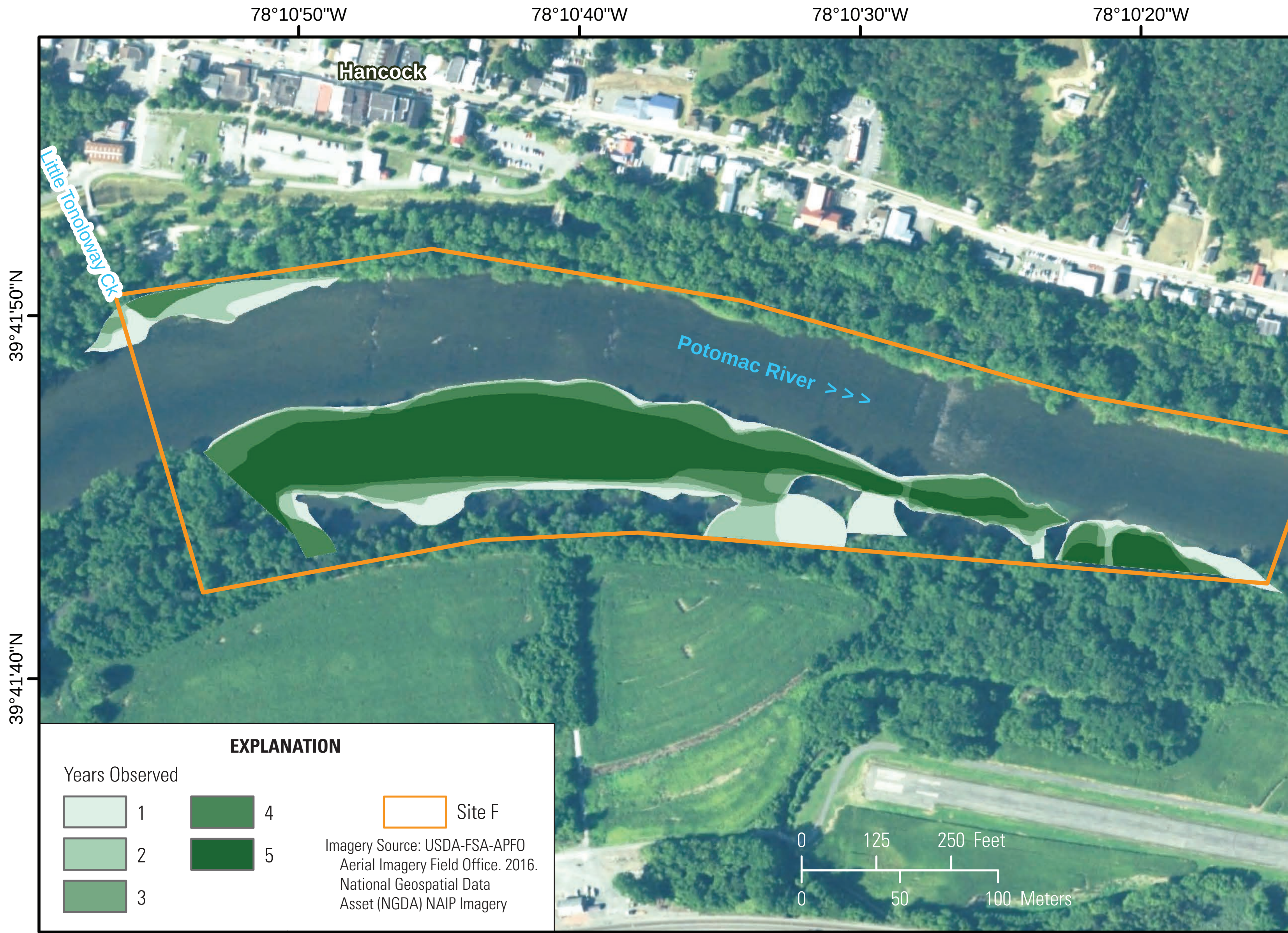

Figure 19. Result of multi-year analysis of in-channel bars downstream from the confluence of Little Tonoloway Creek and the Potomac River, site F, Maryland.

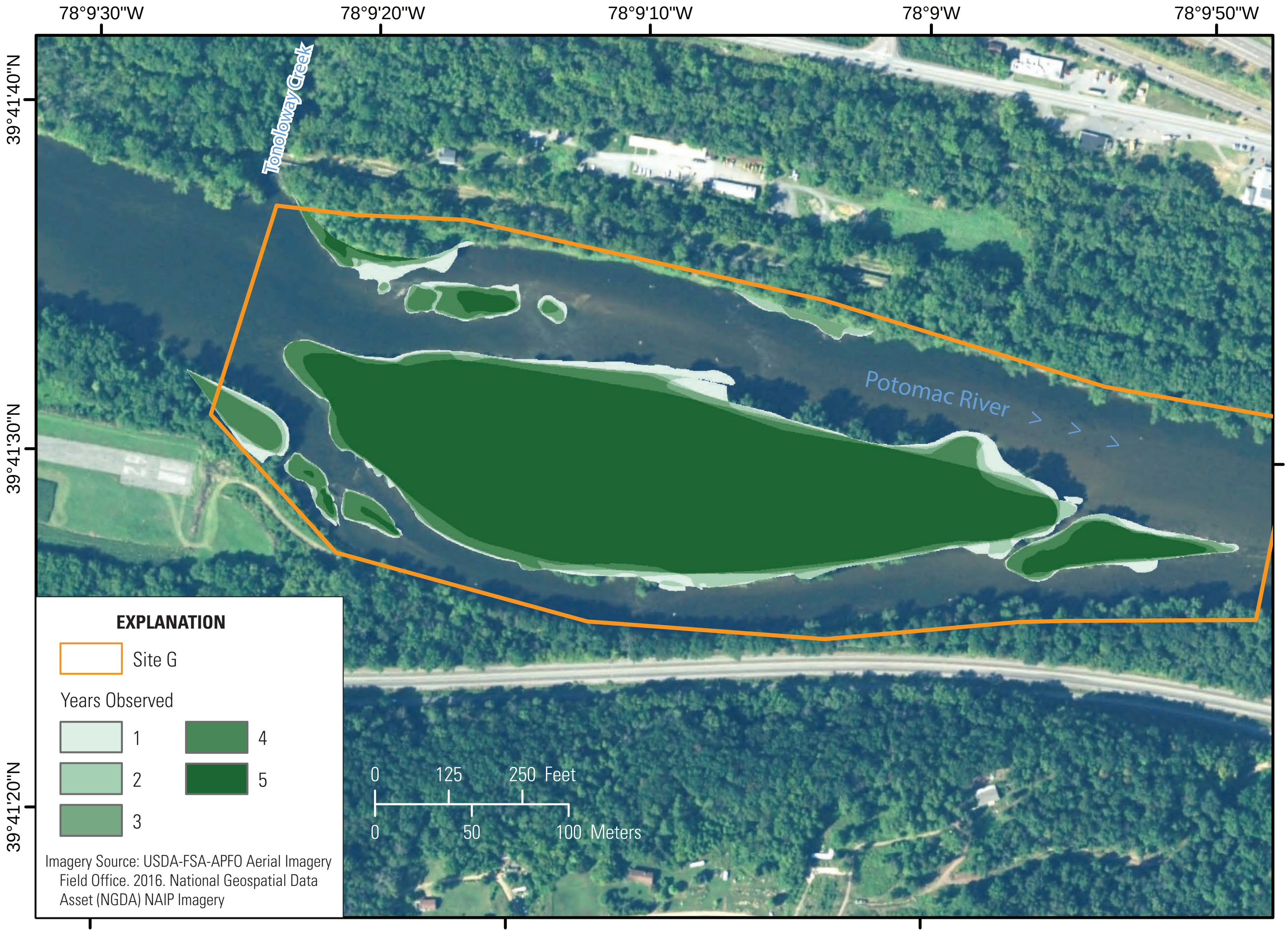

Figure 20. Result of multi-year analysis of in-channel bars downstream of the confluence of Tonoloway Creek and the Potomac River, site G, Maryland.

Table 8. Image counts and file storage requirements necessary for each area of interest study site.

[AOI, area of interest; GB, gigabyte]

AOI no.	Image count	File storage requirements (GB)
1	197	0.92
2	65	0.34
3	331	0.98
4	182	1.06
5	236	0.52
6	275	1.42
7	324	1.98
8	158	0.87
9	356	2.05
10	71	0.57

Unmanned Aerial Systems Imaging

UAS platforms have become increasingly available and affordable as a method of acquiring very high resolution aerial imagery for a wide variety of earth-science applications (Hugenholtz and others, 2012). In this study, the use of UAS to collect imagery of the AOIs, instead of contracting aerial imagery traditionally obtained from aircraft, for example, substantially reduced the cost of acquiring the very high resolution of imagery needed for detailed observation and monitoring of potential harperella habitat. However, UAS imagery remains costly to acquire and requires time-consuming post-processing to generate the necessary orthoimagery and terrain data. Furthermore, the computational processing and storage requirements of the imagery and data produced remain a challenge that limits the realistic extent of imagery acquisition. The GPM and multi-year historical image analysis developed by this study created a multi-scale methodology by which specific areas of interest within the Chesapeake and Ohio Canal National Historical Park and Potomac River could be identified and prioritized for UAS imaging of harperella habitat. The results of this multi-scale analysis were used to select 10 in-channel bar areas for which UAS imagery was conducted in 2019. Additional AOIs could be selected from the results; however, the sites selected for this study ranked highly in the GPM and were found to have persistent in-channel bars in the multi-year historical image analysis. They were also located near documented occurrences of harperella in the Chesapeake and Ohio Canal National Historical Park.

2019 UAS Data Collection

UAS imagery was collected to facilitate detailed observation, terrain modeling, and documentation of 10 AOIs (shown in fig. 21). National Park Service regulations restrict the take-off and landing of UAS on park property, so alternate locations for take-off and landing were identified through field reconnaissance. It was ultimately determined that the in-channel Potomac River area, specifically the edge of in-channel bars, provided the safest area for take-off and landing and the best opportunity for line-of-sight UAS image acquisition covering the entirety of each AOI. The USGS and the Aerial Vision Group, LLC, sought permission to fly a small UAS from both the Maryland and West Virginia Departments of Natural Resources (DNR), which manage the land within the space of the Potomac River. No formal permissions or documentation procedures were found to be necessary for such requests.

UAS imagery covering the 10 AOIs was collected by the Aerial Vision Group, LLC, in July 2019. A DJI Mavic 2 Pro Quadcopter/camera combination unit was used with an ND8 filter. Imagery was collected at 275 ft above ground, with a front-lap of 75 percent and a side-lap of 65 percent. Image overlap was used to tie multiple images together using similar features found in each image as greater overlap leads to nearly seamless models. Table 8 records the number of images collected for each site. This type of data collection is labor and computer-resource intensive. It took 3 days to access and acquire imagery for all 10 AOIs, then several days of data processing to produce orthoimages and other imagery products for each site. The space to digitally store all files associated with this analysis is 104 gigabytes.

The software DroneDeploy was used to process the raw imagery into three-dimensional (3D) surface models. Imaging matching in areas of overlap was completed in 3D space on the basis of sensor look angle. The result of this processing is a semi-photorealistic surface model of the imaged area. These models can also be translated into 3D point clouds from which very high resolution DEMs can be created. 3D point clouds also can be filtered to remove vegetation and other above-ground features to produce Digital Terrain Models (DTM) using methods suggested by Chirico and DeWitt (2017) and DeWitt and others (2017). The datasets produced by UAS imaging are finer in spatial resolution than existing datasets and will be vital in monitoring long-term terrain alterations in these specific locations. Figures 22 and 23 provide examples of the products generated from UAS imagery of each site.

Repeat imaging of these sites using UAS could greatly improve understanding of the in-channel bar environment and its connection to harperella habitat. In particular, the acquisition of imagery prior to and immediately following high-flow hydrological events could improve understanding of harperella occurrence in the Potomac River and along the Chesapeake and Ohio Canal National Historical Park.

High-resolution satellite or traditional aircraft-derived aerial imagery does not have the temporal resolution required to investigate these rapidly changing locales, but UAS imagery provides a reliable, tailored, and flexible data source to support these efforts. Ideally, data would be collected in a period of low flow at the start of every season so that transformation of the in-channel bar substrate can be re-assessed and

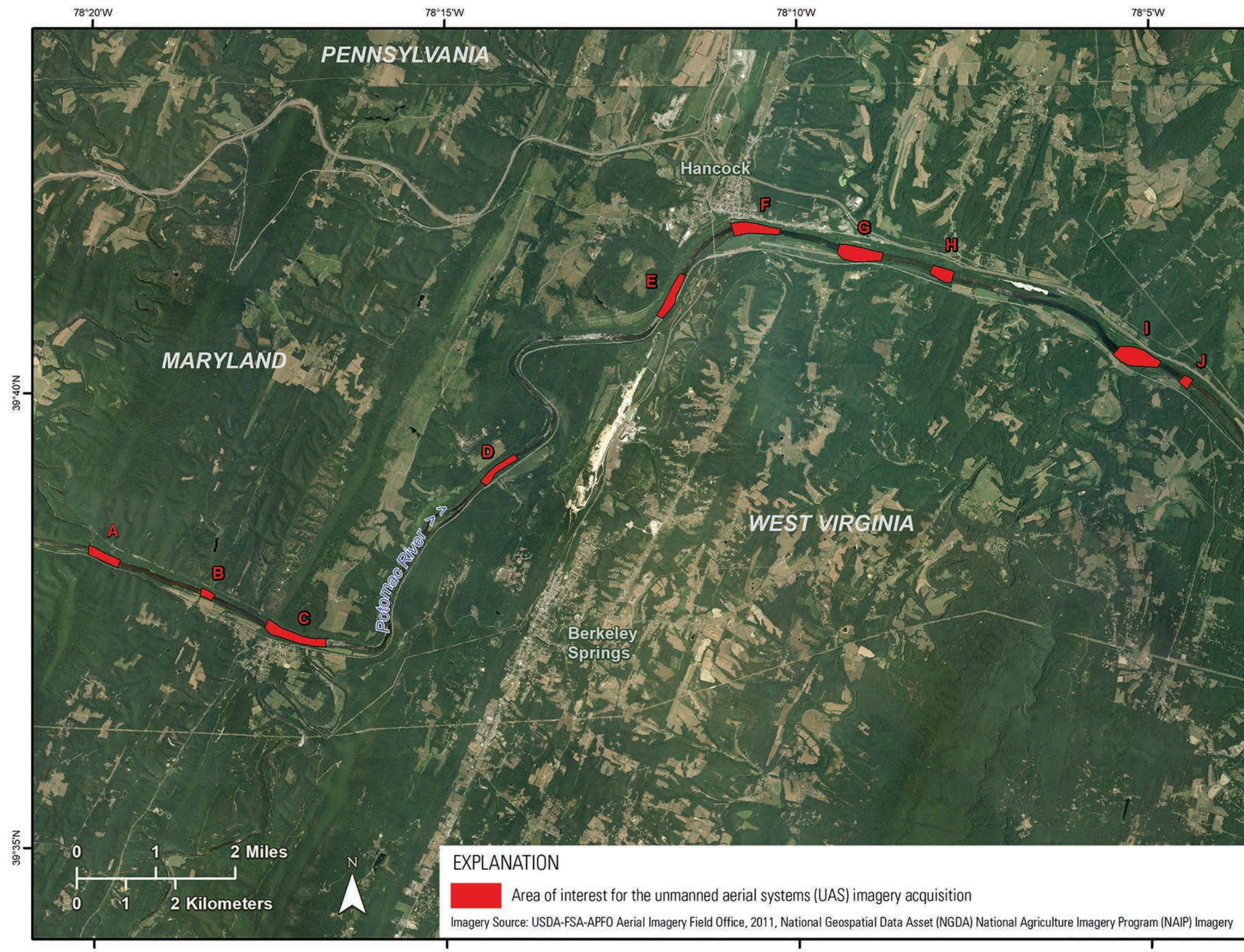

Figure 21. Location of 10 areas of interest (red) for the unmanned aerial systems, determined using the results of the geospatial prediction model and historical aerial image analysis and selected for unmanned aerial system image acquisition in fiscal year 2019.

the effects of seasonal weather and environmental characteristics can be strictly monitored. These data may serve to fill in event gaps in the historical image analysis, while also providing insight to potentially missing variables in the GPM. The next step in analysis of these AOIs for harperella habitat would be to monitor in-channel bars through repeated acquisition of UAS imagery. This additional very high resolution imagery, particularly if acquired immediately after subsequent high-flow hydrologic events, would provide an invaluable opportunity to assess changes to the in-channel bar areas that support harperella habitat.

Summary and Conclusions

This study used multi-scale remote sensing and geospatial analysis techniques to identify habitat areas that potentially support the endangered *Ptilimnium nodosum* (harperella) plant in the Potomac River. Using a broad-scale inductive geospatial prediction model, general locations of potential harperella habitat were identified along the Chesapeake and Ohio Canal National Park in the Potomac River drainage basin from Sideling Hill Creek to Harpers Ferry, West Virginia. Historical image analysis within this broad area and the extensive aircraft-derived aerial imagery archive held by the U.S. Geological Survey were used to investigate persistence patterns of in-channel bar areas of the Potomac River. Results were compared to available field observations of harperella. On the basis of these analyses and selected field surveys, suitable habitats for 10 areas of interest (AOIs) were identified with very high resolution imaging obtained using unmanned aerial systems.

The geospatial prediction model (GPM) developed in this study expanded upon existing literature studies and documented locations of harperella occurrence in order to spatially characterize the environmental conditions of harperella

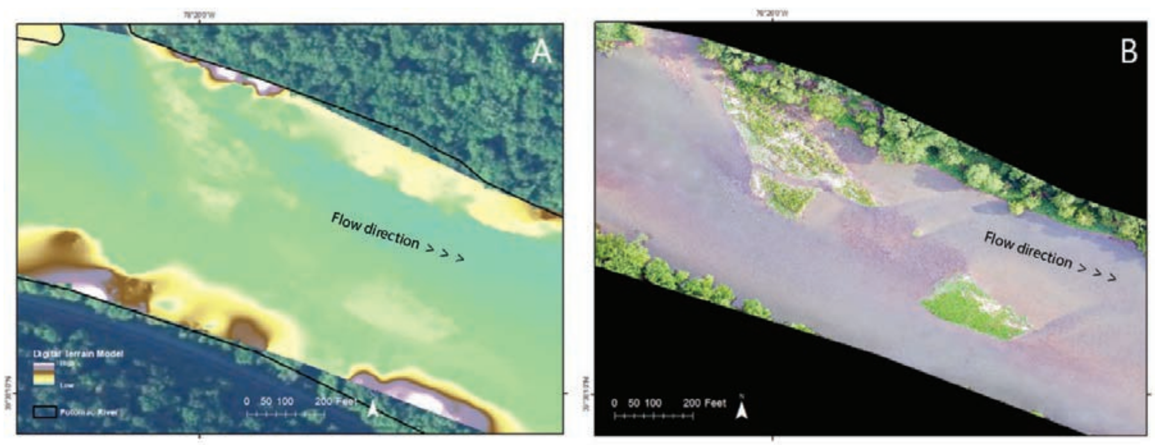

Figure 22. Examples of products created for each area of interest from unmanned aerial systems imagery: A, very high resolution Digital Terrain Models and B, very high resolution orthoimage.

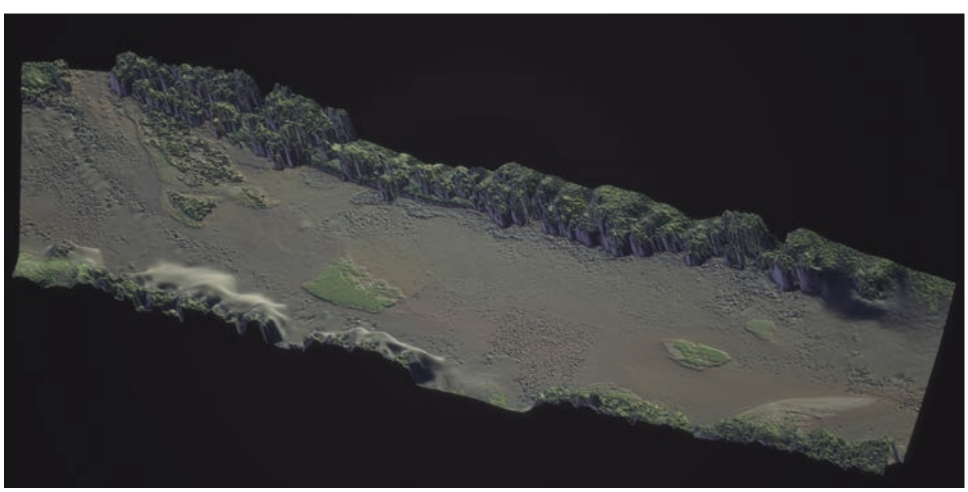

Figure 23. Example of a three-dimensional model created for each area of interest from unmanned aerial systems imagery.

habitat. Six parameters were used to model environmental conditions—soil type, soil moisture, soil slope, fluvial or alluvial terrain, solar radiation, and land cover. For each of these parameters, the range of conditions preferred by harperella were used to isolate specific geographic areas of potential habitat. Integration of the six parameters resulted in a model describing the extent of potential harperella habitat in a large area surrounding the Potomac River and parts of its tributaries' drainage basins.

Historical image analysis was conducted to investigate the conditions of the river environment, specifically the in-channel sediment bars that have been reported from limited observations to support harperella growth. Imagery was selected on the basis of river conditions, where low-flow periods that exposed these in-channel bars for visual interpretation were prioritized. Five specific years of imagery were selected for the analysis—2009, 2011, 2013, 2016, and 2017. The extent of in-channel bars was delineated for each year. A multi-temporal analysis combining all years of interpretation improved the understanding of the geospatial occurrence and persistence patterns of these in-channel bars. This analysis indicated that the extent of in-channel bars, and thus potential harperella habitat, changes substantially from year to year. The extent of in-channel bar area is closely related to river conditions at the time of imaging. It is important to recognize that these areas are part of a dynamic system that is directly affected by extreme weather events and their hydrological effects throughout the year. The multi-year persistence of in-stream bars near the confluence of major Potomac River tributaries indicates that sediment contributions of these tributaries, in-channel bar formation, and harperella occurrence are all closely interconnected. Although studies using historical aircraft-derived aerial imagery provide an information baseline of past conditions, additional in-depth observation of in-channel areas during periods of high flow is necessary to fully understand the causal effect of hydrologic events on in-channel bars and harperella habitat. As a platform for aerial imaging with great temporal flexibility, unmanned aerial systems (UAS) offer the ability to achieve this additional in-river monitoring.

Results from the GPM and historical image analysis were used to identify specific AOIs that potentially support harperella habitat. Ten of these AOIs within the Potomac River were targeted during fiscal year 2018 for additional investigation, including UAS imaging and field observation. UAS imaging of the sites produced very high resolution orthometric imagery, digital elevation models (DEMs), and high-resolution three-dimensional models of areas of potential harperella habitat. These datasets and models can be used to further investigate the environmental conditions of in-channel bars and their potential to support harperella growth. When analyzed alongside future UAS collections, these datasets will allow for detailed remote monitoring of sites at the microscale necessary to offer insight for harperella conservation projects.

Although this study did not result in definitive habitat requirements or locate existing populations of harperella, it laid the geospatial foundation for future studies and monitoring efforts. Using the hierarchy of information generated by this study, future efforts could prioritize sampling and observation, possibly reducing time and research costs in the process. If sufficient additional occurrence data are collected through a well-defined plant sampling and identification protocol, a traditional species distribution model can be completed to fully investigate and document a fundamental harperella niche along the Potomac River and its tributaries. Additionally, the multi-temporal sampling methods demonstrated here through historical aerial image analysis and UAS surveys could provide the spatial and temporal resolution necessary to monitor the status and persistence of this elusive species. More frequent assessments could greatly improve understanding of the environmental factors that affect the health and spread of harperella populations within the Potomac River system.

Datasets produced during this study, including the study area boundaries, results of the GPM, results of historical image analysis, and extent of UAS sites are available from DeWitt and others (2019). The imagery, 3D models, and DEMs for each of the UAS sites are available upon request.

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Appendix 1. Harperella Occurrence Data

Investigation of environmental characteristics for the geospatial predication model (GPM) was conducted by evaluation of the range of conditions in the vicinity of harperella occurrence locations. Through detailed analysis of the occurrence locations, it was determined that the global positioning system (GPS) locations recorded did not accurately describe the locations of plant occurrences. This section describes the evaluation of the available points.

There are multiple point datasets indicating the occurrence and abundance of harperella in or near the study area (fig. 1.1). Sources of these datasets include

- Occurrence data from the USDA PLANT database, accessed from the USGS BISON Database (U.S. Department of Agriculture, Natural Resources Conservation Service, 2019; U.S. Geological Survey, 2019).
- Occurrence data from the National Park Service (NPS). Harperella were observed in 2016 and 2019, and data were shared via email (Andrew Landsman, NPS, written commun., 2019).
- Detailed plant counts recorded by the Maryland Natural Heritage (Diane Pavek, NPS, written commun., 2018). The 45 locations are distributed over a very small area. Although the locations are accurate to within 30 meters of the GPS locations, they are not necessarily indicative of the range of conditions for harperella habitat throughout the study area.
- Occurrence data recorded by Wells (2012). These 17 locations are considered spatially inaccurate owing to their distribution on or immediately next to the Chesapeake and Ohio Canal towpath or nearby roads, rather than near the water where the plant is most likely to grow. It is assumed that GPS coordinates for these occurrences were recorded at the nearest access point to the plant sightings, indicating that the location is only in the general vicinity of harperella habitat.

In summary, 21 points (U.S. Department of Agriculture, Natural Resources Conservation Service, 2019; Andrew Landsman, NPS, written commun., 2019; Wells, 2012) were used in the evaluation of harperella habitat characteristics. Development of the parameters for the geospatial prediction model (GPM) for the full extent of the study area was achieved using these points in addition to detailed observations from the Maryland Natural Heritage Program (Diane Pavek, NPS, written commun., 2018).

Based on research of key habitat characteristics, it was expected that individual harperella occurrences would share similar environmental conditions; however, the results of this preliminary analysis show a substantial amount of variation in environmental observations. An example of this high variation is shown in table 1.1, where 10 of the 21 points were used to assess the slope and the upstream contributing area of occurrence sites. Slope at these 10 sites range from 0.06 degrees (flat) to 30 degrees, and upstream contributing areas range from 25 square meters (m^2) to 14,334,200 m^2. Several additional environmental factors were examined in this manner, with similar results of substantial variability between points.

The substantial variation in environmental characteristics between harperella occurrence sites, and the scant number of such sites, limits their quantitative use in traditional species distribution modeling. The use of occurrence sites as a direct input for geospatial prediction modeling is also limited. These point datasets would not realistically reflect harperella habitat if applied as measures of key habitat characteristics. Available occurrence data are, however, still a valuable source of information for GPM development. Occurrence data were incorporated into the study by evaluating the range of values for each environmental characteristic or GPM parameter within the local drainage area of each point.

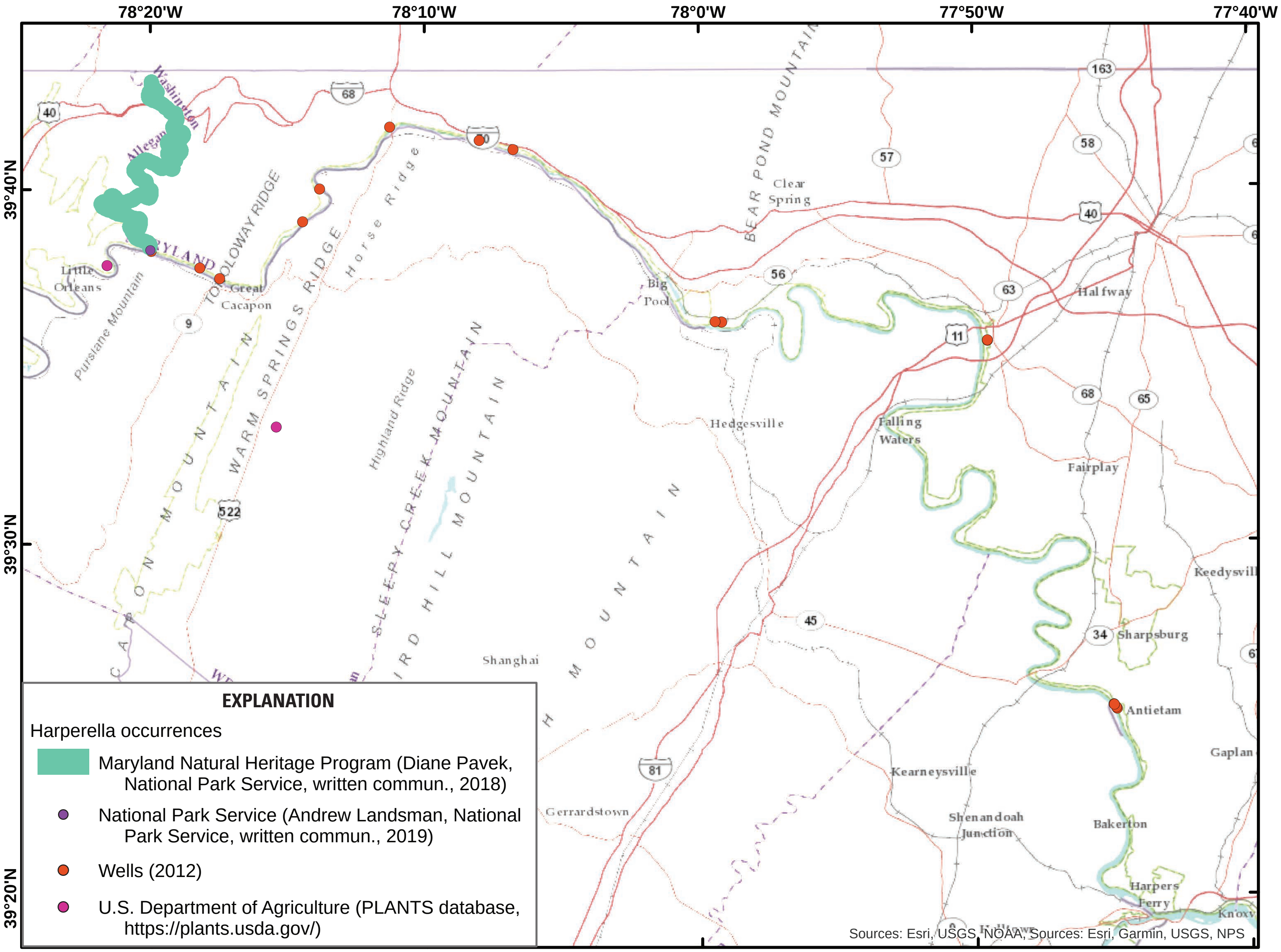

Figure 1.1. Locations of 21 documented harperella occurrences in the geospatial prediction model area.

Table 1.1. Examples of high variation in environmental variables (slope and upstream contributing area) at harperella occurrence points.

Point ID	Slope (degrees)	Upstream contributing area (m^2)
0	0.06	3,300
1	6	14,334,200
2	13	14,334,200
3	16	615,400
4	30	125
5	7	5,089,508
6	3	2,925
7	2	1,779,450
8	7	25
9	2	1,850,800
10	12	460,100

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Appendix 2. Local, Site-Scale Observations

This appendix details the study methods that allowed for local, site-scale analysis of potential habitat conditions in or near the river. Site accessibility from trails or nearby roads was evaluated and is reported herein. Using the result of the geospatial prediction model (GPM), 10 small areas of interest (AOIs) were selected for detailed investigation via unmanned aerial systems (UAS) imaging, and 5 of these were selected for field observation in fiscal year 2018. These sites are located within the Potomac River between Sideling Hill Wildlife Management Area and Pecktonville, Maryland. Figure 21 indicates the locations of UAS imaging of AOIs, whereas figure 2.1 indicates the locations of sites selected for field observation.

Timing of Observations

Preliminary field observations conducted in September 2018 were used to determine specific streamgage height and flow conditions that would enable successful observation of in- and near-river sites. During this initial observation, a gage height of 8.2 feet (ft) and a flow rate of about 10,000 cubic feet per second (ft^3/s) were measured at the Hancock, Md., streamgage 01613000. Some vegetation in the vicinity of in-channel bars was barely visible above the water surface in these conditions, and it was determined that detailed observation of the selected sites would be conducted when the Hancock streamgage was at or below 5 ft.

Owing to an unusually rainy fall with record precipitation, the gage height remained too high for field observation for the remainder of 2018. The conditions necessary for fieldwork did not occur until late spring 2019.

Field Observation

Fieldwork was conducted to assess the hydrologic and vegetation conditions of in-channel bars in the Potomac River. Visual assessment of the specific conditions within the project's AOIs is necessary to validate the harperella habitat distribution model and to develop an understanding of the local riverine environment. These on-the-ground observations are also required to link UAS imagery and geospatial analysis to specific habitat conditions. Multiple observations were made within each AOI, including

- Vegetation growth and habitat conditions, such as the type and density of plants, amount of soil moisture, sunlight availability, and soil pH;
- Surficial sediment characteristics, such as grain size, angularity, and sorting; and
- Photographic records of each site and observation point created using a hand-held camera.

Site A is directly downstream from the Sideling Hill Creek confluence. Site F is next to the boat ramp in the town of Hancock, Md. Site G is directly below the Tonoloway Creek and Potomac River confluence. Fieldwork was not conducted for site D because the terrain was inaccessible by land.

Access to sites A, B, and C was accomplished through a combination of vehicular and bicycle access. A car was driven and parked at the Western Maryland Rail Trail (WMRT) Pearre Road parking lot near Sideling Hill. Access to the sites from this point was achieved via WMRT and Chesapeake and Ohio (CHOH) trail networks. The distances from the parking lot to sites A and C are approximately 1 kilometer (km) and 3 km, respectively. To access these remote sites, bicycles and a cart were rented from a rental shop in downtown Hancock, Md. This bicycle-based transportation solution was found to be very effective, as it allowed for efficient transport of persons and field supplies without the need for vehicular access permits for the rail trails.

Sample Design

At each field site, a random point sampling pattern was established for observation of sediment grain size, sunlight availability, soil moisture, height above the water surface, and other variables. Owing to changing water conditions (U.S. Geological Survey, 2017) and the spatial variability of dry portions of the in-channel bars, point sampling locations were determined using a field map at the time of observation. Observation locations were randomly distributed within the extent of the above-water portion of the in-channel bar, with a minimum separation radius of 10 meters (m). At smaller observation sites, only 1 or 2 sample points could be distributed within the bar area. Sample locations are shown in the field maps for each site (figs. 2.8–2.16).

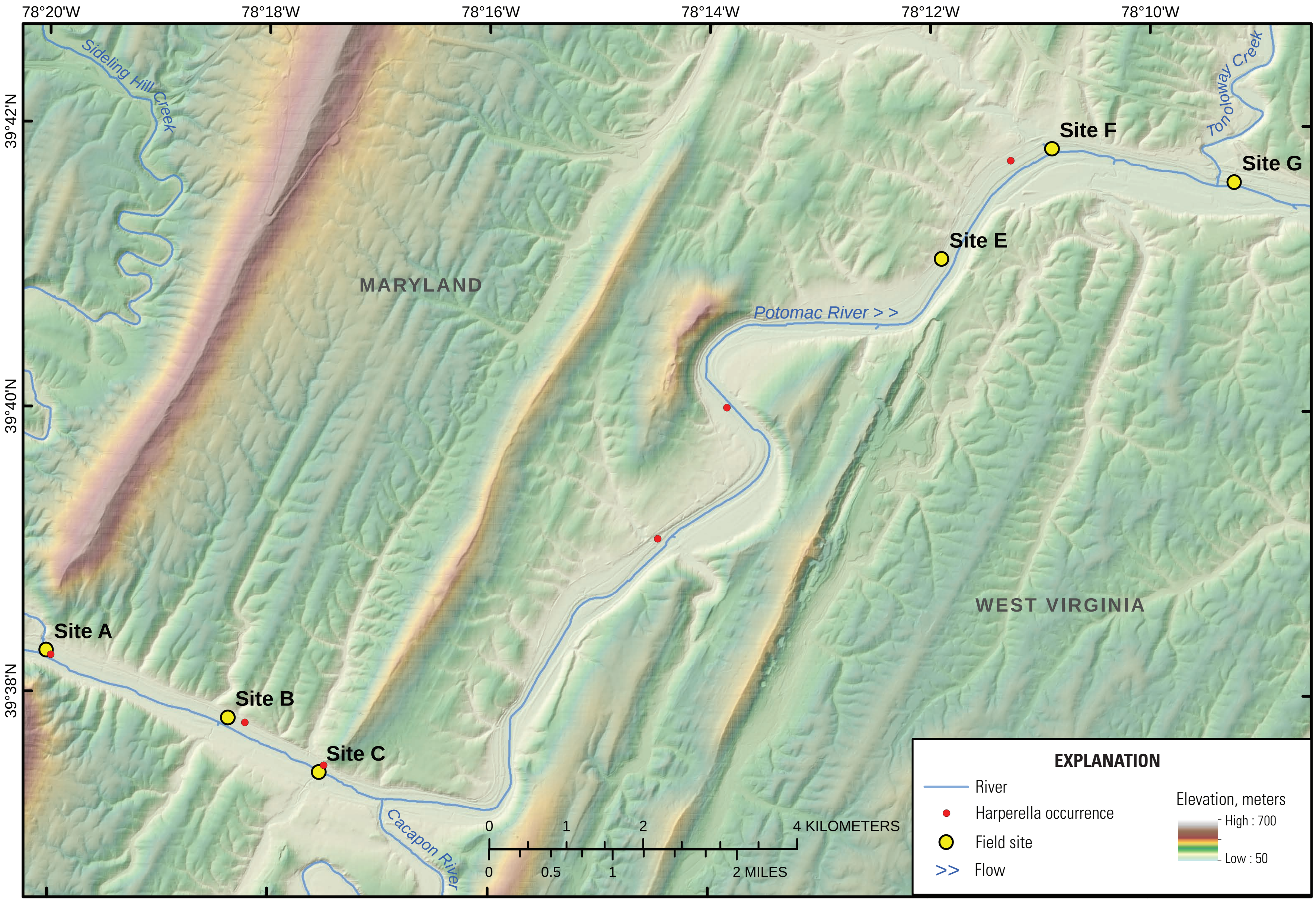

Figure 2.1. Locations of sites A, B, C, E, F, and G selected for field observation on June 6 and 7, 2019, in Maryland.

Types of Observations

At each site, weather for the survey date and 2 days prior was recorded to assess potential effects on river flow. The most recent precipitation event was also noted. The Hancock (01613000) and Pawpaw (04102500) streamgages were closest to the fieldwork study sites. Stage and flow data were collected at the two streamgages. Qualitative descriptions of in-channel flow characteristics were illustrated on the field map where applicable; these included visual turbidity (low to high), flow rate (slow to fast), depth (measured in-channel where possible), water/bank debris, and channel-bed substrate (described as mud, sand, gravel, cobble, boulder). Figure 2.2 shows the field sheet used to record these general observations for site A.

Observations at each point on or near the in-channel bar were made to document the state of specific environmental conditions, such as water height or height above the water surface, sediments found on the in-channel bars (size, shape, and sorting), and soil conditions if soil was present (soil moisture). Figure 2.3 shows the field sheet used to record these detailed observations for site A.

In-channel bar dimensions were recorded, along with a qualitative description and field sketch of microtopography. Microtopography observations include water height and an explanation of the ground surface; for example, maximum and minimum elevations. Inundation levels (completely submerged, above water) and vegetation health (healthy/dense, dead, none) also were indicated.

SiteName: PotomacR_site# A   Date: 06/06/2019   LogPg: 1 of 1

Observer names: Jessica DeWitt, Kelsey O'Pry

Weather: (summary of weather today + past 2 days + date of last rain event) Partly sunny; wind 5-10kts, past 2 days have been mostly sunny, with temperatures in the 80s; scattered showers overnight; no accumulation

River condition: 1) Turbidity of water: Very low
2) Rate of flow:
3) Estimated depth of channel: ankle in water, some woody debris on bank
4) Debris in water, banks: None in water, some woody debris on bank
5) Channel bed substrate: Gravel in small areas, mostly cobble-boulder

Pawpaw: Stage 5.3 ft, Flow: 1.7 kcfs   Hancock: Stage 4.1 ft, Flow: 1.9 kcfs

Bar dimensions: Bar was too large and densely vegetated to measure accurately
(longitudinal length [in direction of water flow], width)

Bar microtopography: Max 3ft above water, other measurements: 1'3", 1'6"
(max height above water surface, avg. height above water surface)

Surface condition: W = completely submerged
PW = partly submerged
D = above water

Veg condition: HV = healthy/dense vegetation
LV = low vegetation/new growth
DV = dead vegetation (from flooding, etc.)
NV = no vegetation present

Figure 2.2. Example field sheet used to record general site observations.

SiteName: PotomacR_site# A LogPg: 1 of 1

Pt	Cobble bar	Control pt (Y or N)	GPS			Height abv/belw wtr surface (cm)	Ambient temp (°C)	Avg grain size	Largest/smallest grain size	Grain angularity	Sorting	Soil pH	Soil moisture	Soil temp (°C)	Soil depth (cm)	Soil sunlight	Photos	Comments
			Y	X	Z													
BC	1	Y	39.6381 6179	-78.333 6264	127.83	~2'	82	CG- VCG	Boul/FS	A4	No	7.5	4	-	3.5	2000	1060-1068 611-613	
1	1	Y	39.6383 06	-78.333 739	121.2	1'6"	77	CG- VCG	Boul/VFS	-	-	7.5	4	-	3	1000	1069-1109 614	
2	1	Y	39.6381 84	-78.33 4112	220	7"	72	CG- VCG	Boul/VFS	A4	No	8	7	-	3	2000	615-621	
3	-	-	-	-	-	-	-	-	-/	-	-	-	-	-	-	-	-	-
4	1	Y	39.6377 5921	-78.333 80547	175.304	-1"	73	CG- VCG	Boul/VFS	A4	No	7	10	-	4	1000	1110-1117	Windy
5	2	Y	39.637 62	-78.33 335	168.9	3"	80	CG- VCG	Boul/VFS	A4	No	-	-	-	-	-	1118-1122	B2 has max elevation of ~1' above surface
6	2	Y	39.63 718	-78.33 328	114	4"	82	CG- VCG	Boul/VFS	A4	No	7.5	10	-	3	2000	1134-1145	Sunny
7	2	Y	39.63 728	-78.33 325	102	1'2"	87.5	CG- VCG	Boul/VFS/Fines	A4	No	-	-	-	-	-	1146-1148 624-628	Sunny
8	1	Y	39.637 408	-78.33 2805	120	7"	86.5	CG- VCG	Boul/VFS	A4	No	-	-	-	-	-	1149-1155 629-637	Sunny
9	1	Y	39.63 745	-78.33 261	127.8	4"	87	VFS	VCG/Fines	-	Yes	7	10	-	4	2000	1156-1168 638	Sunny
10	3	Y	39.63 724	-78.33 2317	128	5"	81	CG- VCG	VCG/Fines	-	No	-	-	-	-	-	1169-1199 639-644	Sunny
11	1	Y	39.63 765	-78.33 278	127.6	0"	92	Fines	VFS/Fines	-	Yes	7	10	-	4	2000	1200-1206 45-650	Sunny
12	1	Y	39.63 781	-78.33 3043	128	~9"	82	CG- VCG	Boul/G	-	No	7	8	-	3	2000	1216-1221 655-657	
13	1	Y	39.637 709	-78.33 2998	128	1.5'	90	VFS	Few CG/Fines	-	Yes	7	10	-	4	2000	1207-1215 652-654	
14	1	Y	39.6379 7350	-78.33 3093	128.8	~8"	85	Fines	Boul/VFS	-	Yes	7	9.5	-	3	2000	1222-1228 658-661	
15	1	Y	39.637 987	-78.333 2486	128.2	1.5"	91	CG- VCG	Lg. Boul/VFS	-	No	-	-	-	-	-	1229-1236 662-667	
									/									
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Figure 2.3. Example field sheet used to record detailed sample observations.

Detailed observations of in-channel bar characteristics were made at specific points distributed around the in-channel bar. These observations are listed below, and the meters and other tools used to measure them are shown in figures 2.4–2.7.

1. Cobble bar: identifier given to the in-channel bar on which the point was recorded.
2. Control point: indicates whether the point was recorded using real-time kinematic (RTK) global positioning system (GPS) (Y – yes, or N – no); this is a rough indication of the horizontal and vertical accuracy of the point.
3. GPS XYZ: coordinates.
4. Height above or below water surface: measured in inches.
5. Ambient temperature: recorded at the time of data collection in degrees Centigrade.
6. Average grain size: assigned using the gravelometer (fig. 2.4).
7. Largest and smallest grain sizes: category assigned using gravelometer and soil reference card (fig. 2.5).
8. Grain angularity: category assigned using soil reference card (fig. 2.6).
9. Sorting: indicates observed sorting of grain sizes at the sample point; category assigned using soil reference card (fig. 2.6).
10. Soil pH: measured using a three-way soil meter (fig. 2.7).
11. Soil moisture: measured using a three-way soil meter (fig. 2.7).
12. Soil temperature: measured in degrees Centigrade, using a three-way soil meter (fig. 2.7).
13. Soil depth: how far the soil meter could be inserted into the ground, measured in centimeters.
14. Soil sunlight: recorded using a three-way soil meter (fig. 2.7).
14. Photos: the identification name or number of the photograph taken at this survey point.
15. Comments: any additional comments about the individual survey point.

Figure 2.4. Gravelometer used to measure larger particle sizes (gravel – cobble). Photograph by Jessica DeWitt, U.S. Geological Survey.

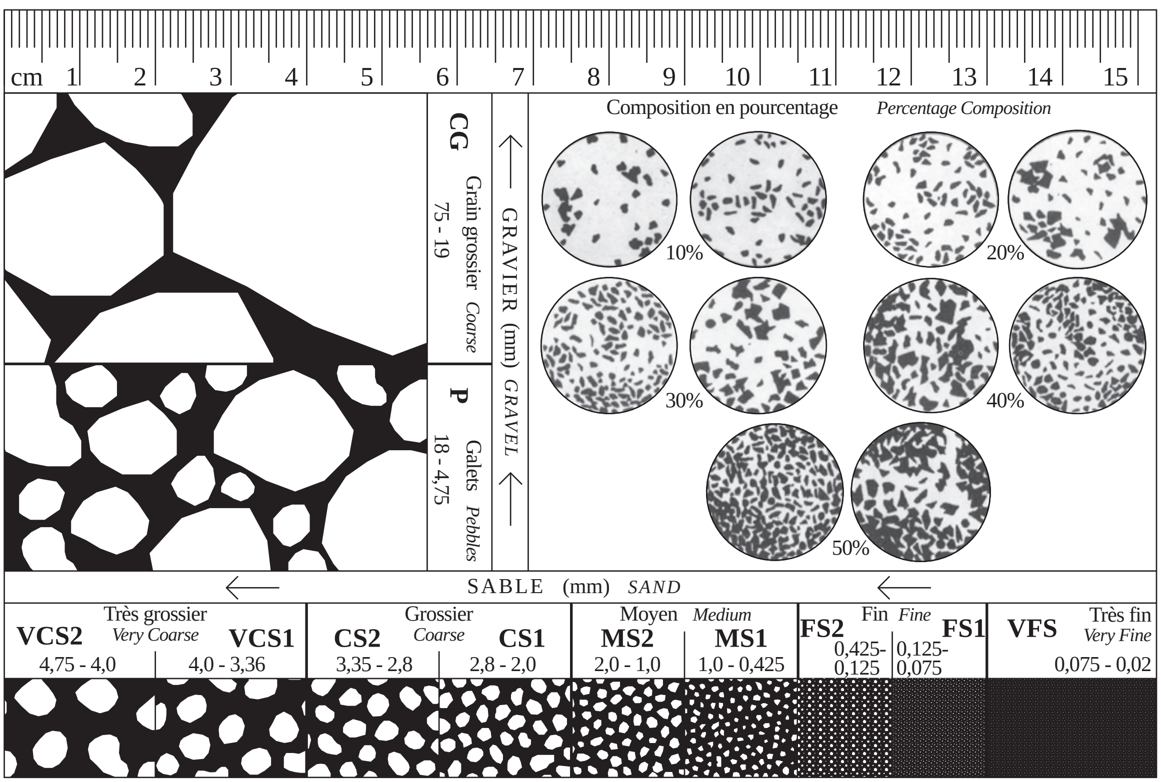

Figure 2.5. Card used to determine particle size.

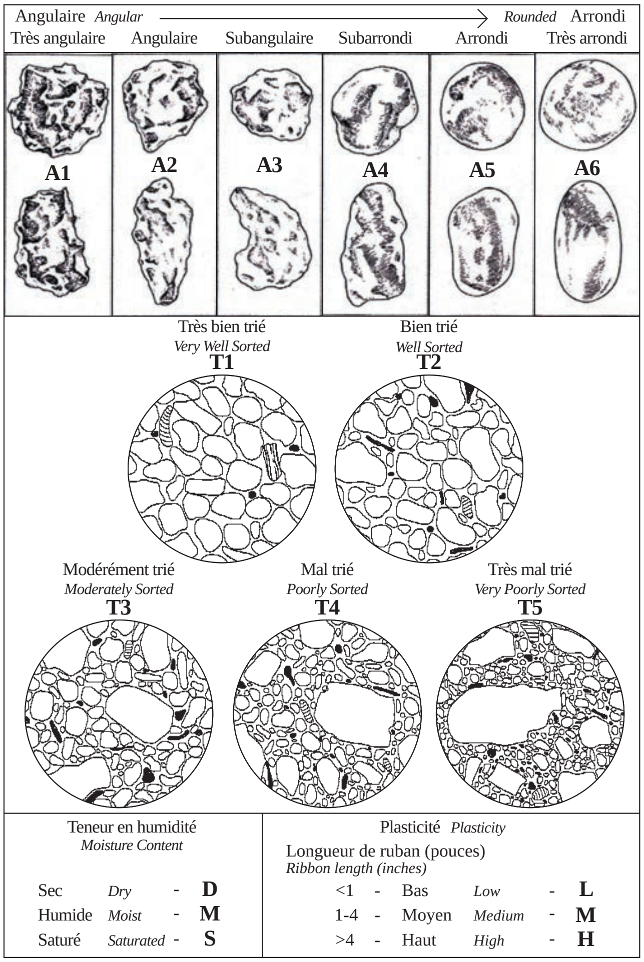

Figure 2.6. Card used to determine angularity and particle size sorting. Photograph by Jessica DeWitt, U.S. Geological Survey.

Figure 2.7. Three-way soil meter used to record soil moisture, soil pH, and sunlight availability. Photograph by Jessica DeWitt, U.S. Geological Survey.

Field Observation Results

The following sections provide photographs and a brief summary of conditions observed at each site.

Site A

Site A was the first site visited on June 6, 2019. The site is roughly 1 kilometer (km; 0.62 mile) west of the Western Maryland Rail Trail Parking Lot near Chesapeake and Ohio (C&O) Canal Lock 56, immediately downstream from the Sideling Hill Creek and Potomac River confluence. Access to the river from the C&O Canal path was difficult and required approximately 100 meters (m; 328 feet [ft]) of transit through hip- to chest-high dense vegetation, down a 10- to 30-degree embankment to the river's edge. The site was found to be a sidebar extension of the riverbank, with the low river height allowing access to and from the bank without need for wading. Three different in-channel bars were found to be above water, and detailed sample observations were made for each. The field map for site A is shown in figure 2.8, and figure 2.9 shows two "satellite in-channel bars."

Weather conditions experienced during observations at site A were mostly sunny and hot, with no rain in the prior 2 days. Water turbidity was observed to be very low, and large parts of the in-channel area were shallow and wadeable. Channel substrate in this wadeable part of the river was primarily composed of cobble-boulders, with gravel patches in small areas. Channel depth ranged from ankle deep near the in-channel bar to hip deep or deeper in the channel thalweg. No debris was observed in the water; however, substantial amounts of woody debris were observed on the primary in-channel bar and along the riverbanks. The main bar was found to be extremely large and densely vegetated with Sycamore saplings, as shown in figures 2.10 and 2.11. These two factors limited measurement of the overall dimensions of the bar. The microtopography of the bar was low lying, with a maximum height above the water surface estimated to be 1 m (3 ft). Other areas above the water surface were estimated at 0.45 m (1.5 ft).

Mean sediment particle size at 11 of the 16 sampling locations was classified as coarse gravel to very coarse gravel (CG–VCG), with a maximum and minimum particle size classification of boulder and very fine sand, respectively. Other sampling locations were observed to have a mean particle size classification of very fine sand or fines, with a maximum and minimum of very fine sand to fines, respectively. In general, these sites were on the leeward side of the in-channel bar, indicating that sorting of sediment and particle sizes occurs across the horizontal space of the in-channel bar. This sorting may also occur vertically; however, auger sampling was not possible owing to time constraints and the large typical particle size.

Site B

Site B was observed in the late afternoon of June 6, 2019. Detailed sampling could not be performed here because of accessibility issues. The site is adjacent to the C&O Canal trail and (similar to site A) required extensive bushwhacking through hip-high vegetation down a very steep slope to the edge of the river terrace. Access to the in-channel area required navigation of a steep 1.5-m (5-ft)-high, (shown in fig. 2.12). The in-channel bars at this site were found to be on the far side of the river, and it was determined that the channel and thalweg were too deep to safely forge across (fig. 2.13). A field sketch of the topographic profile from the trail to the river's edge is shown in figure 2.14. Photographs and a GPS point were taken using the Garmin GPS, but no RTK GPS or other measurements were collected.

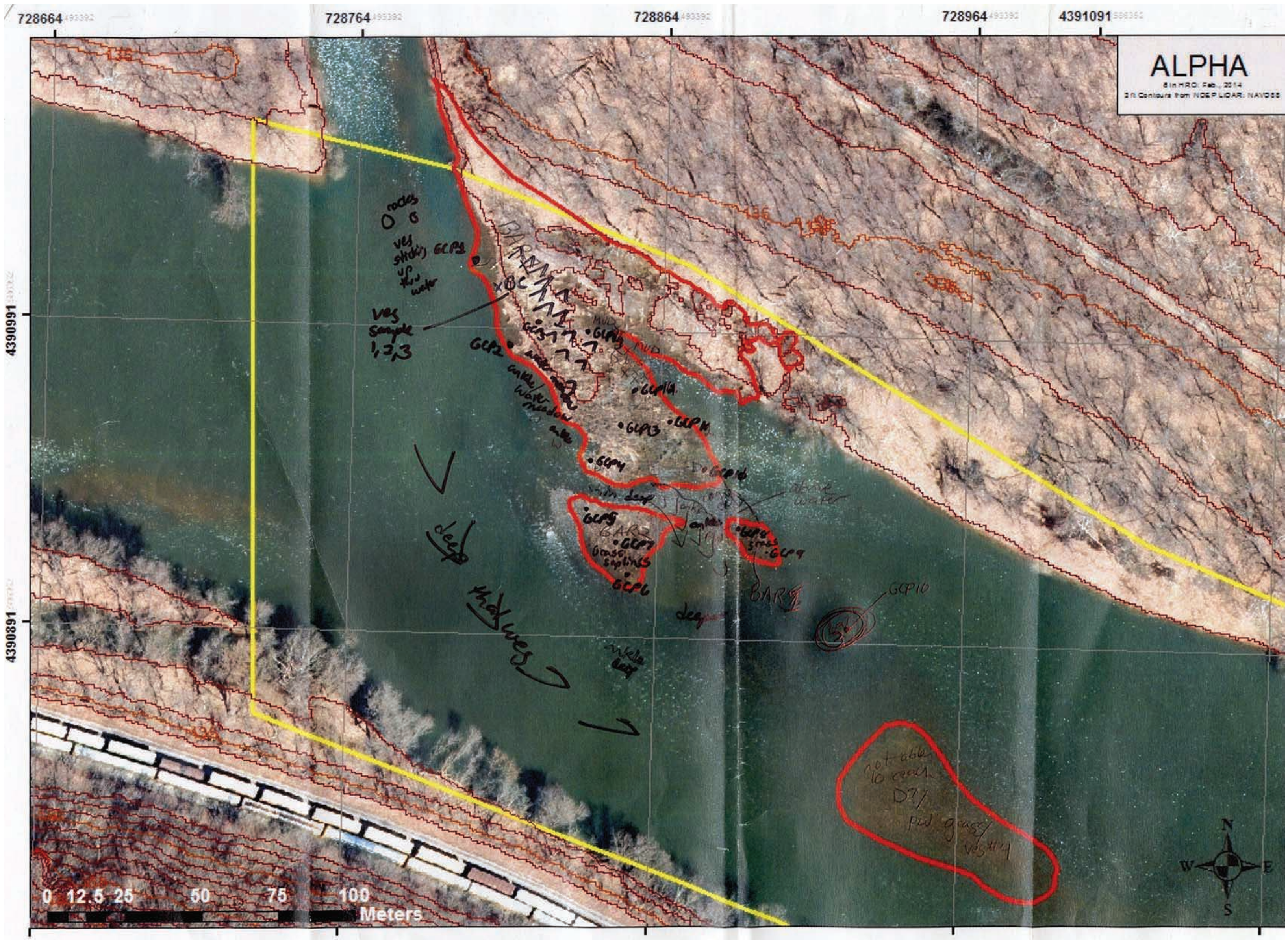

Figure 2.8. Field map for site A.

Figure 2.9. View (looking upstream) of two satellite in-channel bars downstream of main in-channel bar. Multiple satellite in-channel bars were cut off from the main cobble by the channel. Photograph by Jessica DeWitt, U.S. Geological Survey.

Figure 2.10. Main in-channel bar at site A. View looking downstream from the center of the bar. Photograph by Jessica DeWitt, U.S. Geological Survey.

Figure 2.11. Dense vegetation of primarily Sycamore saplings, as well as woody debris, covered large parts of the main in-channel bar at site A. View from downstream looking upstream at the main in-channel bar. Photograph by Jessica DeWitt, U.S. Geological Survey.

Figure 2.12. Embankment and channel-edge area at site B. View looking downstream. Photograph by Jessica DeWitt, U.S. Geological Survey.

Figure 2.13. The in-channel bar at site B is located on the other side of the river and is not accessible from the Chesapeake and Ohio Canal Trail. View looking across the river. Photograph by Jessica DeWitt, U.S. Geological Survey.

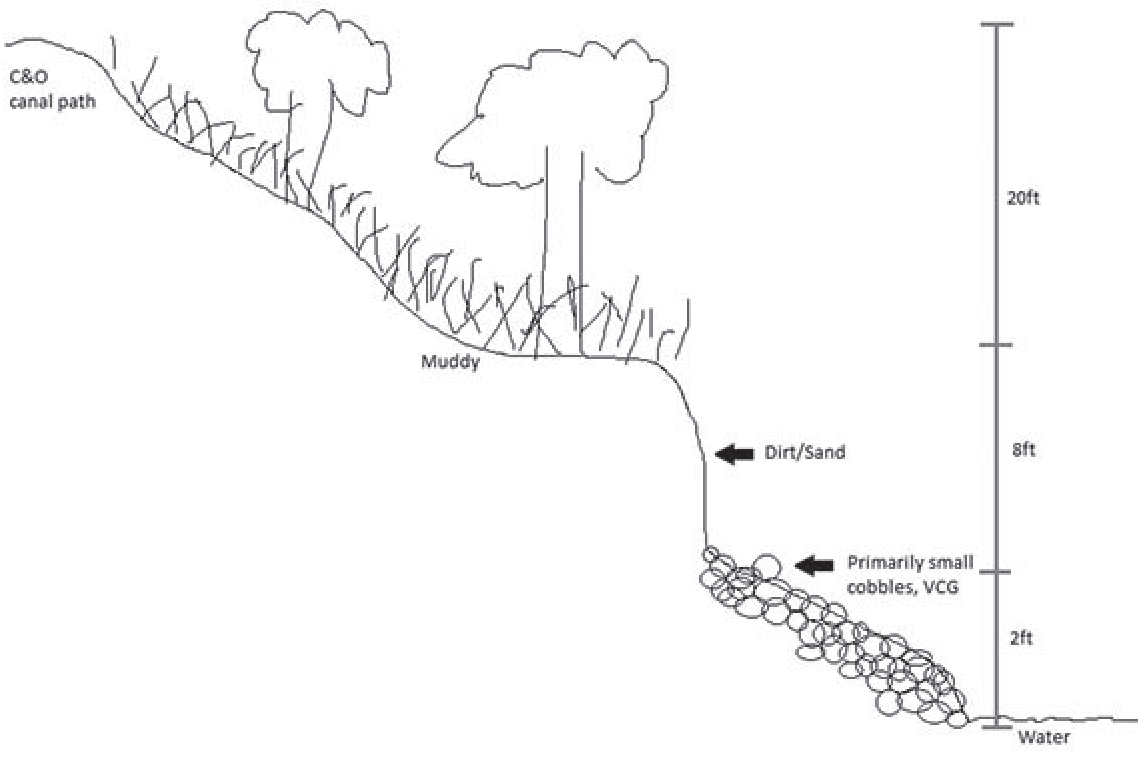

Figure 2.14. Profile field sketch of access from the Chesapeake and Ohio Canal path to the river's edge at site B. VCG, very coarse gravel.

Site C

Site C was visited in the early afternoon on June 6, 2019, and is located approximately 3 km (1.86 mi) east of the Pearre Road Western Maryland Rail Trail parking lot. It was anticipated that this site would be ideal for detailed in-channel bar observations because it juts well into the river channel and is present in almost all imagery of the river. However, the in-channel bar area was found to be created by previous anthropogenic construction, possibly a bridge or other cross-river structure. The in-channel bar area rises out of the water at a substantial angle to a nearly uniform 1.82 m (6 ft) and was almost entirely covered by boulder-size riprap, armoring it against erosion from the river. This severe angle and armoring cause it to resist changes over time in response to erosion or other in-channel processes. Figure 2.15 shows a planimetric (*A*) and profile (*B*) sketch map of site C. Figure 2.16 shows the field map for this site.

As a substantially armored bar, the in-channel bar observed at site C (fig. 2.17) restricts river flow to approximately one-half of the river's normal width. This causes the main thalweg adjacent to the bar to be deep and fast moving. Downstream from the bar, the current immediately slows and deposits sediments, resulting in the formation of multiple in-channel bars. Access to these areas was blocked by a deep section of the thalweg. Figure 2.18 shows the in-channel bars downstream from site C. These areas were barely visible above the surface of the water and were not accessible from the C&O Canal side of the river. The highest point of this bar is approximately 1.82 meters (6 feet) above water level.

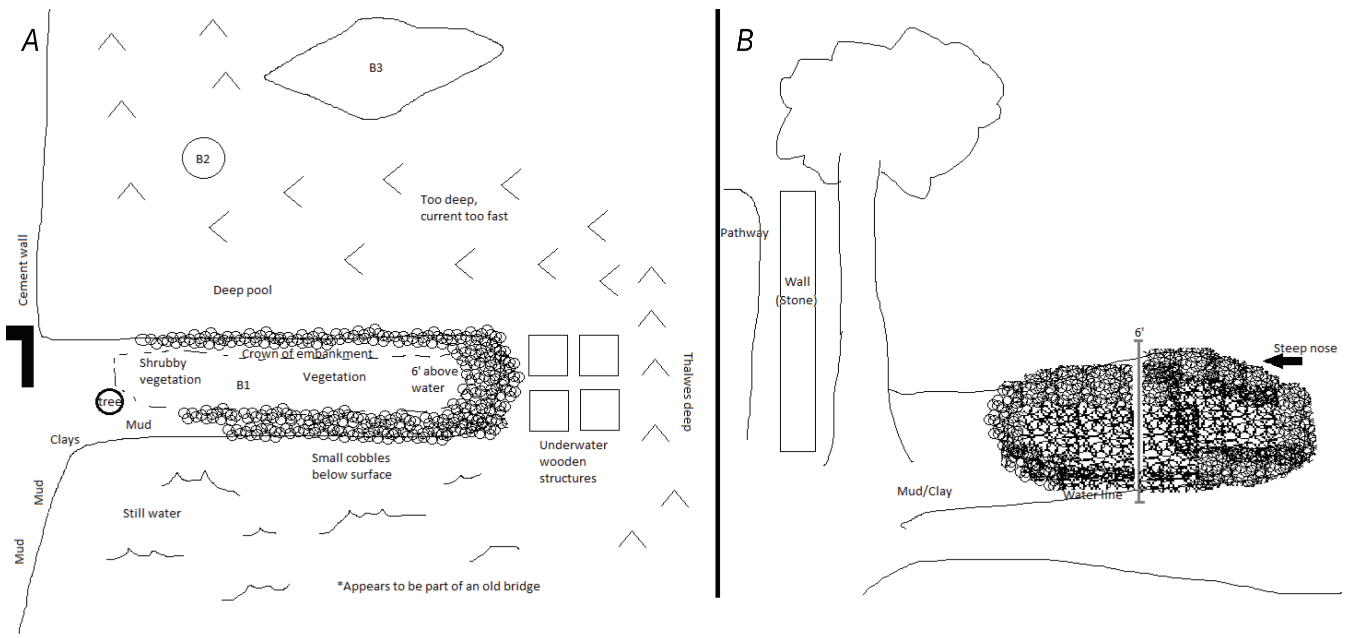

Figure 2.15. Field sketch of site C in *A*, planimetric view and *B*, profile view. The height of the in-channel bar area above the water surface measured at a nearly uniform 1.82 meters (6 feet), and the bar was entirely armored with boulder-size riprap extending into the channel.

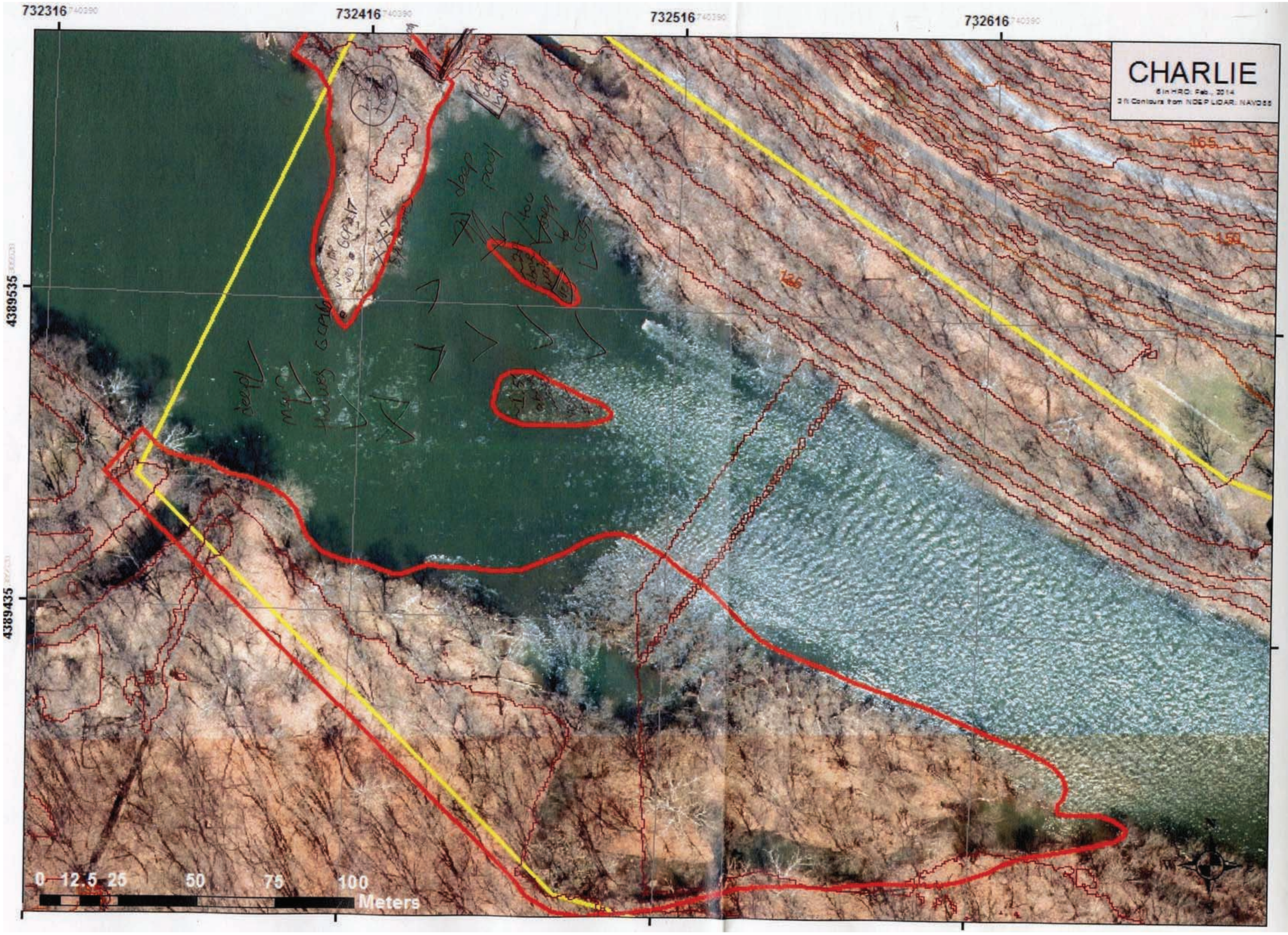

Figure 2.16. Field map for site C.

Figure 2.17. View of site C from the water's edge looking down the length of the in-channel bar. View looking southeast. Photograph by Kelsey O'Pry, Natural Systems Analysts, Inc., under contract to the U.S. Geological Survey.

Figure 2.18. In-channel bars visible downstream from the main bar with deep water/thalweg in between. View looking north along the upstream side of the bar. Photograph by Kelsey O'Pry, Natural Systems Analysts, Inc., under contract to the U.S. Geological Survey.

Site E

Site E is 2 km (1.24 mi) southwest of Hancock, Md., and was observed around noon on June 7, 2019. Despite being several hundred meters from the C&O Canal trail, access to the site was not difficult because a pathway through the undergrowth had been cleared (presumably by a local resident for fishing or river access). Because of the wide clearing of this path, terracing of the riverbank was clearly visible and is shown in the site field sketch (fig. 2.19).

The main in-channel bar at this site was near the shore and measured to be approximately 70 m (230 ft) long (running down the channel) and 29.26 m (96 ft) wide (stretching into the channel). It was a comparatively low-lying bar, partly or completely submerged below the water surface in several areas (figs. 2.20 and 2.21). Vegetation was observed to grow on submerged, partly submerged, and dry areas of the bar. Sycamore saplings were growing from what appeared to be previously larger trees or tree stumps, indicating that regrowth had occurred following a disturbance, possibly flooding. Particle sizes at this site were generally smaller than those observed at site A; most sample locations had an average grain size of coarse sand and a maximum grain size of very coarse gravel. A maximum particle size of boulder was recorded at only 1 of 6 sampling locations. Similar to site A, very little sorting was observed at each sampling location; however, additional analysis may indicate sorting across the horizontal space of the bar.

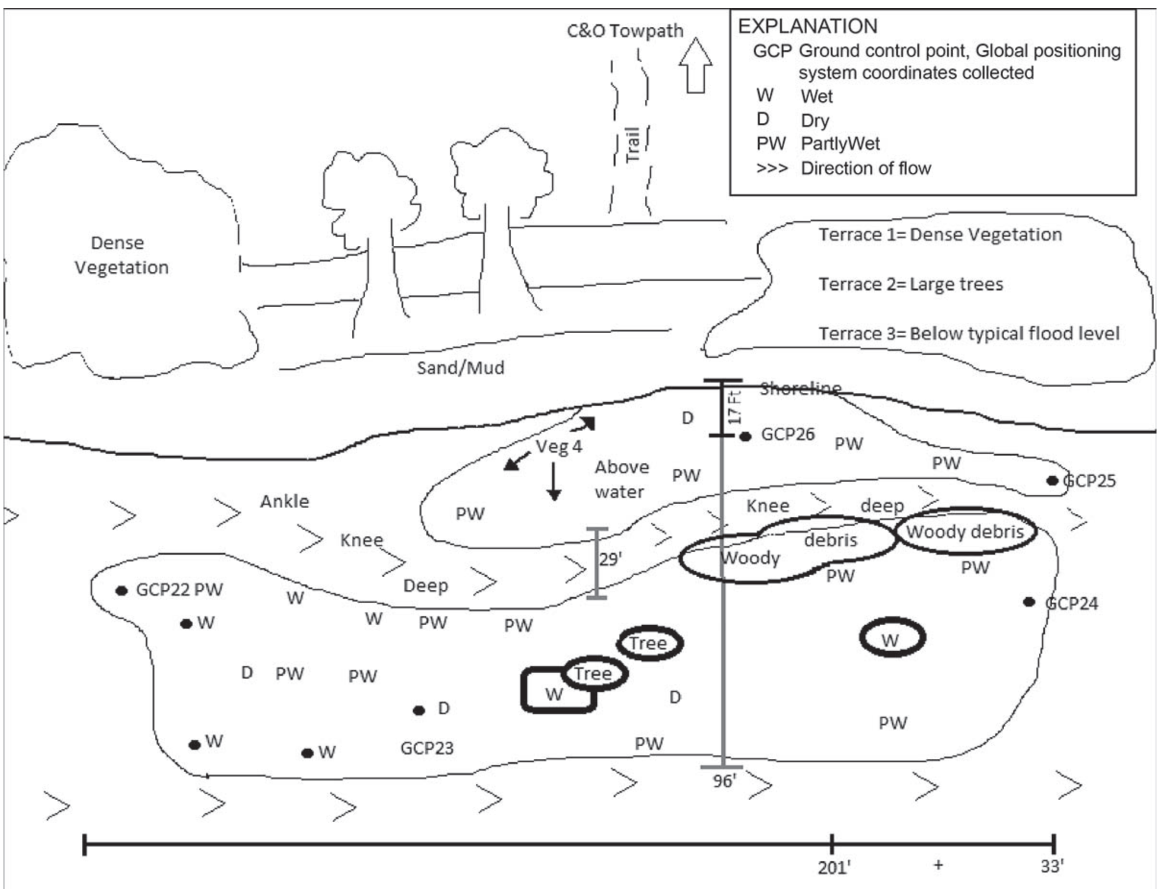

Figure 2.19. Field sketch of site E layout and depth of water at various locations around site. Water depth measurements were not collected using a global positioning system.

Figure 2.20. View looking downstream (east) from the northern bank of site E. A low-lying, in-channel bar is visible mostly above the water's surface. Photograph by Jessica DeWitt, U.S. Geological Survey.

Figure 2.21. Gravelometer and RTK GPS instrument at site E. Photograph by Jessica DeWitt, U.S. Geological Survey.

Site F

Site F is immediately adjacent to the boat ramp at Hancock, Md. It was accessed from the river's edge next to the boat ramp on the morning of June 7, 2019. The weather at the time of observation was mostly overcast but dry. Figure 2.22 shows a field sketch of the in-channel bar layout at site F.

Figure 2.23 shows much of the extent of the in-channel bar, which was submerged or partly submerged in most areas. Like site E, the particle size was smaller than that at site A, with an average size classification of coarse sand and a maximum grain size of very coarse gravel. The minimum grain size observed was very fine sand. Owing to submersion of the bar, soil measurements (that is, pH, moisture, temperature, depth, and sunlight) could not be made. Multiple types of vegetation were observed and sampled from the bar and the riverbank. A second in-channel bar was visible on the other side of the river (fig. 2.24) but could not be accessed from the Hancock, Md., side.

Site G

Site G is approximately 2.75 km (1.7 mi) east-southeast of Hancock, Md., adjacent to the C&O Canal Lock 52. It was accessed in the early afternoon of June 7, 2019. The C&O Canal National Historic Park Visitor's Center is just east of the site, near the entrance of major tributary Tonoloway Creek. Like site A, site G was found to be a sidebar extension of the riverbank. However, the microtopography of the site (visible in fig. 2.25) indicates that at higher river heights, water cuts between the bar and the riverbank creating an in-channel bar. The sidebar was found to be 138 m (452.7 ft) long and part of a series of in-channel bars that extends into the middle of the river. Detailed measurements of the site were not made because of deteriorating weather conditions, but the site was thoroughly photographed (examples found in figs. 2.25 and 2.26). Fully grown vegetative canopy covered much of the site and included Sycamore and other tree species, as well as low-growing herbaceous vegetation and grasses. Extensive woody debris was observed throughout the site.

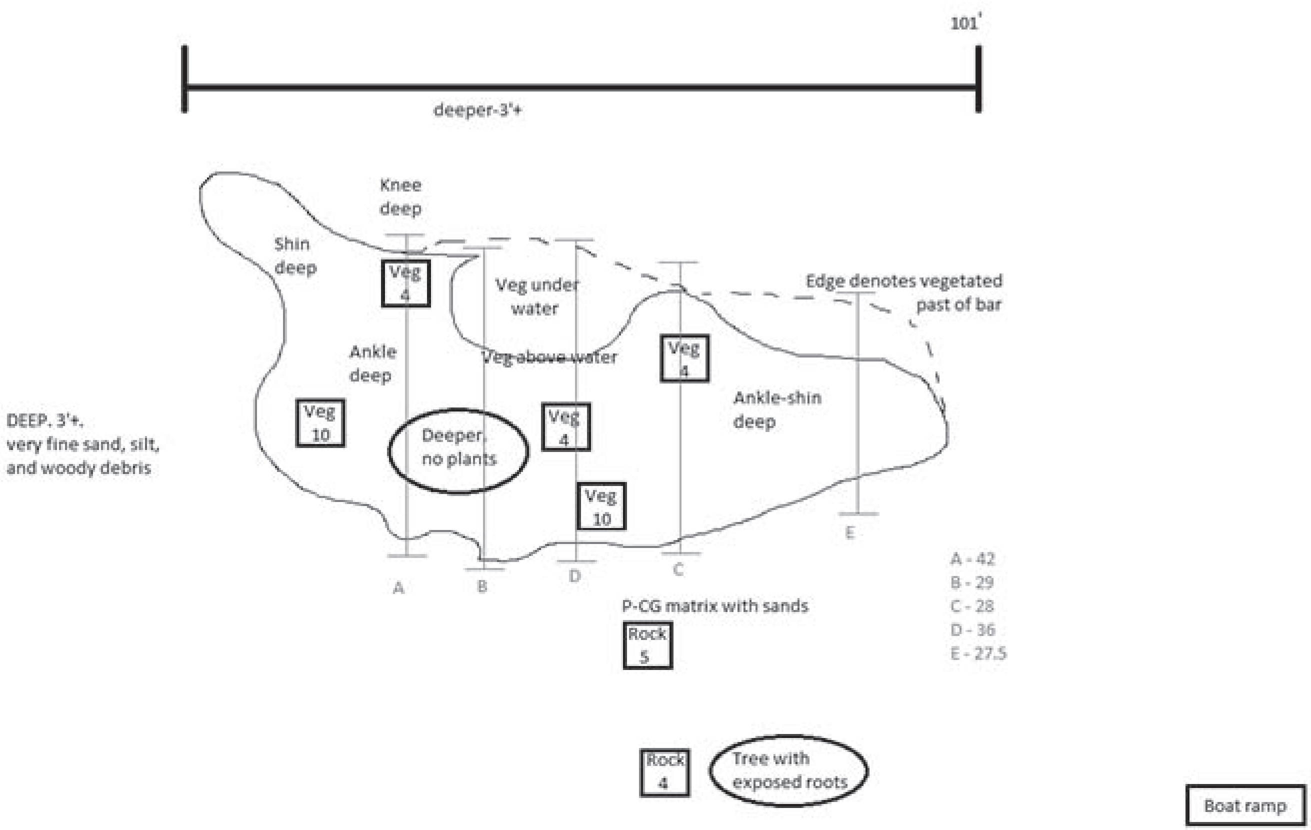

Figure 2.22. Field sketch of site F layout and depth of water at various locations around site. Water depth measurements were not made using a global positioning system.

Figure 2.23. In-channel bar(s) at site F almost completely submerged in 2.54 centimeters (1 inch) to 25.4 centimeters (10 inches) water. View looking toward the northern bank of the stream. Photograph by Jessica DeWitt, U.S. Geological Survey.

Figure 2.24. View looking to the south across the river to other in-channel bars from site F. Photograph by Jessica DeWitt, U.S. Geological Survey.

Figure 2.25. Microtopography of site G indicates that at low flow the bar becomes a sidebar extension of the riverbank. View looking towards the western bank of the river. Photograph by Jessica DeWitt, U.S. Geological Survey.

Figure 2.26. Site G near C&O Canal Lock 52. The photograph view shows the entrance of Tonoloway Creek into the Potomac River. View looking east across the Potomac River. Photograph by Kelsey O'Pry, Natural Systems Analysts, Inc., under contract to the U.S. Geological Survey.

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U.S. Geological Survey, 2017, USGS water data for the Nation: National Water Information System; web interface, accessed November 17, 2017, at https://waterdata.usgs.gov/nwis.

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