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Development of a Habitat Suitability Index for the Eastern Oyster (Crassostrea virginica) in Great Wicomico River, Virginia

Seth Joseph Theuerkauf
College of William and Mary

Development of a Habitat Suitability Index for the Eastern Oyster (*Crassostrea virginica*) in Great Wicomico River, Virginia

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by

Seth Joseph Theuerkauf

Accepted for Honors

Dr. Matthias Leu, Co-Chair

Dr. Romuald Lipcius, Co-Chair

Dr. Jonathan Allen

Dr. Sarah Glaser

Williamsburg, VA
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ABSTRACT

The eastern oyster, *Crassostrea virginica*, provides critical ecological functions to Chesapeake Bay. Unfortunately, as a result of overharvesting, disease, and poor water quality, the native oyster population of the Bay currently stands at less than 1% of its historic size. Within the Great Wicomico River, a tributary of the Bay, the United States Army Corps of Engineers (USACE) Norfolk District has successfully restored approximately 85 acres of "no take" sanctuary oyster reef. This study developed a habitat suitability index (HSI) for the eastern oyster in the Great Wicomico River in order to identify areas of suitable oyster habitat. The model was validated using live adult oyster density data derived from the 2011 VIMS monitoring survey of the USACE restored reefs. The results from this model can be used to inform the rehabilitation of the existing sanctuary oyster reef network and the construction of additional oyster reef in the Great Wicomico River.

INTRODUCTION

The Chesapeake Bay's native eastern oyster, *Crassostrea virginica*, is an ecosystem engineer that performs critical ecological functions, including water filtration, sediment stabilization, and provision of habitat for a diversity of estuarine species (Grabowksi and Peterson, 2007). Naturally, these sessile, bivalve mollusks form three-dimensional reefs composed of stratified layers of oysters. As water temperatures rise to above 20°C, adult oysters broadcast spawn eggs and sperm into the water column (Kennedy et al., 1996). If an egg is successfully fertilized, it can develop in the upper surface of the water column as a free-swimming, planktonic larva. Though oyster larvae are free-swimming, they are subject to local hydrodynamic conditions and can be dispersed hundreds of kilometers from their reef of origin (North et al., 2008). After approximately two weeks, oyster larvae begin settling towards the benthos and use chemical cues from other living oysters to determine where to permanently adhere (Kennedy et al., 1996). Through this process, eastern oysters form reef structures that provide valuable benthic habitat for many estuarine species (e.g., blue crabs [*Callinectes sapidus*], mud crabs [*Panopeus herbstii*], oyster toadfish [*Opsanus tau*]).

Prior to the European colonization of North America, the native oyster population of Chesapeake Bay was described as being so abundant throughout the Bay and its tributaries that they posed a navigational hazard to ships (Kennedy et al., 1996). As a result of overharvesting and the destructive fishing practices that removed the shell material required for reef persistence, oyster fishery landings steadily declined from the mid-1890s until the 1950s. During the late-1940s and 1950s, two major protozoan, endoparasitic oyster diseases, *Haplosporidium nelsoni* and *Perkinsus marinus* were introduced into Chesapeake Bay and further decimated the Bay's oyster populations (Carnegie and Burreson, 2011). Additionally, human activity within the

Chesapeake Bay watershed led to excessive nutrient and sediment loading of the Bay's waters which reduced the Bay's water quality (Boesch et al., 2001). As a result of overharvesting, destructive fishing practices, disease, and poor water quality, the native oyster population of the Chesapeake Bay currently stands at less than 1% of its historic population size (Schulte et al., 2009).

State and federal shell subsidies were established during the early 20th century to restore oyster populations (Burke, 2010). These shell subsidy programs provide state and federal funding for the purchase and placement of shell throughout the Bay in attempts to restore oyster populations for both fishery and ecological purposes (Lipcius et al., 2010). These efforts have generally failed to restore oyster populations due to persistent fishery pressure and poor planning resulting in inappropriate reef location, scale of restoration efforts, and restored reef height (Schulte et al., 2009).

In 2004, the U.S. Army Corps of Engineers (USACE) Norfolk District, in conjunction with the Virginia Institute of Marine Science (VIMS) and other federal and state agencies, constructed nearly 85 acres (equal to 40% of the river's historic oyster habitat) of "no take" sanctuary oyster reef habitat in the severely degraded Great Wicomico River, a tributary of the Chesapeake Bay in Virginia (Figure 1; Schulte et al., 2009). The Great Wicomico River was selected for oyster restoration because it is a "trap" estuary where hydrodynamic conditions promote the circulation of larvae generated by the spawning of oysters living within the river's reef network (Schulte et al., 2009). During the planning phase, researchers utilized maps of historic oyster reef locations and hydrodynamic models to identify potential locations in the river for oyster reef placement and stock enhancement. They focused largely on reestablishing the historic population through the development of a network of oyster reefs that would produce sufficient oyster larvae to replenish the constructed reefs and to be carried by currents to other locations in the river (Lipcius et al., 2008). Once these oyster larvae reach a location with suitable existing reef material, they settle and can begin to colonize the location (known as recruitment), thereby increasing the total oyster population of the river. In addition to the enhanced planning of these restoration efforts, restored reefs were also built taller (known as high-relief reef; HRR) and encompassed a larger area than previous efforts (Schulte et al., 2009). As a result of the improved planning and construction, these sanctuary reefs, where no harvest is allowed, are currently thriving and supplying larval oysters to other non-restored locations throughout the river (Schulte et al., 2009).

As hydrodynamic models only utilize water flow data, a location that the model shows may be receiving a large volume of larvae may in fact be unsuitable due to any of a number of environmental or physical variables, such as low dissolved oxygen levels, absence of suitable reef material, or high sedimentation rates (Battista, 1998). To properly identify suitable oyster habitat, environmental and physical factors controlling the distribution of oyster populations must be determined, reclassified according to physiological tolerances, and analyzed through development of a habitat suitability index (HSI) within a Geographic Information System (GIS) (Figure 2). Once areas of suitable oyster habit (i.e., areas of restoration and conservation interest) have been identified through development of the HSI, this information can be integrated with information derived from other tools (i.e., hydrodynamic models, Marxan conservation planning models, etc.) to determine optimal sanctuary reef reserve designs.

Cake (1983) developed the first two HSIs for the eastern oyster in Galveston Bay, Texas. HSI1 was composed of six biotic and abiotic variables: percent of bottom covered with suitable oyster reef material, mean summer water salinity, mean abundance of living oysters, historic mean water salinity, frequency of killing floods, and substrate firmness. HSI2 was composed of the previous six variables and also the abundance of the southern oyster drill (*Thais haemostoma*) and the intensity of the oyster pathogen *Perkinsus marinus*. Soniat and Brody (1988) field validated each Cake (1983) HSI with the same oyster density information used in HSI development. They tested the hypothesis that the output of each HSI was correlated with oyster density and identified a significant correlation between HSI1 and oyster density (r^2 = 0.674, p <0.001, n = 38). As oyster density data were utilized in the development of the HSI, Soniat and Brody (1988) were unable to utilize a fully independent dataset to validate the model output.

Brown and Hartwick (1988) developed a HSI for the Pacific oyster (*Crassostrea gigas*) along the coasts of Vancouver Island and mainland British Columbia, Canada based on the following datasets: water temperature, available food, suspended sediment concentration, water movement, disease, fouling organism density, predator density, salinity, dissolved oxygen concentration, and pH. The HSI was field validated at 10 sites within the study area and significantly correlated with oyster growth rates (r^2 = 0.88, p <0.001), but not survival.

Additional HSIs have been developed for the eastern oyster in the Hudson River, New York (Starke et al., 2011), the Maryland main stem portion of Chesapeake Bay (Battista, 1998), the Caloosahatchee Estuary, Florida (Barnes et al., 2007), and the Mission-Aransas Estuary, Texas (Pollack et al., 2012). No recent studies have validated HSI output with an independent demographic dataset. Additionally, no studies have utilized high-resolution spatial data in the model development process.

This study focused on the development and validation of a high-resolution HSI for the eastern oyster in the Great Wicomico River. This HSI incorporated seabottom type, water depth, and salinity variables to determine the relative suitability of specific areas within the river to host oyster populations. Adult oyster densities (m^{-2}) derived from the 2011 Great Wicomico River reef monitoring were plotted against the HSI values associated with each sampling point to test the hypothesis that HSI values were correlated with oyster densities. This model is intended to aid the identification of suitable areas for both the rehabilitation of the existing sanctuary oyster reef network and the construction of additional oyster reef in the Great Wicomico River.

METHODS

Index development

This study developed an HSI for the eastern oyster in the Great Wicomico River, Virginia. The Great Wicomico River is located approximately 10 km south of the Potomac River and approximately 25 km north of the Rappahannock River (Figure 3). This study defined the Great Wicomico River as beginning at its forked headwaters and ending where Crane's Creek and Ingram Bay converge (Figure 4). This HSI utilized modified methods developed by the U.S. Fish and Wildlife Service for *C. virginica* in the Gulf of Mexico (Cake, 1983) and the University of Maryland at College Park for *C. virginica* in the northern Chesapeake Bay (Battista, 1998). This HSI was developed in ArcGIS 10.1 (ESRI, 2011).

At the 2010 Chesapeake Research Consortium (CRC) Virginia Oyster Restoration Review workshop, oyster restoration researchers collectively stated that geo-referencing seabottom types and mapping water depth were some of the most important practices for oyster restoration projects, prior to site selection for restoration to increase the likelihood of successful oyster growth and recruitment in Chesapeake Bay (Sellner, 2010). Thus, this HSI utilized the following spatially explicit environmental and physical variable layers: seabottom type, depth, and salinity. Seabottom type was included in this study as oyster reefs constructed on sand, rock or oyster shell seabottom types are less likely to subside and degrade than those built on mud or silt seabottom (Burke, 2010). Depth was included as oyster density and recruitment data derived from previous VIMS monitoring surveys of the USACE constructed oyster reefs in the Great Wicomico River indicated that depths less than 12 ft (4 m) had high dissolved oxygen (DO) levels, depths between 12 ft and 15 ft (4-5 m) had DO levels between 0 and 6 mg/L, and depths greater than 15 ft (5 m) were anoxic during neap tides in the summer (R. Lipcius, unpublished data). These general trends appear to be due to seasonal anoxia and hypoxia events induced by bacterial decomposition of phytoplankton and subsequent stratification of the water column. Salinity was included as the eastern oyster cannot tolerate extremely low or high salinities for long periods, and prefer upper mesohaline to polyhaline salinities (Barnes et al., 2007; Carnegie and Burreson, 2011; Battista, 1998). Other environmental variables that have been included in previous HSIs developed for the eastern oyster, such as temperature, chlorophyll concentration, disease intensity, and total suspended solids (Battista, 1998; Cake, 1983), were not included in this index due to the lack of available spatial data.

Seabottom type data were derived from multiple sources including: 1) a 2009 NOAA acoustic seabed mapping survey (1 m x 1 m resolution), and 2) field notes taken by VIMS researchers during the 2012 reef monitoring sampling of the USACE reefs (Bruce et al., 2010). Seabottom type data derived from the 2009 NOAA acoustic seabed mapping survey included the majority of downriver seabottom, but excluded inshore areas shallower than 2 m due to the inability of the research vessel to navigate shallow waters (Bruce et al., 2010). Seabottom type data derived from field notes (approximately 40 points per reef) were imported into ArcGIS (ESRI, 2011) as point data and were subsequently used along with the seabottom type data derived from the 2009 NOAA acoustic seabed mapping survey to delineate seabottom type contours. Seabottom type information derived from the 2009 NOAA acoustic seabed mapping survey was utilized for the areas outside of the USACE constructed oyster reef polygons, while seabottom type information from the field sampling notes taken by VIMS researchers was also utilized for the areas within the USACE constructed oyster reef polygons. This provided a baseline (i.e., pre-construction) seabottom type dataset for integration into the HSI. This baseline seabottom type dataset was necessary as some of the reefs within the sanctuary reef network were originally constructed on unsuitable seabottom and have degraded since the 2009 NOAA acoustic seabed mapping survey (R. Lipcius, pers. comm.).

Mean bottom salinity data were derived from a VIMS hydrodynamic model (J. Shen, unpublished data). Salinity data were imported into ArcGIS (ESRI, 2011) as point data, and were subsequently interpolated using inverse distance weighting to produce a raster grid (1 m x 1 m resolution). Bathymetric data were derived from a NOAA bathymetric digital elevation model of the Chesapeake Bay (1 m x 1 m resolution) (Bruce et al., 2010).

Within ArcGIS (ESRI, 2011), each input variable layer was assigned suitability index values based on physiological tolerance ranges available in the literature, or from on-going research of the USACE reefs in the Great Wicomico River (Figures 5, 6, 7, and 8). Data cells within each input variable layer were classified on a gradient between 0, indicating highly unsuitable habitat, and 1, indicating highly suitable habitat, with varying degrees of suitability in between. In order to ensure that the HSI would assign a particular location a value of ‘0’ if any single input variable layer had a value of ‘0,’ the geometric mean of each input variable layer was calculated to produce the HSI (Figure 8). Mathematically, the HSI was computed as follows:

$$HSI = \sqrt[3]{BottomType * Depth * Salinity}$$

Using the Spatial Analyst toolbar within ArcGIS (ESRI 2011), histograms were generated showing the distribution of habitat suitability values within the seabotttom type, depth, and HSI output layers for the entire Great Wicomico River, the private shellfish aquaculture leases, public oyster harvest (Baylor) grounds, and the USACE restored reefs (Figures 10, 11, and 12).

Index Validation

In Chesapeake Bay, a live adult oyster density of 50 m^{-2} is the target for a restored reef to be considered successful (known as the Sustainable Fisheries Goal Implementation Team of the Chesapeake Bay Program, or "GIT," target) (Oyster Metrics Workgroup, 2011). Thus, live adult oyster density data derived from the 2011 VIMS monitoring survey of the USACE restored reefs in the Great Wicomico River were used to validate the model (Figure 13). Adult oyster densities were plotted against the HSI values associated with each sampling point from the 2011 Great Wicomico River reef monitoring. Sampling points were divided into low- and high-relief reef categories for analysis. Maps were produced showing the output of the HSI, the live adult oyster densities associated with each sampling point from the 2011 USACE reef monitoring, the distribution of low- and high-relief reef, and the private shellfish aquaculture leases in the Great Wicomico River (Figures 14, 15, 16 and 17).

Results

For high-relief reefs, HSI values ≥ 0.5 exceeded the 50 live adult oysters m^{-2} GIT target (Figure 12; Oyster Metrics Workgroup, 2011). All values, but one, of HSI ≥ 0.3 exceeded the GIT target. For low-relief reefs, the HSI was generally able to predict live adult oyster densities that meet or exceed the GIT target at HSI values ≥ .3 (Figure 13). However, for low-relief reefs, there was more variation between the HSI value and the corresponding live adult oyster density than for high-relief reefs. To maximize the potential for success of oyster reef restoration and rehabilitation, suitable oyster habitat was defined as all areas with an HSI value ≥ 0.5, and marginal oyster habitat was defined as all areas with an HSI value ≥ 0.3.

Suitable oyster habitat

This study identified that approximately 390 ac (157.8 ha) of suitable oyster habitat (e.g., cells with a HSI value between 0.5 and 1.0) occur in the Great Wicomico River (Figure 18). Approximately 6 ac (2.4 ha) of marginally suitable oyster habitat (e.g., cells with an HSI value between 0.3 and 0.5) occur in the Great Wicomico River. Approximately 229 ac (92.7 ha) of suitable oyster habitat lay within private shellfish aquaculture leases, along with approximately 2 ac (0.8 ha) of marginally suitable oyster habitat. Within the 713 ac (288.5 ha) of public oyster harvest (Baylor) grounds, approximately 130 ac (52.6 ha) of suitable oyster habitat and 0 ac of marginally suitable oyster habitat exist. On the USACE high-relief reef, approximately 33 ac (13.4 ha) of suitable oyster habitat and approximately 0.5 ac (0.2 ha) of marginally suitable habitat exist. On the USACE low-relief reef, approximately 24 ac (9.7 ha) of suitable oyster habitat and approximately 0.5 ac (0.2 ha) of marginally suitable oyster habitat exist. It is important to note that, due to the lack of available seabottom type data for shallow areas, the total amount of suitable habitat available in the Great Wicomico River is greater than the amount estimated here. As the majority of shallow areas in the Great Wicomico River are held in the form of private shellfish aquaculture leases, most of this additional suitable habitat is likely contained within the private shellfish aquaculture leases.

DISCUSSION

This HSI provides an assessment of the extent of suitable oyster habitat within the Great Wicomico River. Additionally, the methods utilized in the development of this HSI provide a framework that can be used to develop additional HSIs for other coastal waterways.

Executive Order 13508 and the Development of Success Criteria

In 2009, President Obama implemented Executive Order 13508 (Strategy for Protecting and Restoring the Chesapeake Bay Watershed). One of the key goals of the Executive Order is to restore native oyster populations in 20 tributaries of Chesapeake Bay by 2025. The federal agency entrusted with oyster restoration under the Executive Order is the U.S. Army Corps of Engineers, and the criteria used to define successful restoration (i.e., a live adult oyster density of 50 m^{-2}) are derived from the findings of the Sustainable Fisheries Goal Implementation Team of the Chesapeake Bay Program (Oyster Metrics Workgroup, 2011). The target live adult oyster density of 50 m^{-2} is considered comparable to the mean oyster density in Maryland's waters of Chesapeake Bay 100 years ago.

Relationship between Live Adult Oyster Density and HSI

Rittenhouse et al. (2010) evaluated habitat suitability indices for wood thrush (*Hylocichla mustelina*) and yellow-breasted chat (*Icteria vireos*) using species abundance data. The authors recommended the "validation of HSI models with the particular demographic data of interest (i.e., density, productivity) to increase confidence in the model used for conservation planning." Thus, live adult oyster density data derived from the 2011 VIMS monitoring survey of the USACE restored reefs in the Great Wicomico River were used to validate the model (Figure 13). Division of the analysis of live adult oyster densities and corresponding HSI values into low and high-relief reef categories was necessary as some of the low-relief reefs constructed in the Great Wicomico River had degraded due to sedimentation and subsidence into mud seabottom. Thus, for low-relief reefs, reef persistence depends greatly on whether live oyster shell accretion outpaces subsidence and sedimentation. In several cases, low-relief reefs in the Great Wicomico River with HSI values greater than 0.3 exhibited low adult oyster densities (Figure 13). These low-relief reefs containing suitable oyster habitat should be examined as candidates for rehabilitation to high-relief reefs through the placement of additional shell material on the low-relief sites. The majority of high-relief reefs in the Great Wicomico River have persisted due to the presence of additional shell material that allows live oyster shell accretion to outpace subsidence and sedimentation. It is important to note that one limitation of the live adult oyster density data used to validate the HSI is that samples were only collected from the USACE sanctuary oyster reef network, while the HSI was computed for the entirety of the Great Wicomico River.

Adult live oyster abundance at a particular site and the corresponding HSI value for that site may not be directly related due to additional physical, environmental, and anthropogenic-influenced variables that control habitat suitability. These additional physical and environmental variables may include: water temperature, chlorophyll concentration (surrogate for phytoplankton concentration), pH, DO concentration, population connectivity, frequency of “cold snaps” that may kill intertidal oysters on hardened shorelines, and a variable depth trend along the length of the river (i.e., waters > 15 ft (3 m) depth near a river’s mouth may remain well oxygenated due to enhanced tidal flushing). Additional anthropogenic-influenced variables may include: probability of juvenile oyster mortality due to a freshwater influx event (a function of adjacent land use), probability of a pollution event, probability of a sanctuary reef poaching event, and likelihood of sanctuary reef enforcement success.

This HSI was computed with equal weighting of each variable. However, it is likely that certain variables may more heavily influence habitat suitability than others. It is also possible that certain variables, such as salinity and temperature, may interact to determine oyster habitat suitability. Additional analyses of models composed of the various possible variables that could be utilized in the HSI, coupled with sensitivity analyses of the various possible variables, should be conducted to ensure the addition of variables would not reduce the model’s strength.

Separating Ecological Restoration from Fishery Enhancement

Native oysters provide economic, ecosystem, and intrinsic (non-use) values to humans living within the region surrounding Chesapeake Bay. Economically, oysters provide a direct benefit through the commercial fishery and growing aquaculture industry (Lipton et al., 2006). Oysters also provide an ecosystem value through the enhancement of fish production (i.e., secondary production), water filtration, and the production of oyster larvae that can disperse, settle, and grow on substrate contained on public oyster harvest grounds or private oyster aquaculture leases associated with oyster reef structures (Peterson et al., 2003; Lipton et al., 2006). Intrinsically, the sanctuary oyster reef structures and the oysters living on them have non-use value as a symbol of a pristine Chesapeake Bay.

Unsuccessful efforts to restore the Chesapeake Bay's native oyster have attempted to simultaneously achieve ecological and fishery goals. Mann (2000) detailed the need to separate ecological and fishery goals, stating that self-sustaining oyster populations (and their associated ecosystem services) capable of supporting a high level of fishing pressure would be an unreasonable goal. Thus, the existence of separate areas within the Chesapeake Bay and its tributaries to be reserved as sanctuary oyster reef networks, public oyster harvest grounds, and private oyster aquaculture leases should be a goal of resource managers to maximize the diverse values associated with the native oyster.

Garnering Public and Political Support for Ecological Restoration

Despite the apparent benefits associated with sanctuary oyster reef networks, political support for these protected areas remains weak while public support is on the upswing. Public and political support could be strengthened through media campaigns aimed at disseminating information to the general public about how sanctuary oyster reef networks are essential to restoring the health of the Chesapeake Bay and are economically useful through producing oyster larvae that can disperse, settle, and grow on substrate contained on public oyster harvest grounds or private oyster aquaculture leases. Mann (2000) describes the significance of recruiting, educating, and involving citizens residing within the Chesapeake Bay watershed to "support such efforts on a long-term basis." Additionally, through utilization of Marxan conservation planning software, all stakeholders (e.g., Virginia Marine Resources Commission, USACE, VIMS, watermen, oyster aquaculturists) can collaborate to select the best sanctuary reef reserve design that meets minimum ecological targets while minimizing relative social, economic, and ecological costs.

Enforcement and Protection of Sanctuary Oyster Reef Networks

Enforcement and protection of marine protected areas (MPAs) has historically been difficult and contentious (Mascia, 2003). In coral reef ecosystems, research has identified that MPA success or failure is often largely dependent on social factors and not biological or physical variables. Thus, sufficient enforcement and public support for the protection of sanctuary oyster reef networks is required to ensure their success (defined as their ability to retain self-sustaining oyster populations). During the 2012 VIMS monitoring sampling of the USACE sanctuary oyster reefs in the Great Wicomico River, VIMS researchers noted that some of the reefs appeared to have been “poached” (i.e., an absence of large adult oysters and “clusters” of oysters, and the presence of pulverized shell fragments) (Figure 19; R. Lipcius, pers. comm.). These “poached” sanctuary reefs may have been purposefully or accidentally dredged as they are unmarked and are often adjacent to private shellfish aquaculture leases. These “poached” reef locations may explain the presence of adjacent low and high oyster densities in certain areas (Figure 14). Oyster restoration researchers at the USACE have considered integrating alternative three-dimensional structures (e.g., oyster reef balls, oyster castles) into restored reefs as “anti-poaching devices” to prevent dredging. Enhanced public support for sanctuary oyster reef networks, integration of “anti-poaching devices,” sufficient sanctuary oyster reef marking, and marine police presence would likely reduce the prevalence of poaching and would enhance the success of sanctuary oyster reef networks.

Oyster Aquaculture: A Potential Use Conflict for Seabottom in the Great Wicomico River

Through the Virginia Marine Resources Commission, public seabottom can be allotted to private individuals in the form of private shellfish aquaculture leases. The permitting process associated with private shellfish aquaculture leases is intended to "help us [VMRC] ensure fair use of the public water bottoms, reduce potential user conflicts, head off navigation issues, limit the chance contaminated shellfish are mistakenly taken from condemned waterways, and preserve underwater grasses that shelter juvenile fish and crabs from predators" ("Shellfish Aquaculture, Farming, and Gardening," 2012). In the Great Wicomico River, private shellfish aquaculture leases are primarily held for oyster aquaculture in the form of off-seabottom cages or floats and spat-on-shell (Figure 20, R. Lipcius, pers. comm.). Within the Great Wicomico River, approximately 1,489 ac (602.6 ha) of seabottom are held in private aquaculture leases. This equates to approximately 36% of the available seabottom in the Great Wicomico River, which contains a total of approximately 4,151 ac (1,679.9 ha) of seabottom.

Submerged aquatic vegetation (SAV) is a critical shallow water component of the Chesapeake Bay ecosystem through its high primary productivity, nutrient buffering capacity, provision of food to waterfowl, and provision of habitat for blue crabs (*Callinectes sapidus*), juvenile rockfish (*Morone saxatilis*), and other aquatic species (Orth and Moore, 1984). This study utilized the most recent 2010 SAV coverage information for the Great Wicomico River to visualize the relationship between suitable oyster habitat and SAV distribution. The distribution of SAV in the Great Wicomico River in 2010 represented the highest abundance of SAV from all available datasets. Although the exact location of SAV beds varies yearly, the 2010 SAV coverage information accounts for nearly all locations within which SAV has been distributed since 2000 ("SAV in Chesapeake Bay," 2012). Within the Great Wicomico River in 2010, SAV occupied approximately 311 ac (125.9 ha) of seabottom.

During the development of this study's HSI and the inspection of the various GIS datasets available for the Great Wicomico River, it was identified that, of the approximately 311 ac (125.9 ha) of submerged aquatic vegetation (SAV) that occurred in the Great Wicomico River in 2010, approximately 147 ac (59.5 ha, 47% of SAV coverage) occurred within private shellfish aquaculture leases (Figure 21, 22). It is important to note, however, that not all of the acreage held in private shellfish aquaculture leases is necessarily utilized for shellfish aquaculture and that the exact distribution of SAV varies yearly. Additionally, the VMRC conducts preliminary survey prior to issuance of a private shellfish aquaculture lease to ensure that the lease does not contain SAV. Regardless, this finding does pose a potential use conflict for seabottom in the Great Wicomico River and elsewhere in the Chesapeake Bay.

Further Research and Suggestions

Integration of robust HSIs into site selection plans for native oyster restoration efforts in Chesapeake Bay and other bodies of water should become common practice. These HSIs should account for and incorporate all relevant and necessary environmental and physical variables controlling the distribution of oysters. The particular variables and reclassification schemes utilized to compute the HSI may vary throughout the geographic range of a particular oyster population or species (e.g., water depth may be a less significant variable in bodies of water where low DO "dead zones" do not exist). Recent and high-resolution datasets should be utilized when developing these indices (i.e., high-resolution seabottom type datasets derived from side-scan sonar and sub-bottom profiling). Other sources of information, such as maps of historic oyster reef locations and hydrodynamic models, should be utilized to determine optimal locations to construct oyster reef. Marxan conservation planning software should also be utilized in developing sanctuary oyster reef networks, including the collaboration with stakeholders to determine optimal sanctuary reef reserve designs that meet minimum ecological targets while minimizing relative social, economic, or ecological cost.

During the spring of 2013, I will continue the development of this HSI for the Great Wicomico River. I will utilize bathymetry and seabottom type data from a 2012 NOAA acoustic seabed mapping survey. The 2012 NOAA survey includes a larger extent of high-resolution data than the 2009 NOAA survey utilized in this study. Adjacent land cover data derived from satellite imagery will be used to calculate a probability of juvenile oyster mortality due to a freshwater influx event layer that will be integrated into the HSI (Figure 23). I also plan to include variable DO versus depth trends depending on location (i.e., upriver versus downriver), and will utilize data derived from a DO versus depth monitoring survey conducted in the Great Wicomico River during the summer of 2012. Additionally, information derived from a hydrodynamic model of the Great Wicomico River will be used to produce a population connectivity layer that will be integrated into the HSI. Further research will determine additional relevant variables that control oyster habitat suitability to include in the HSI. Statistical analyses of potential model variables, along with sensitivity analyses, will be conducted to determine which variables will be included in future iterations of the HSI.

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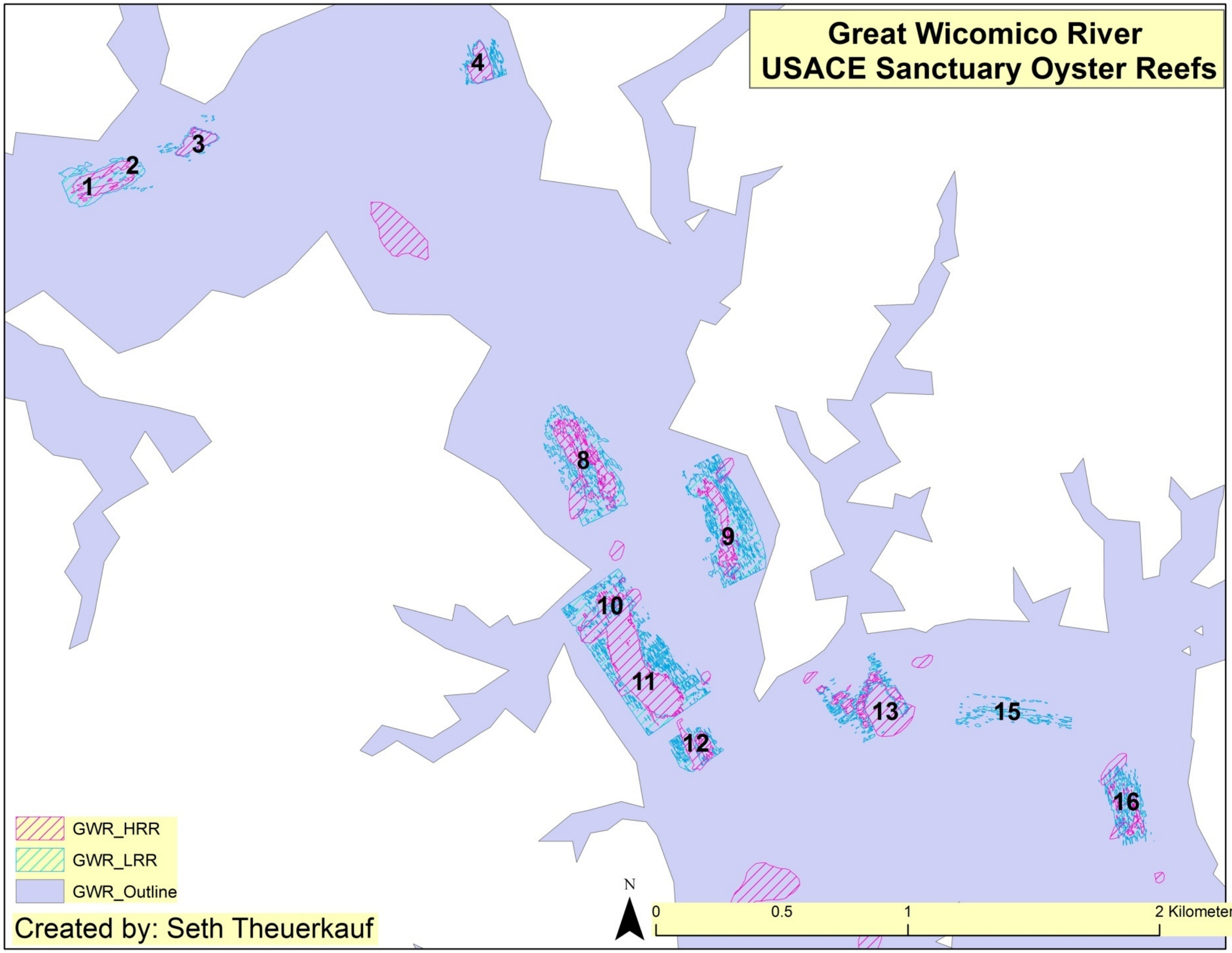


Figure 1: Map showing the distribution of high- and low-relief reefs in the Great Wicomico River; numbered reefs indicate USACE sanctuary reefs (HRR = high-relief reef, LRR = low-relief reef).

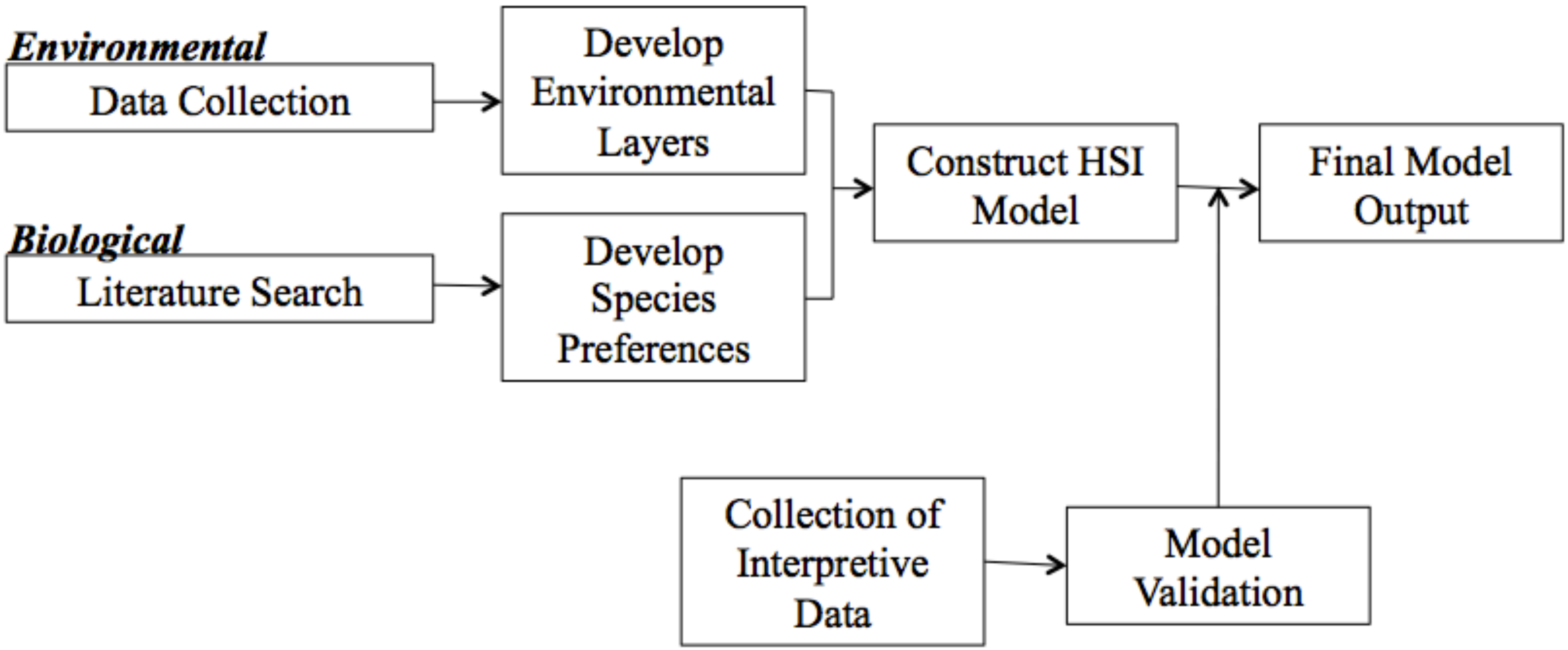


Figure 2: Schematic of the steps involved in the development of a habitat suitability index (Adapted from: Battista, 1998).

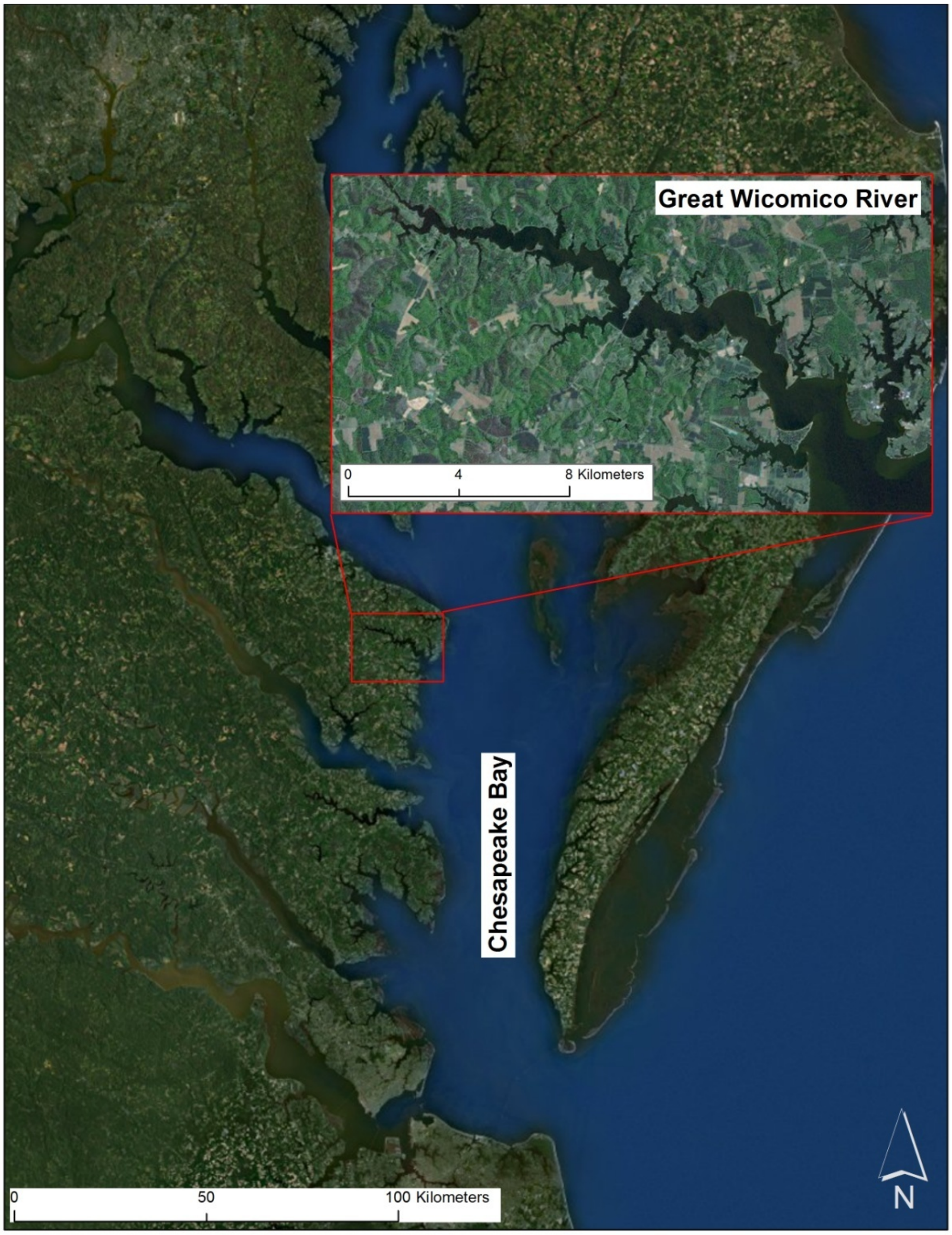


Figure 3: Map showing the location of the Great Wicomico River in relation to Chesapeake Bay.

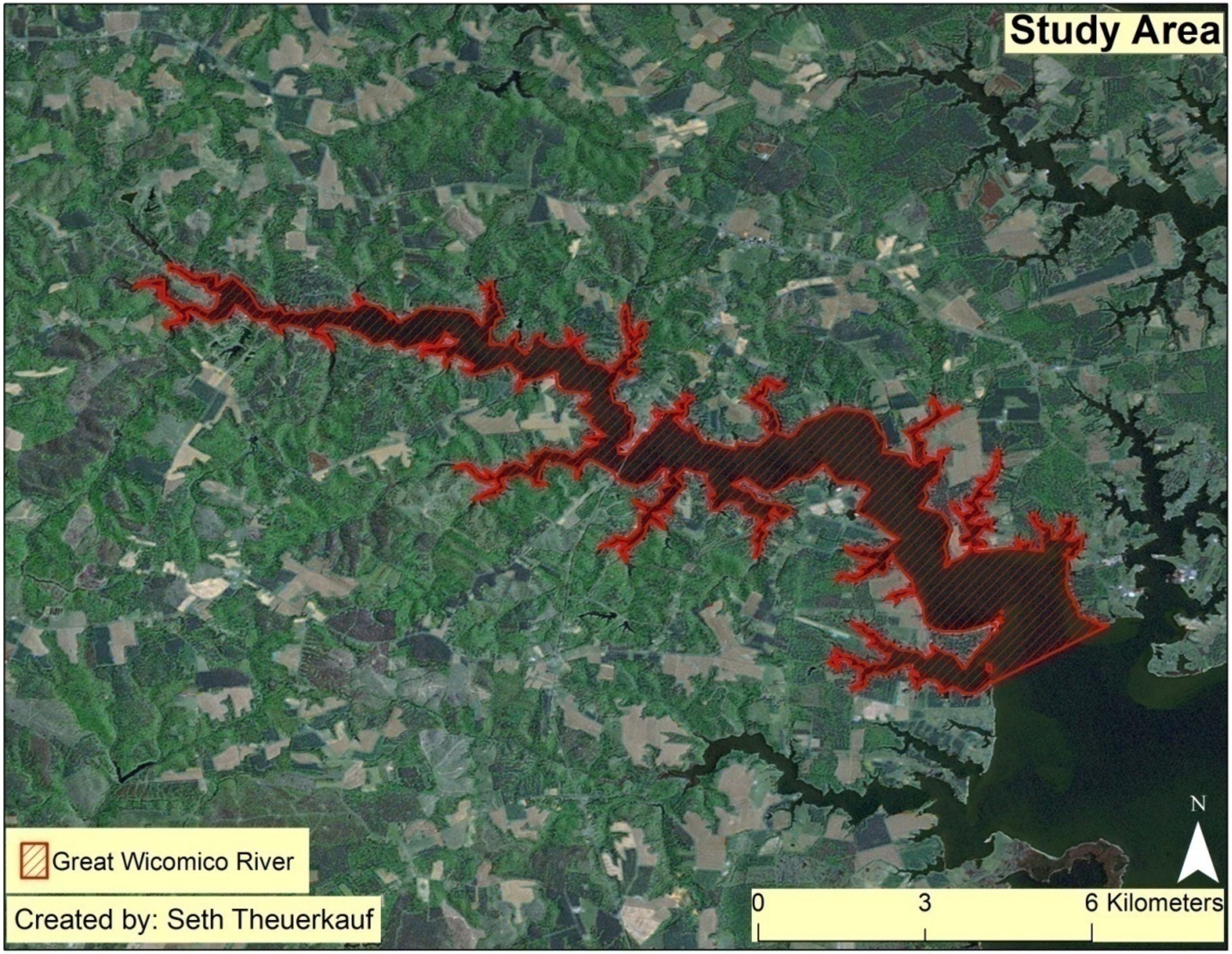


Figure 4: Map showing the extent of the Great Wicomico River.

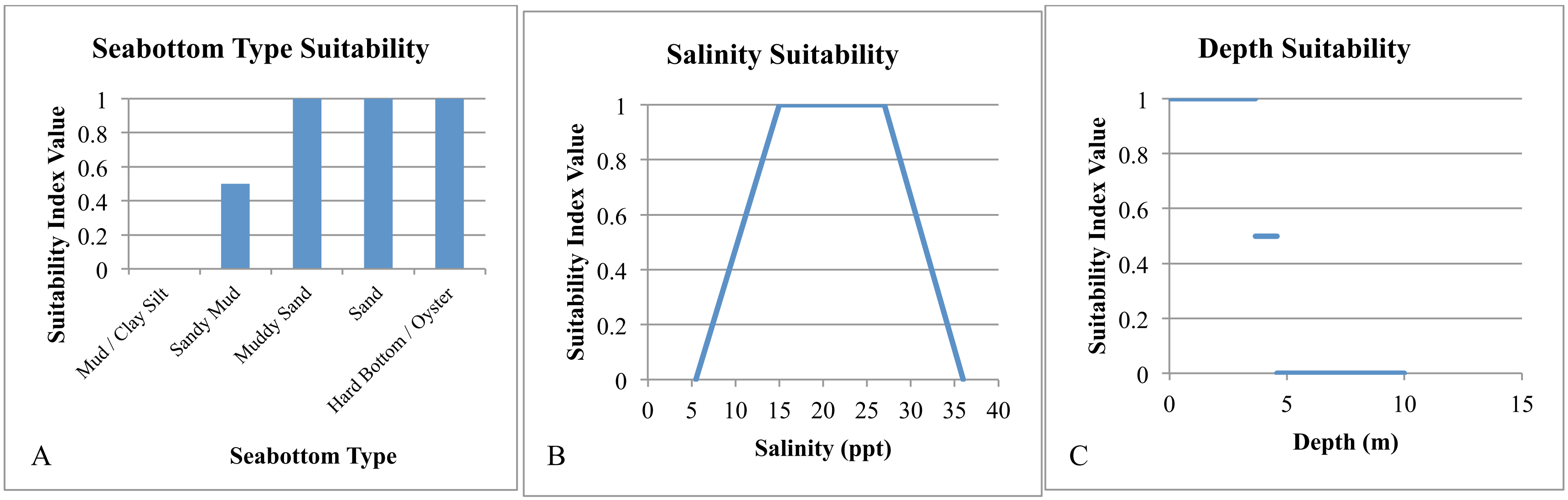


Figure 5: Reclassification schemes for each environmental and physical variable layer included in the HSI (1A: Lipcius et al., 2010; 1B: Barnes et al., 2007, Carnegie and Burreson, 2011, Battista, 1998; 1C: Lipcius pers. comm., 2012, Battista, 1998).

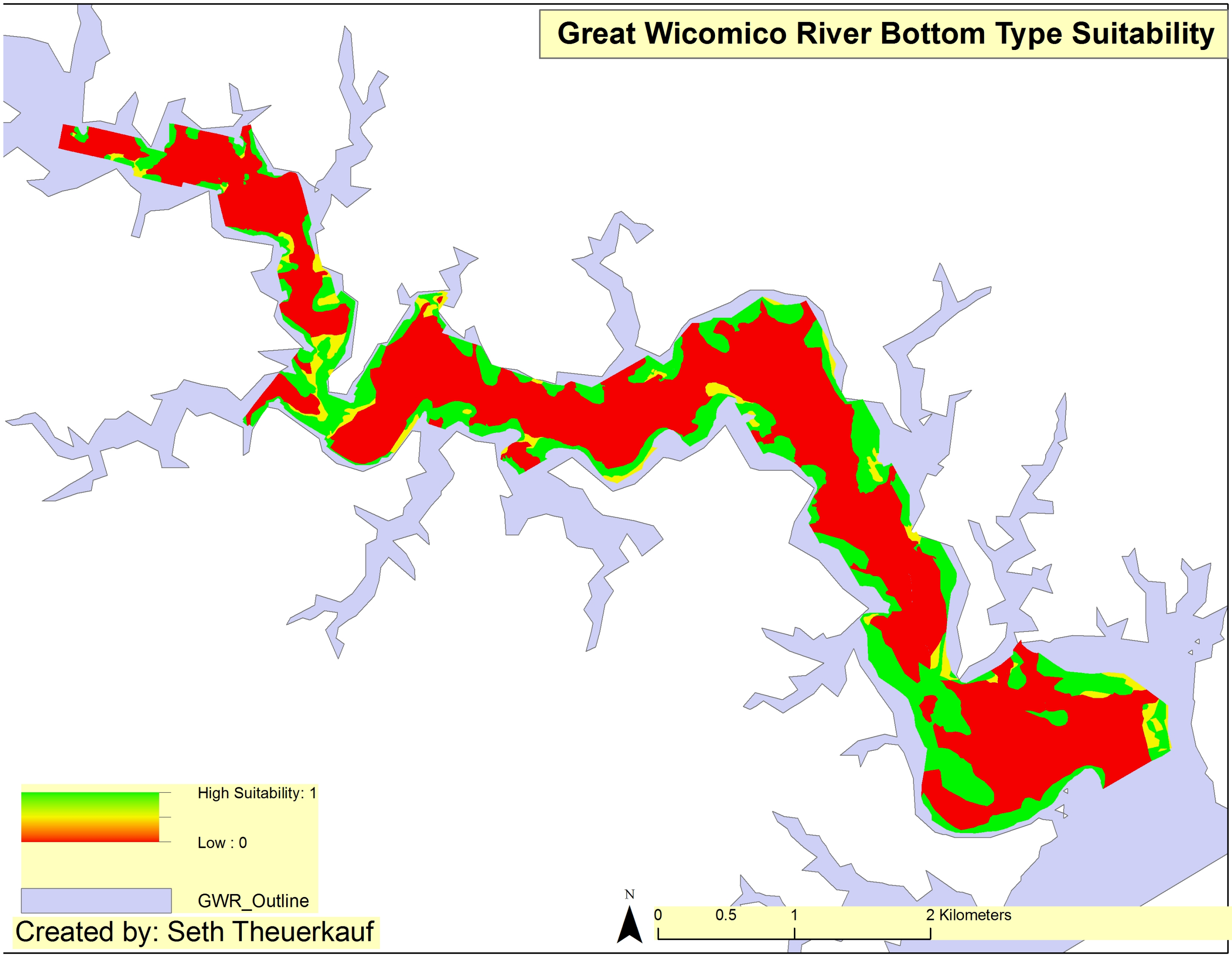


Figure 6: Seabottom suitability map.

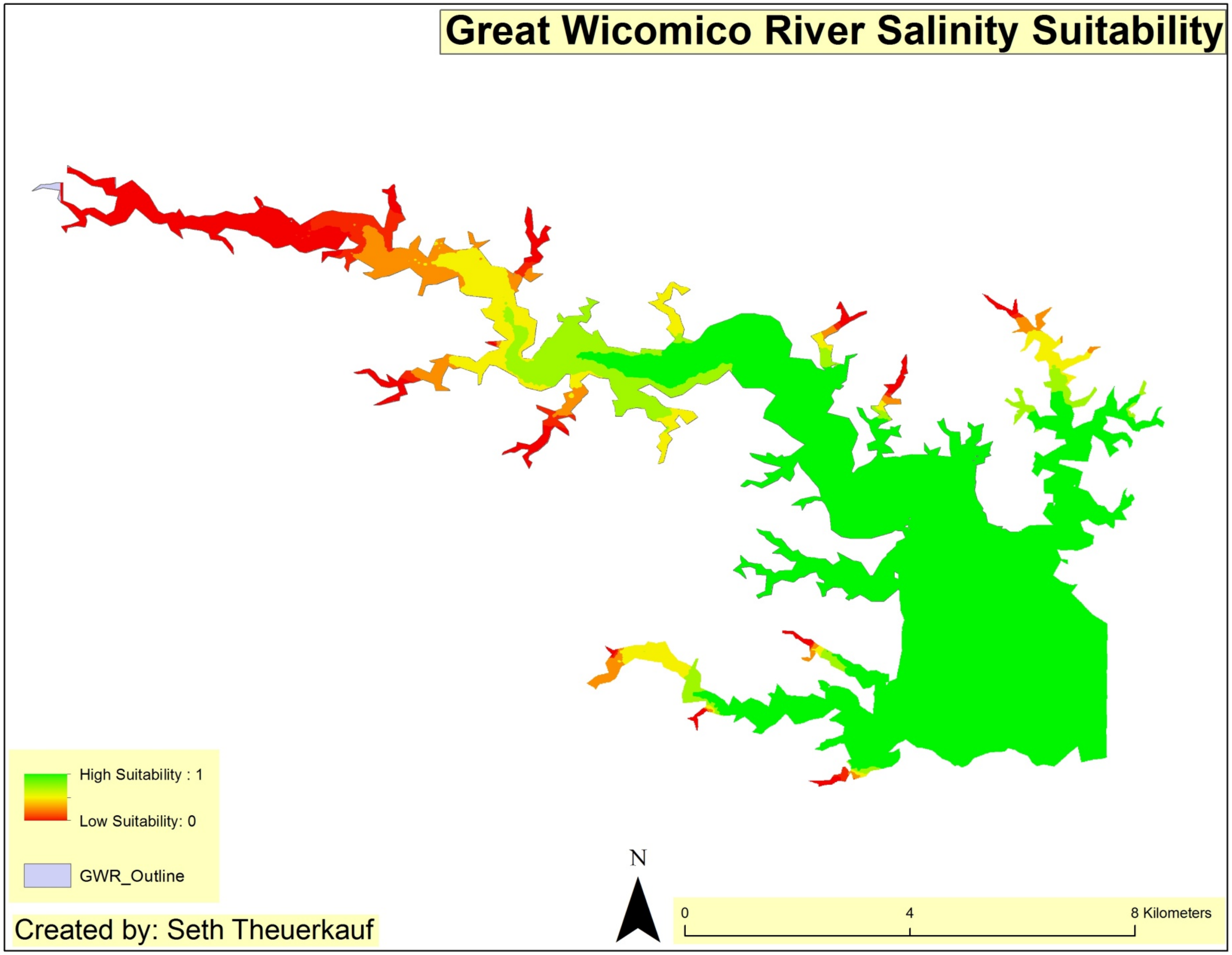


Figure 7: Salinity suitability map.

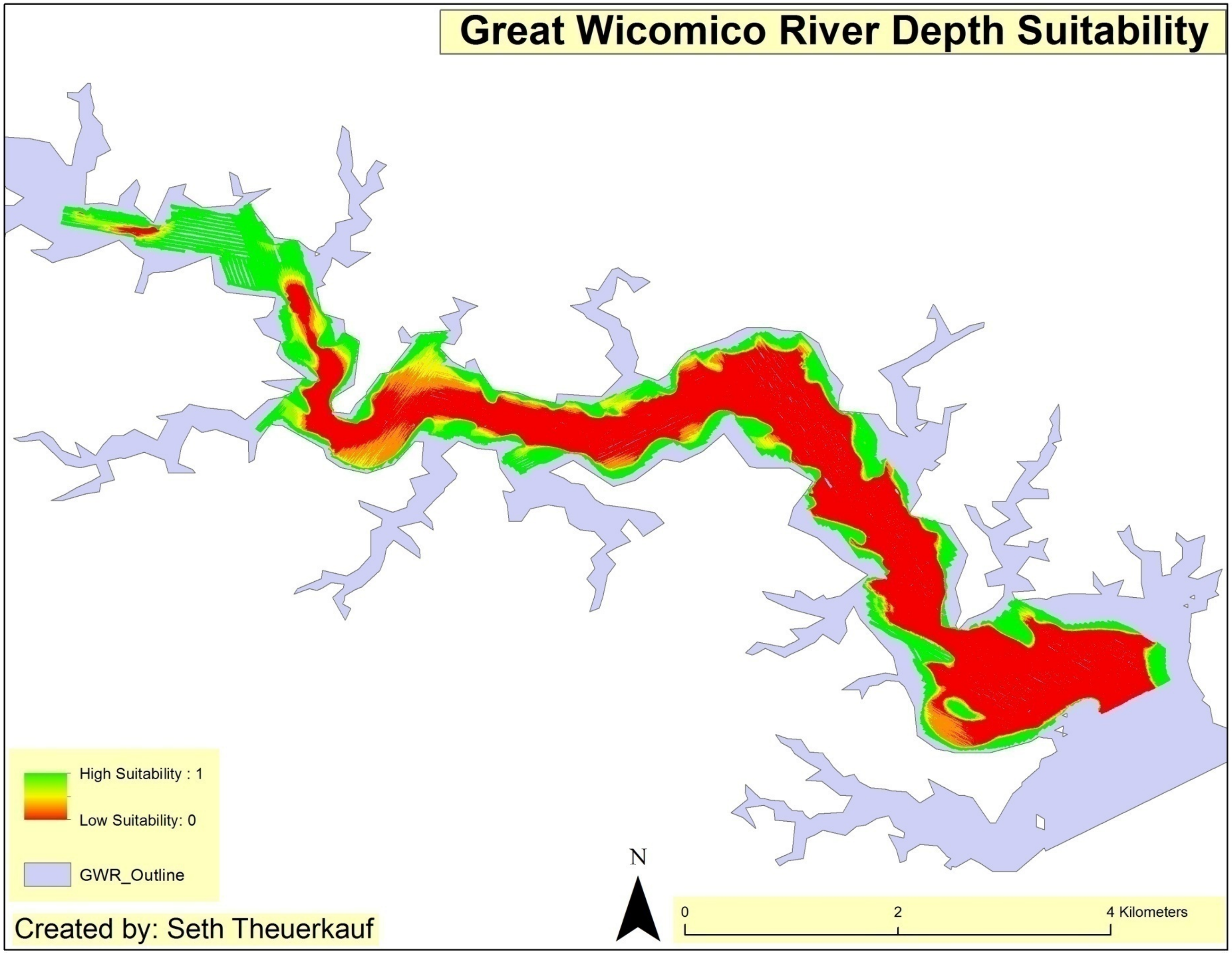


Figure 8: Depth suitability map. Lines in the map are due to holes in the dataset caused by a lack of overlap between transects of the side-scan sonar tows that were used to generate the dataset.

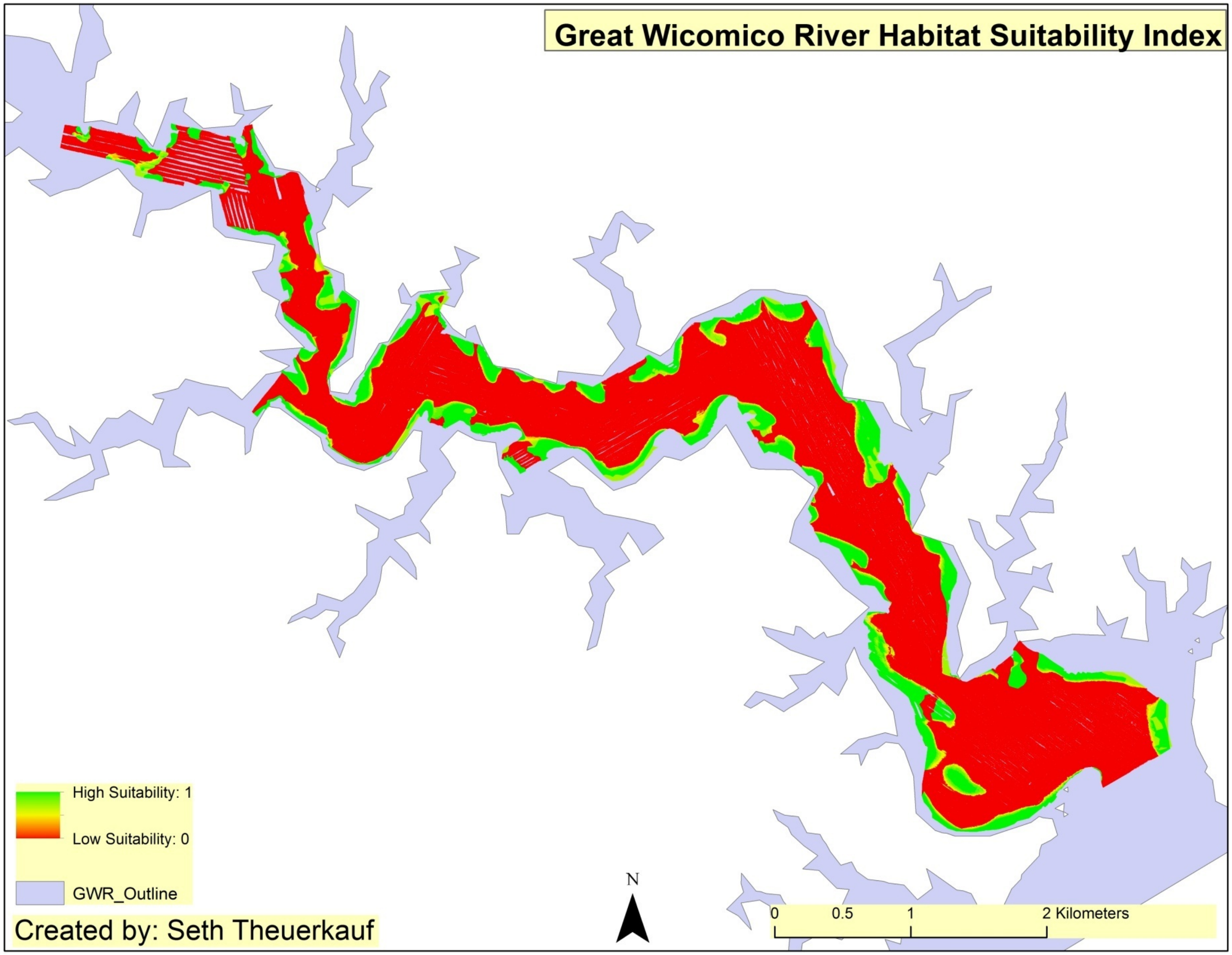


Figure 9: Map of the output of the HSI.

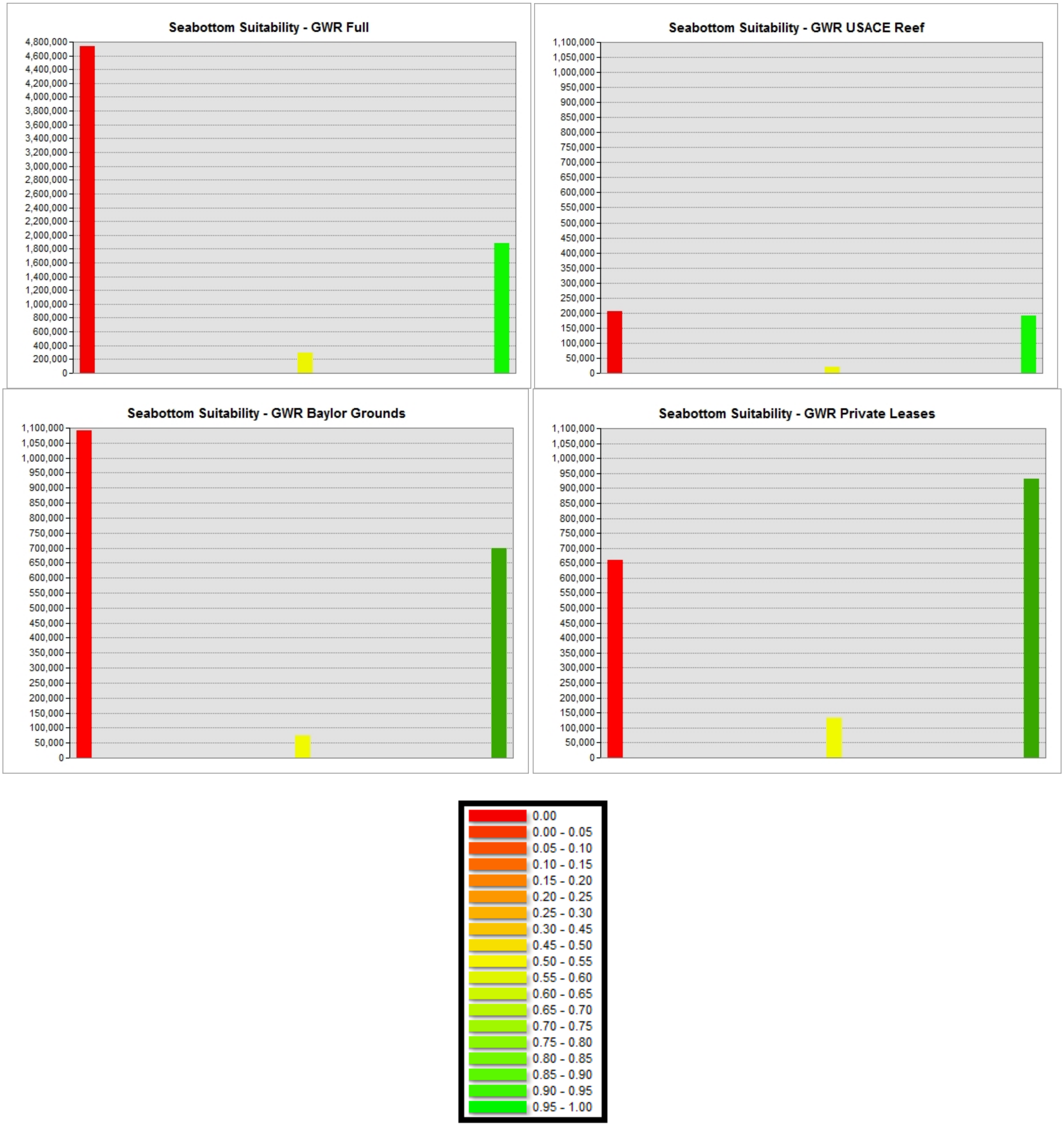


Figure 10A: Distribution of seabottom suitability values for the entire river (GWR Full), the USACE sanctuary reefs, Baylor grounds, and private shellfish aquaculture leases. Histogram interpretation: X-axis = suitability index (0.05 increments); Y-Axis = number of cells within specified range (each cell is 1m x 1m).

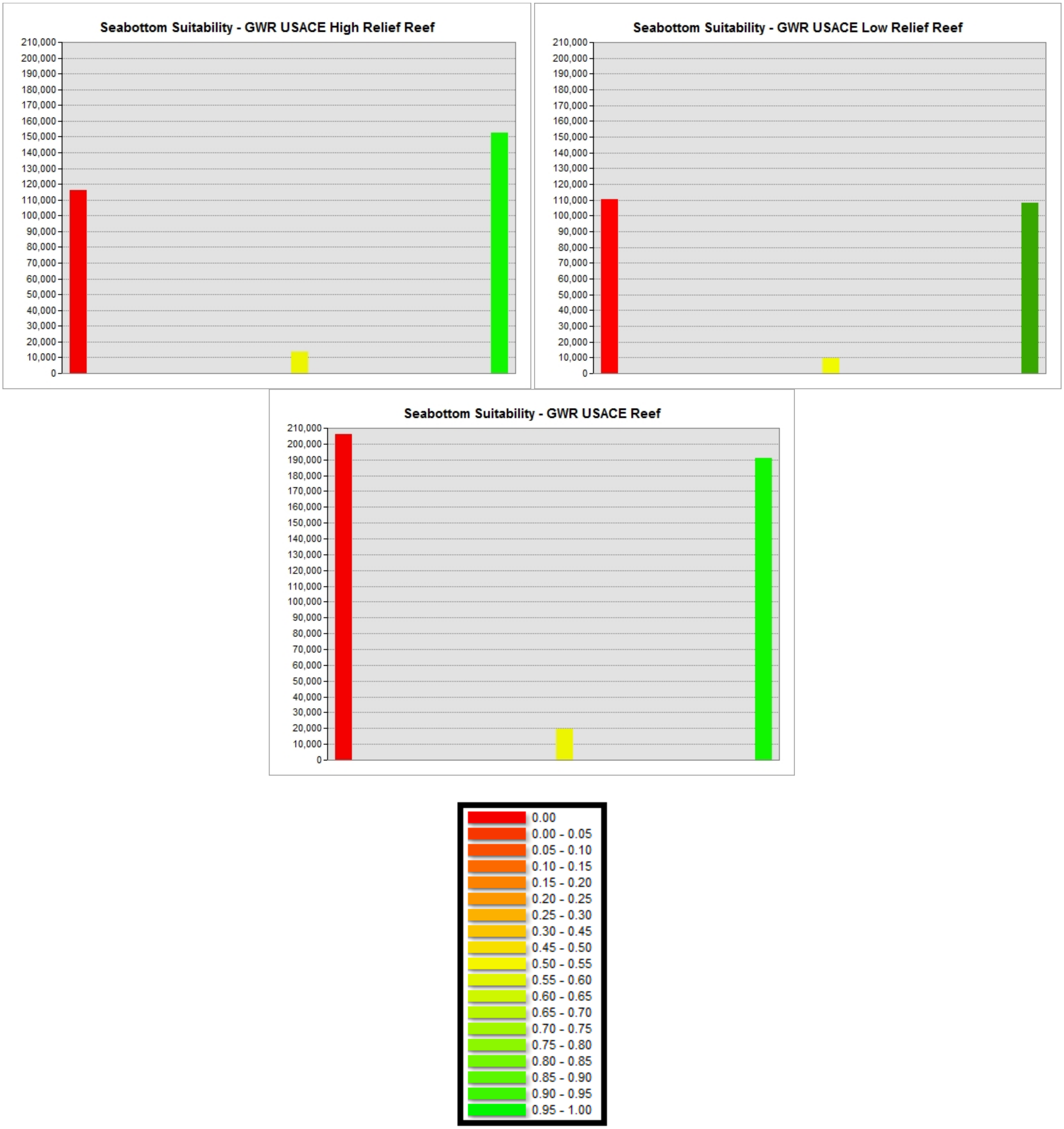


Figure 10B: Distribution of seabottom suitability values for the USACE high-relief reefs, USACE low-relief reefs, and the entire USACE sanctuary reef system (i.e., high-relief reefs and low-relief reefs). Histogram interpretation: X-axis = suitability index (0.05 increments); Y-Axis = number of cells within specified range (each cell is 1m x 1m).

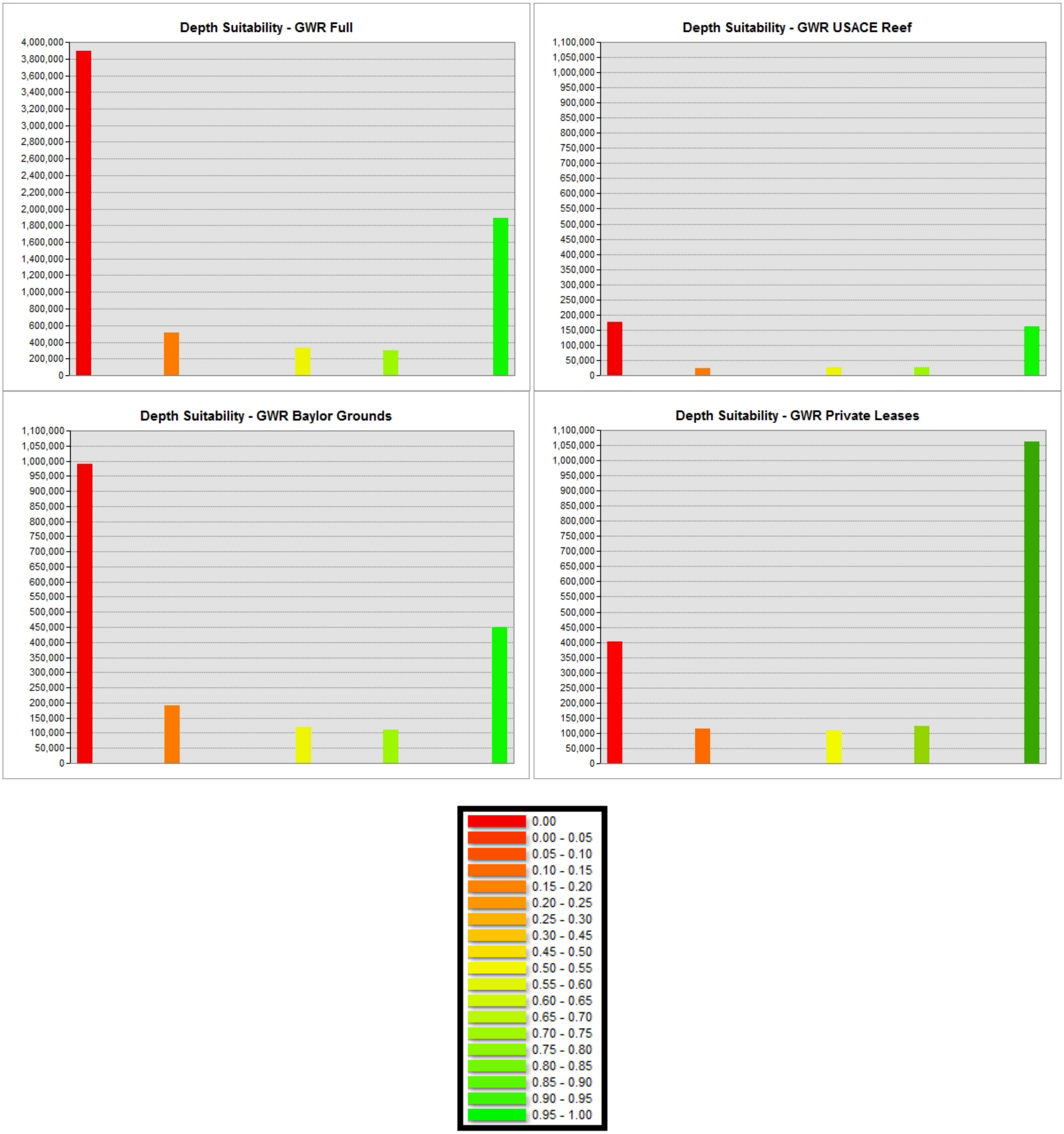


Figure 11A: Distribution of depth suitability values for the entire river (GWR Full), the USACE sanctuary reefs, Baylor grounds, and private shellfish aquaculture leases. Histogram interpretation: X-axis = suitability index (0.05 increments); Y-Axis = number of cells within specified range (each cell is 1m x 1m).

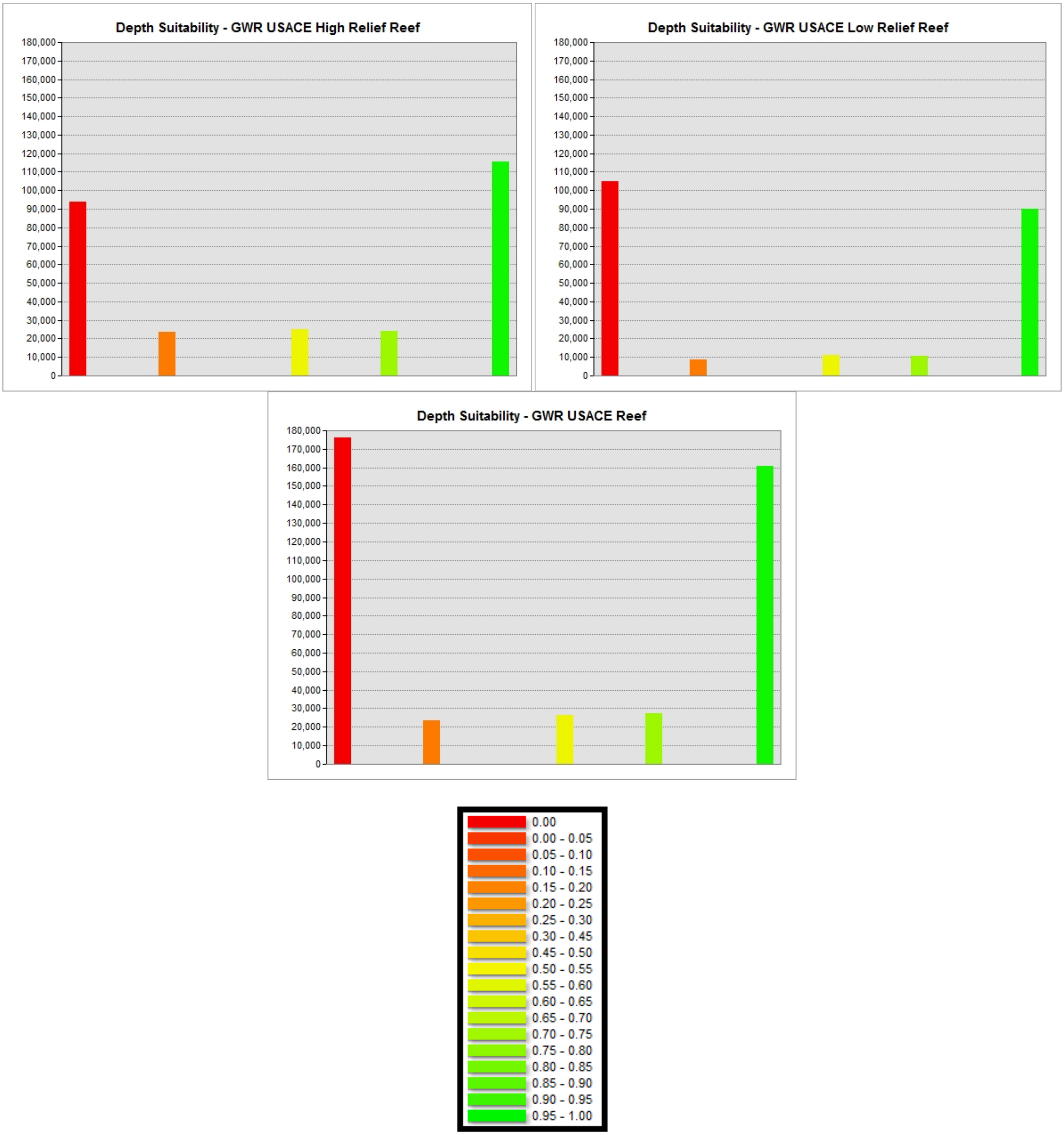


Figure 11B: Distribution of depth suitability values for the USACE high-relief reefs, USACE low-relief reefs, and the entire USACE sanctuary reef system (i.e., high-relief reefs and low-relief reefs). Histogram interpretation: X-axis = suitability index (0.05 increments); Y-Axis = number of cells within specified range (each cell is 1m x 1m).

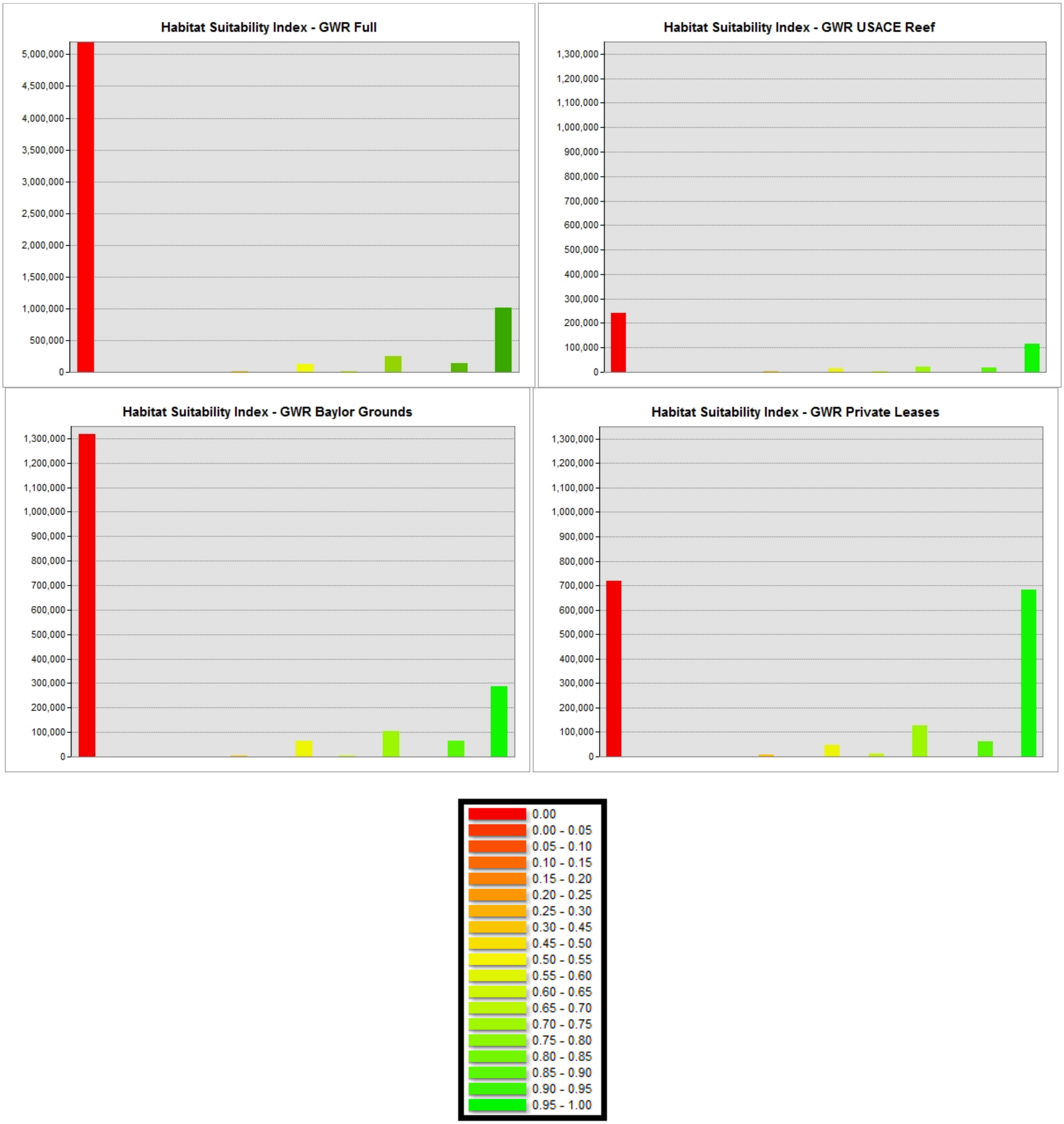


Figure 12A: Distribution of HSI values for the entire river (GWR Full), the USACE sanctuary reefs, Baylor grounds, and private shellfish aquaculture leases. Histogram interpretation: X-axis = suitability index (0.05 increments); Y-Axis = number of cells within specified range (each cell is 1m x 1m).

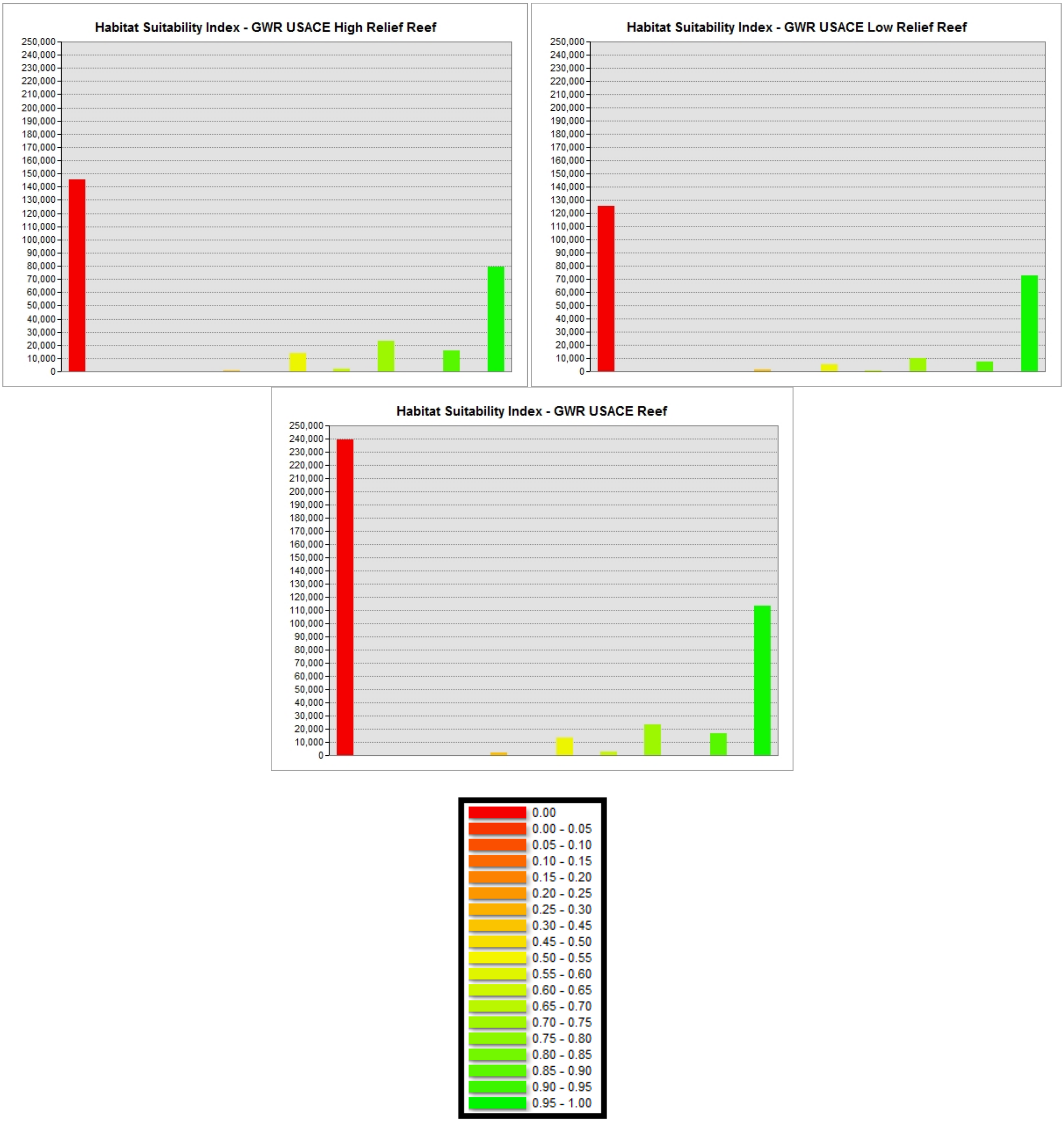
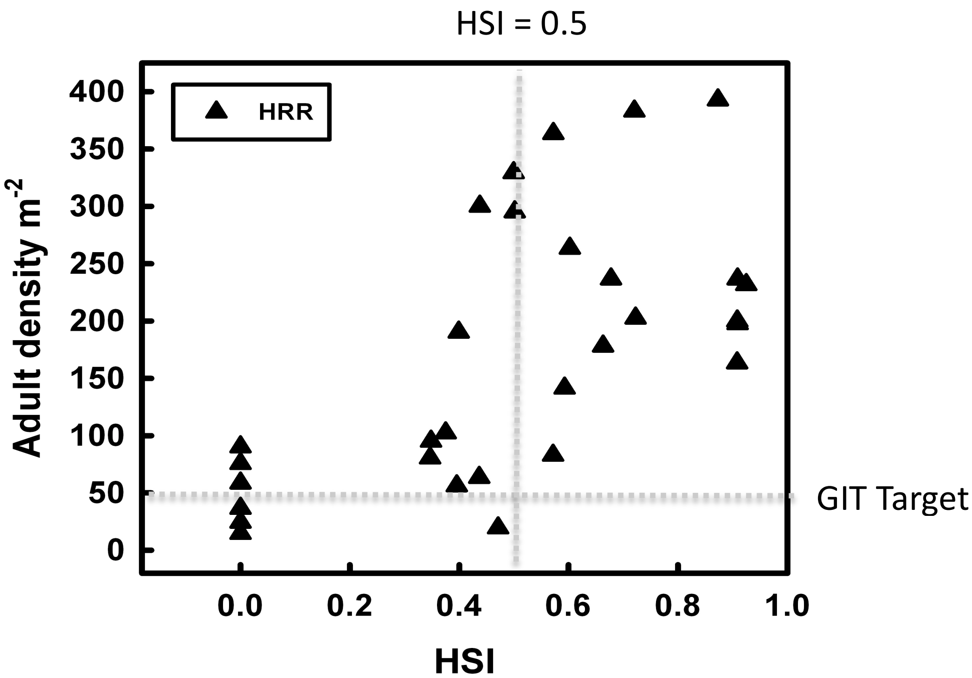


Figure 12B: Distribution of HSI values for the USACE high-relief reef, USACE low-relief reef, and the entire USACE sanctuary reef system (i.e., high-relief reefs and low-relief reefs). Histogram interpretation: X-axis = suitability index (0.05 increments); Y-Axis = number of cells within specified range (each cell is 1m x 1m).

High-Relief Reefs



Low-Relief Reefs

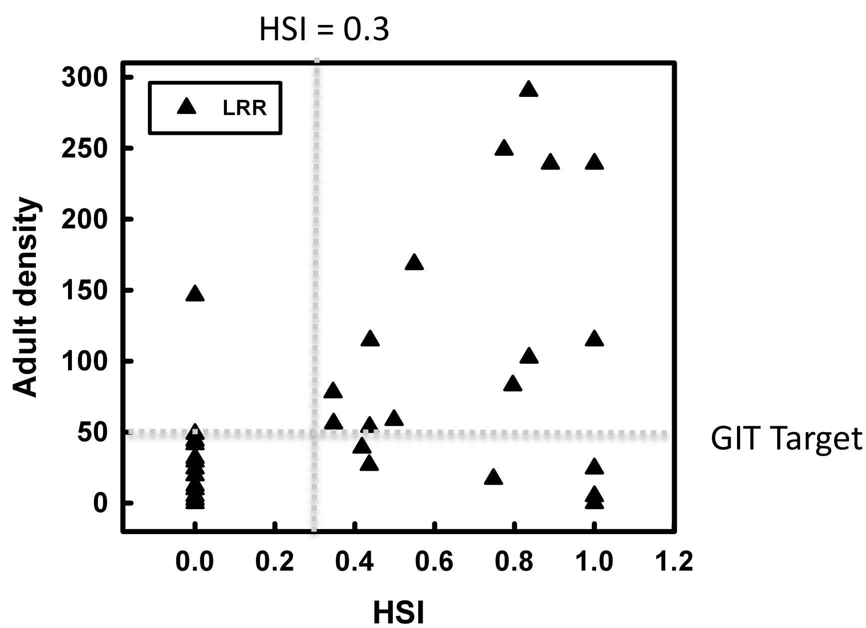


Figure 13: Adult oyster densities (m^{-2}) versus the HSI values associated with each sampling point from the 2011 Great Wicomico River reef monitoring; high-relief reef (top), low-relief reef (bottom). The horizontal grey lines represent the 50 live adult oysters m^{-2} GIT target, or the target criterion for a restored reef to be considered successful. The vertical grey lines represent the minimum HSI value where the GIT target is met.

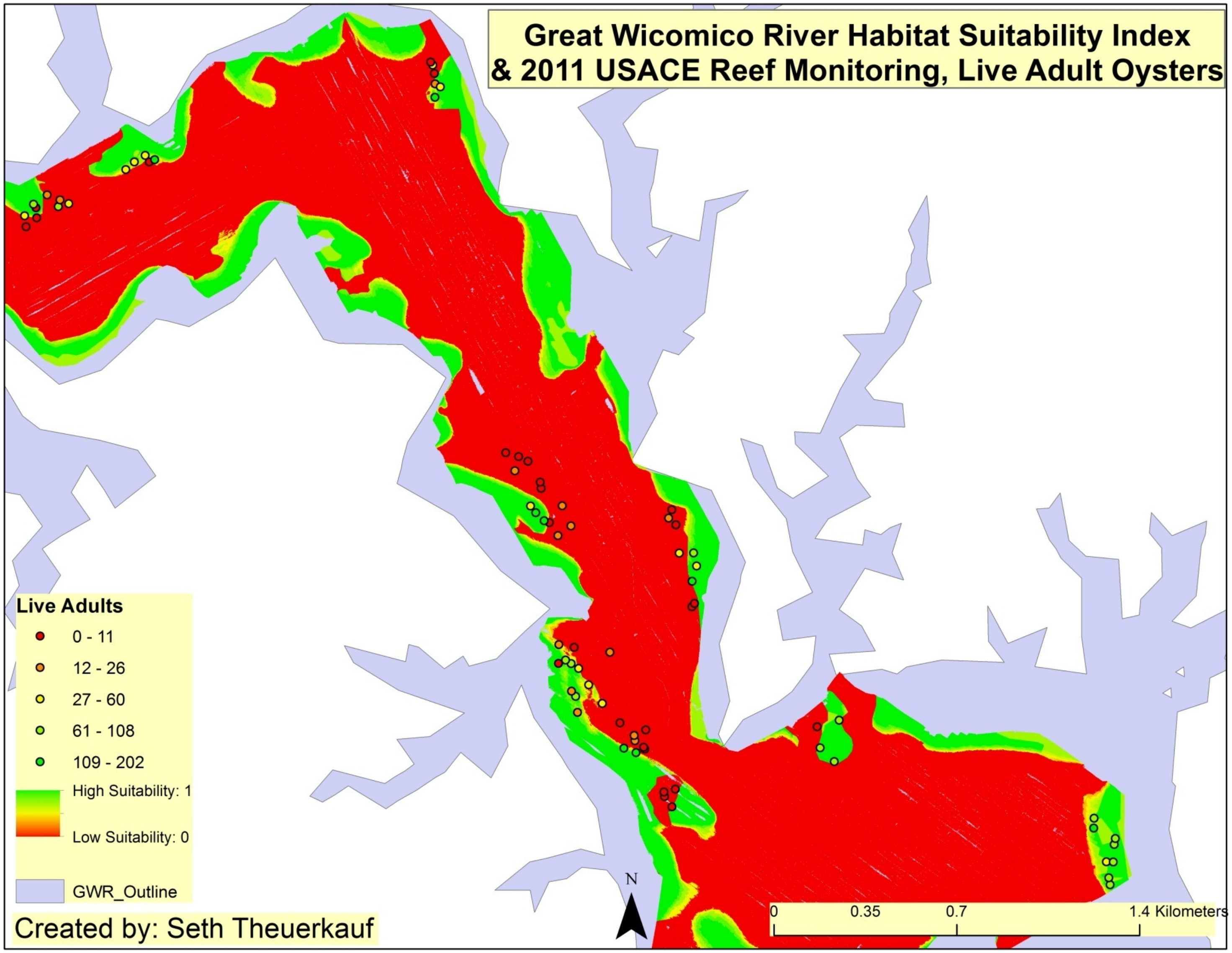


Figure 14: Map showing the output of the HSI along with the live adult oyster densities (m^{-2}) associated with each sampling point from the 2011 Great Wicomico River USACE sanctuary reef system monitoring.

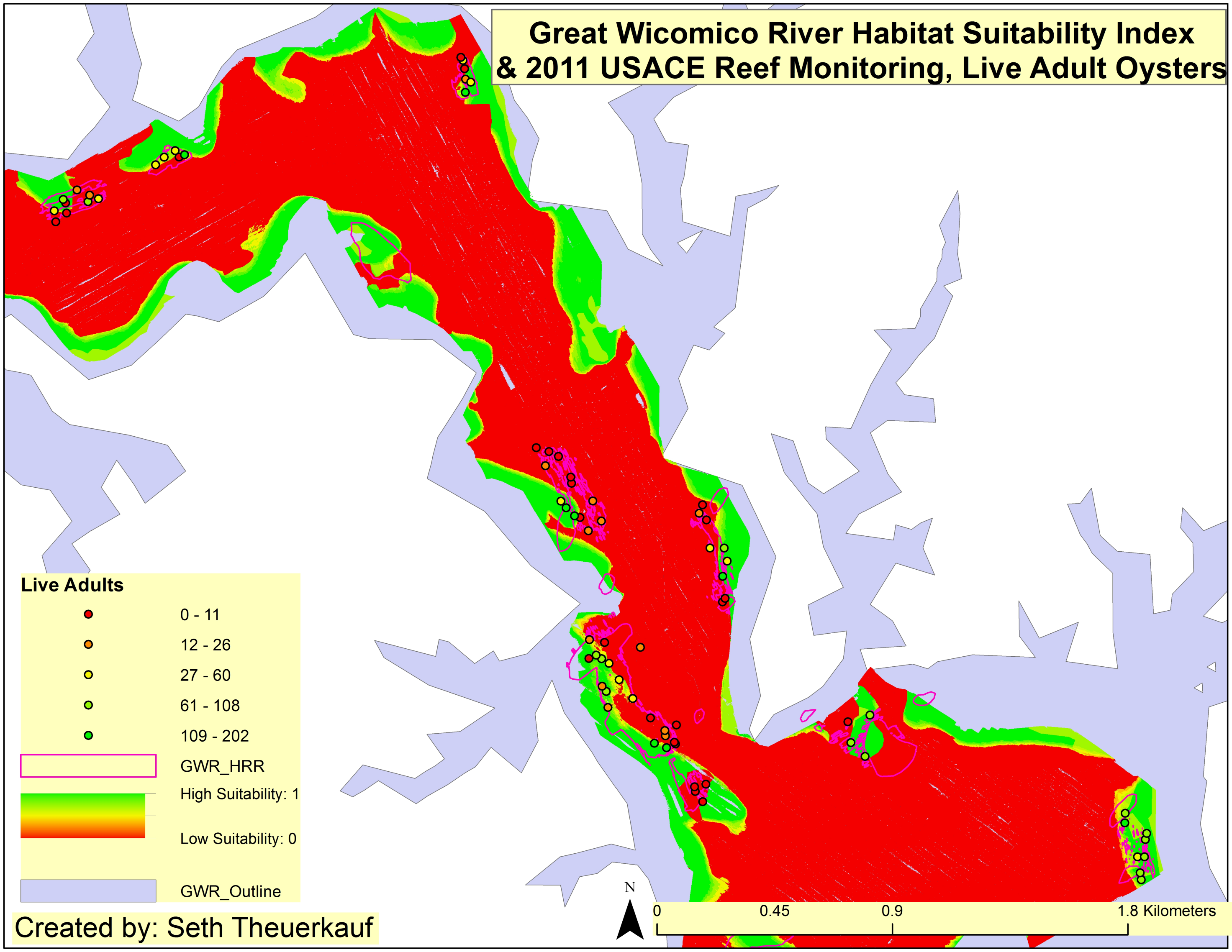


Figure 15: Map showing the output of the HSI, the live adult oyster densities (m^{-2}) associated with each sampling point from the 2011 USACE sanctuary reef system monitoring, and the distribution of high-relief reefs in the Great Wicomico River.

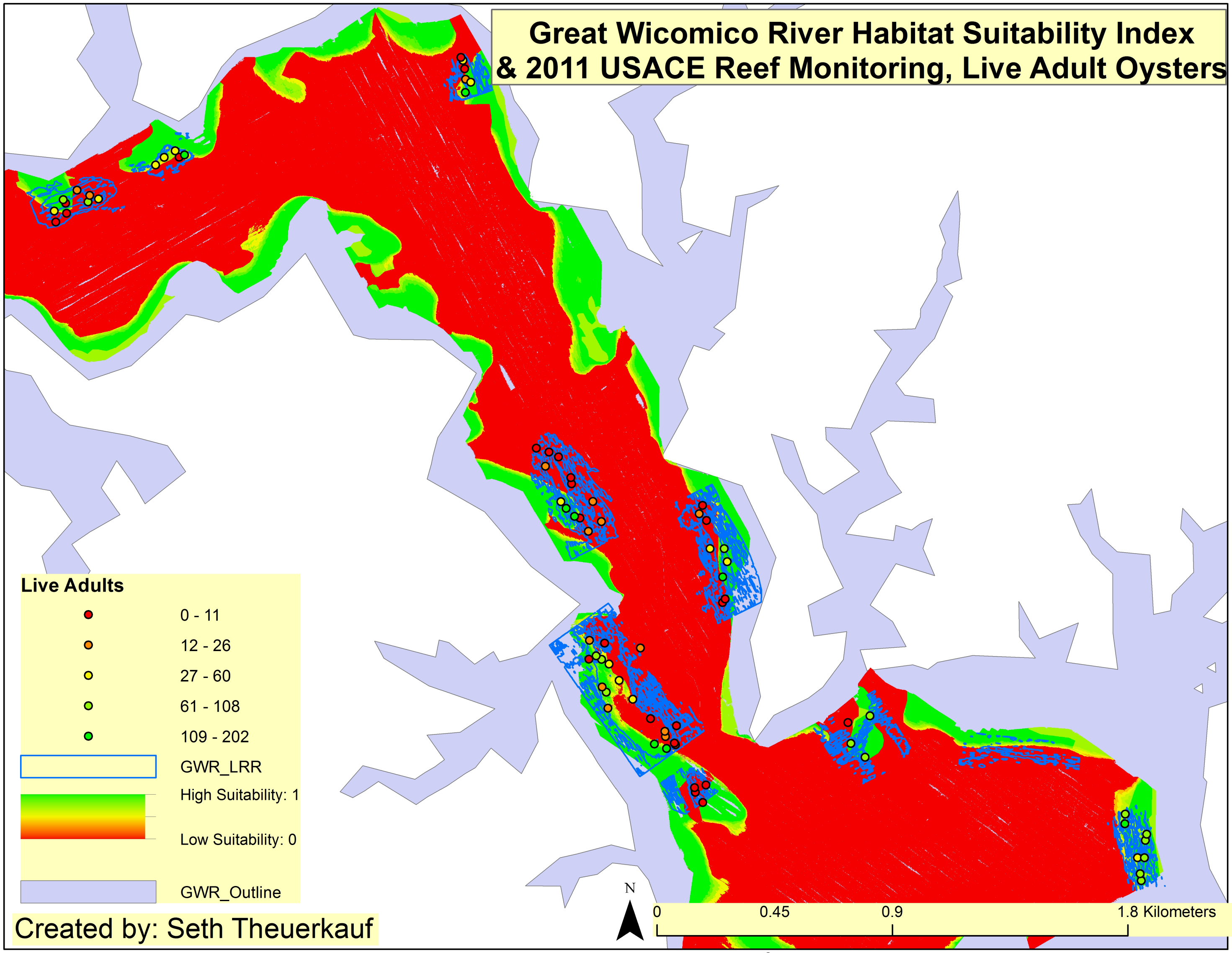


Figure 16: Map showing the output of the HSI, the live adult oyster densities (m^{-2}) associated with each sampling point from the 2011 USACE sanctuary reef system monitoring, and the distribution of low-relief reefs in the Great Wicomico River.

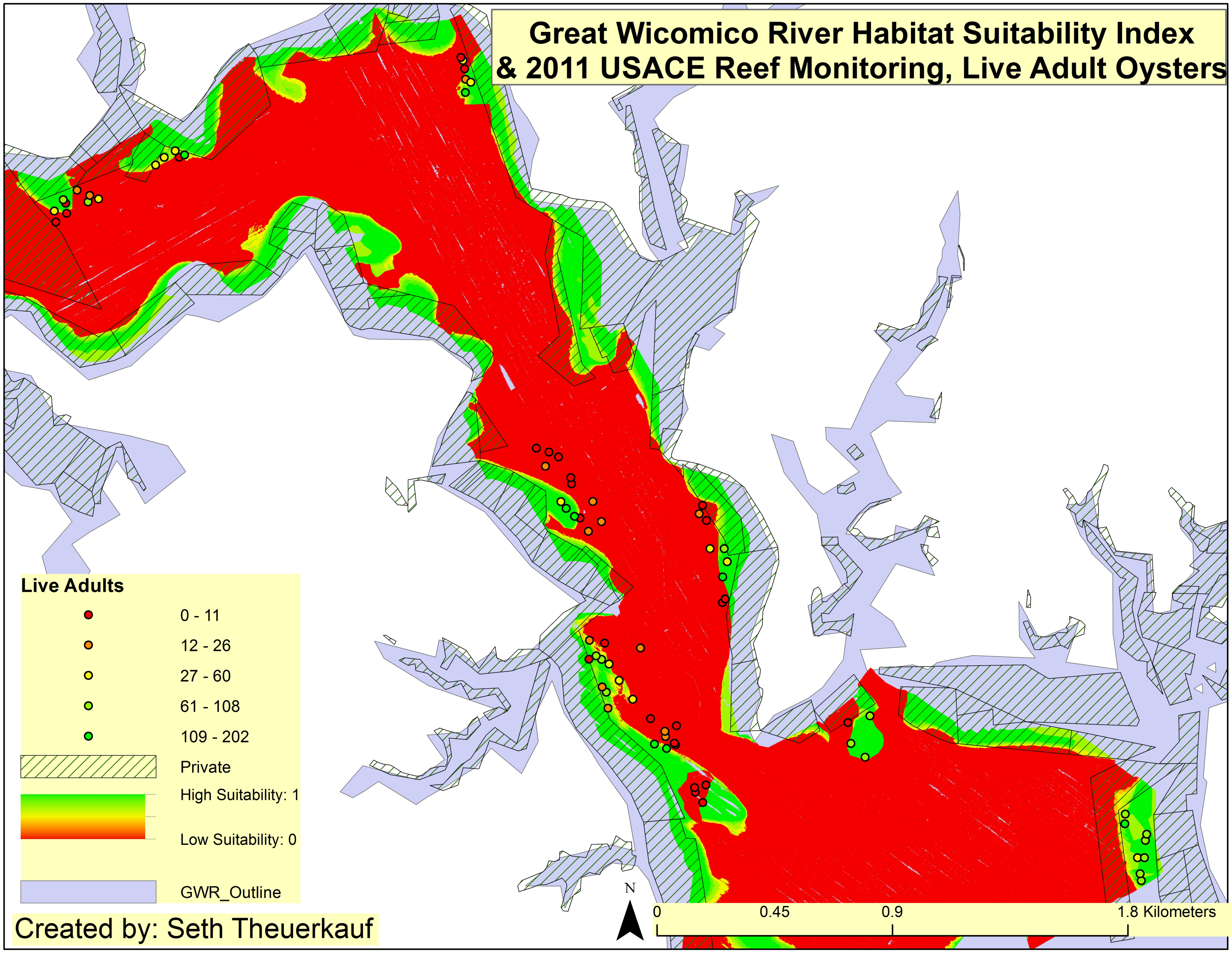


Figure 17: Map showing the output of the HSI, the live adult oyster densities (m^{-2}) associated with each sampling point from the 2011 USACE sanctuary reef system monitoring, and the distribution of private shellfish aquaculture leases in the Great Wicomico River.

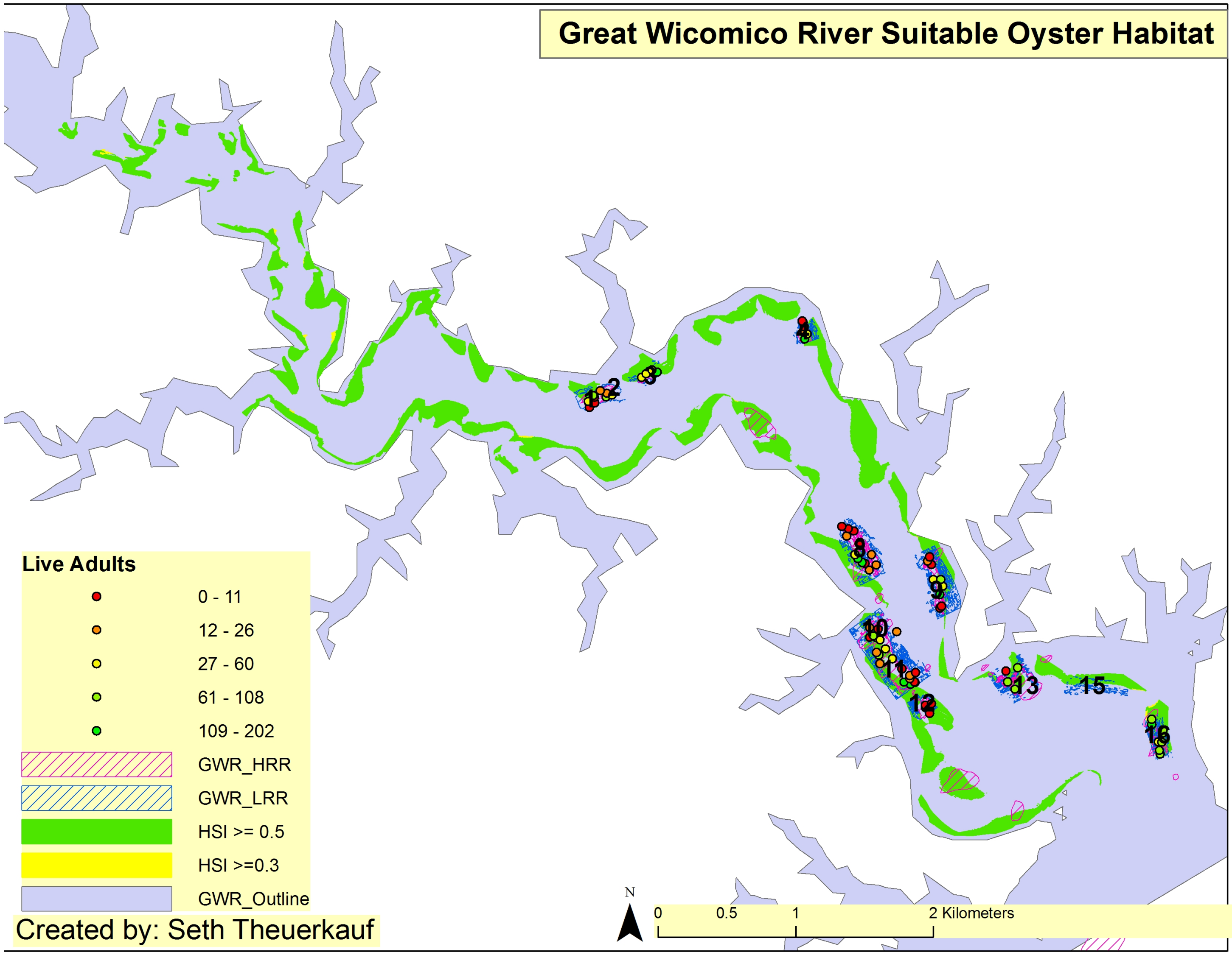


Figure 18: Distribution of suitable oyster habitat (green) and marginally suitable oyster habitat (yellow) in the Great Wicomico River, the live adult oyster densities (m^{-2}) associated with each sampling point from the 2011 USACE sanctuary reef system monitoring, and the distribution of low and high-relief reefs in the Great Wicomico River.

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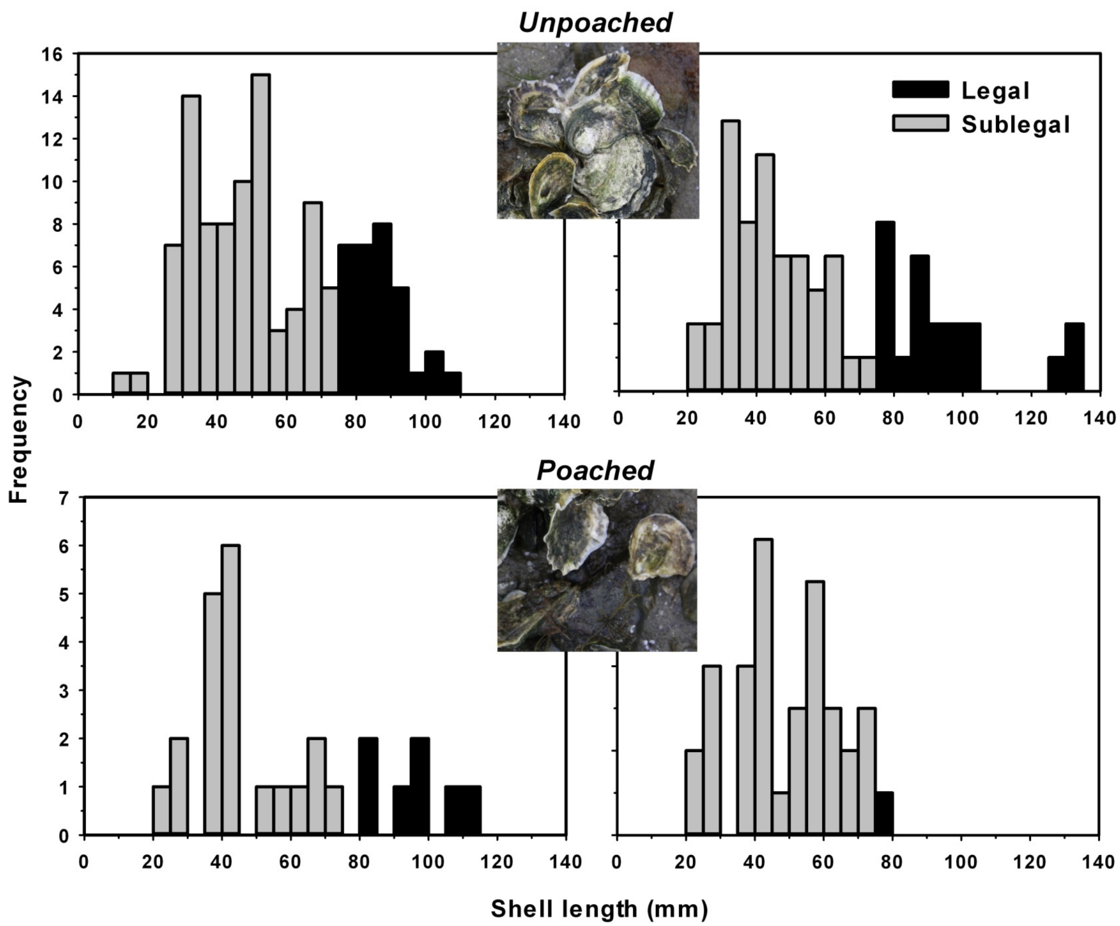

Figure 19: Size frequency histograms for unpoached versus poached oyster reefs derived from the 2011 Great Wicomico River reef monitoring sampling (m^{-2}) (Adapted from Walker et al., 2012 (in prep)).

Figure 20: An example of an oyster cage utilized for oyster aquaculture on a private shellfish aquaculture lease. Source: www.bayoyster.com.

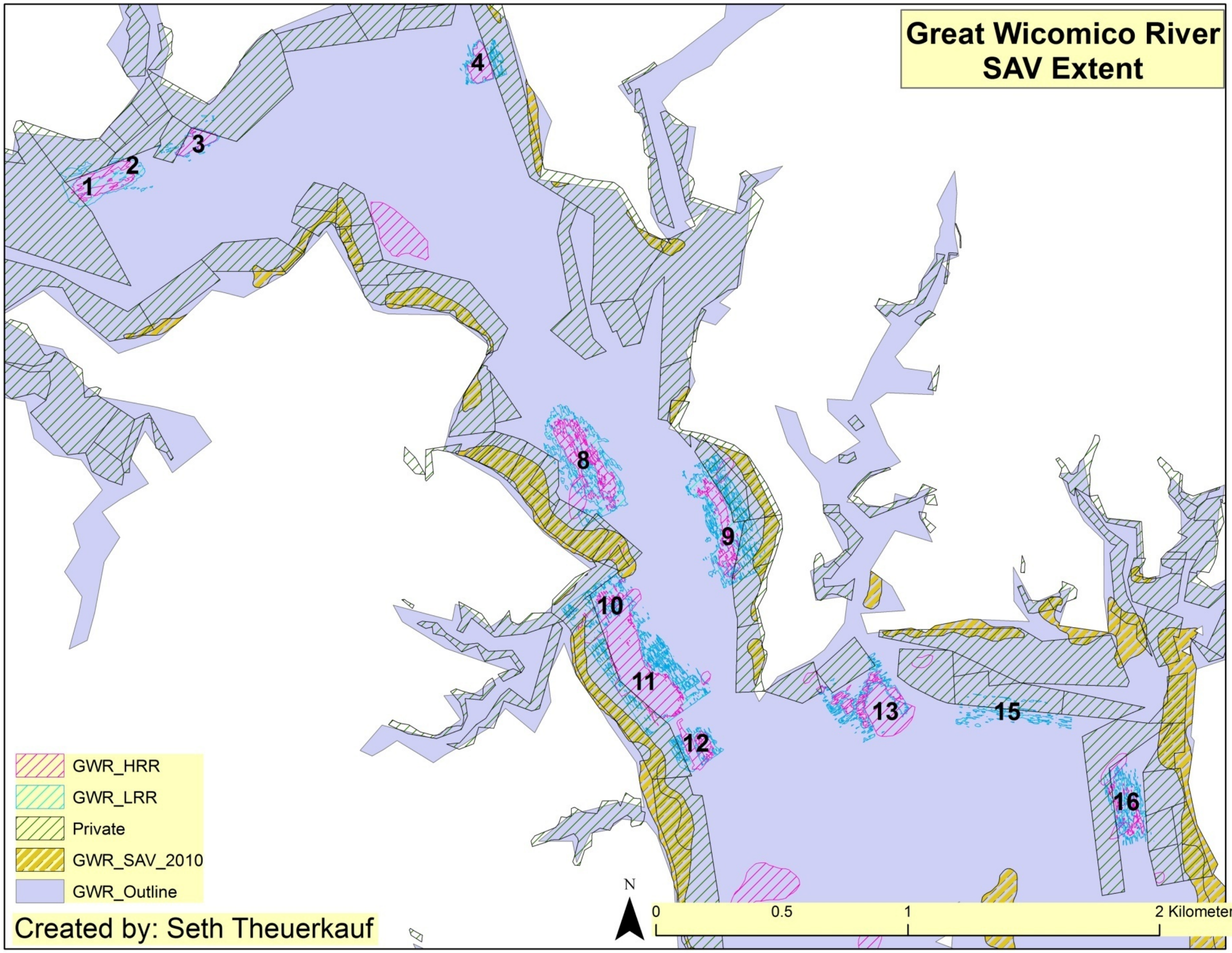

Figure 21: Submerged aquatic vegetation (SAV) distribution in the Great Wicomico River in 2010 in relation to the distribution of high and low-relief reef, and private shellfish aquaculture leases.

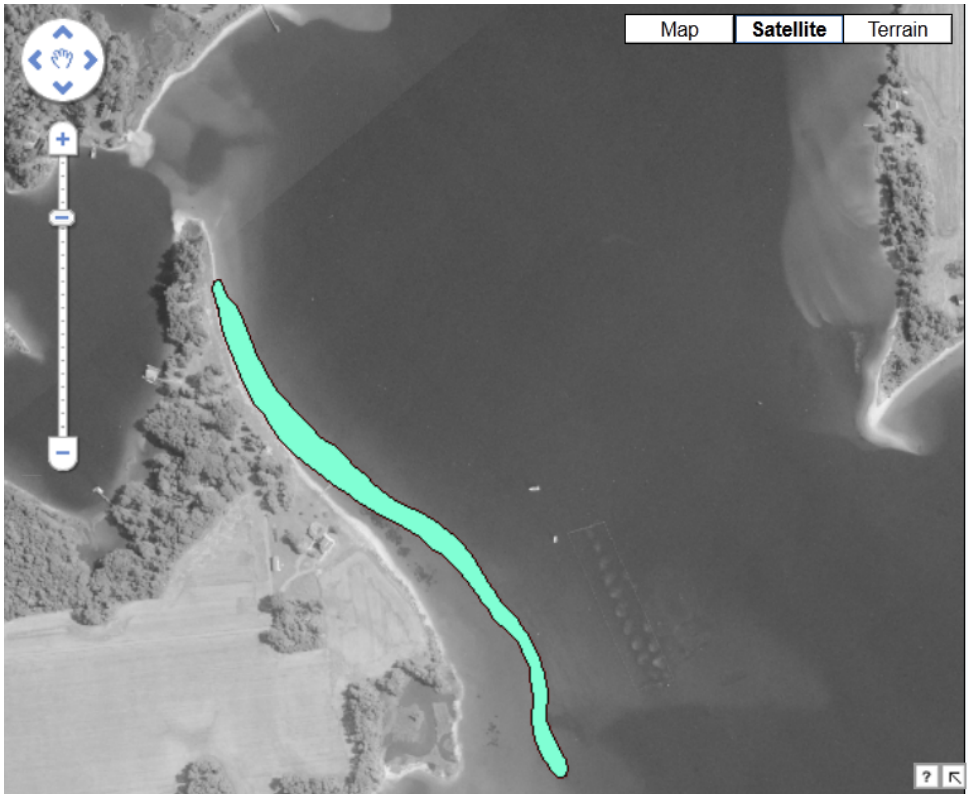

Figure 22. Map showing the 2010 distribution of submerged aquatic vegetation (SAV) within the Great Wicomico River relative to a shellfish aquaculture structure contained on a private lease. Source: Interactive Map – VIMS SAV Monitoring (http://web.vims.edu/bio/sav/maps.html#). Location reference: adjacent to USACE Reefs 10 and 11.

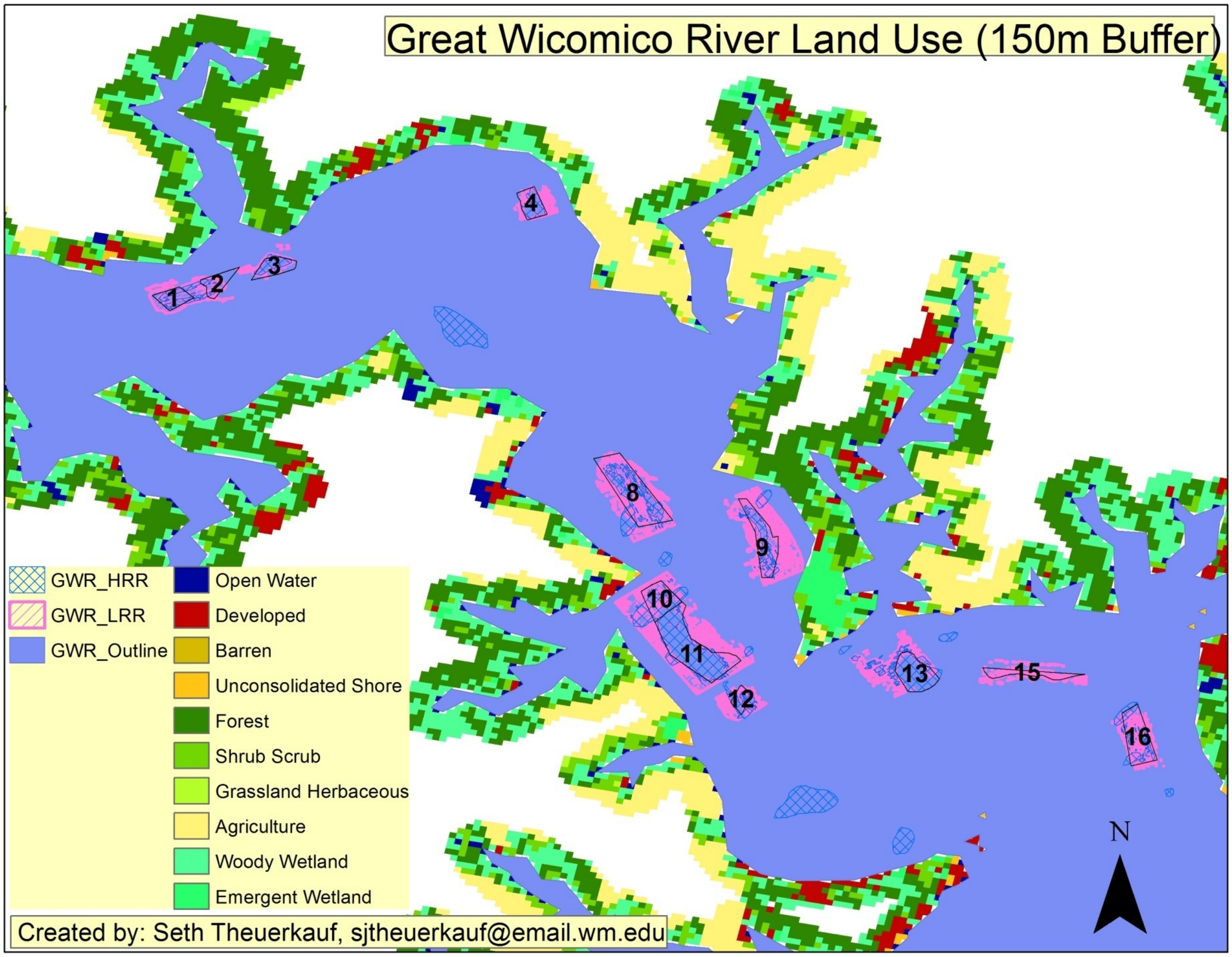

Figure 23: Information regarding the land use directly adjacent to the Great Wicomico River can be used to generate a “probability of freshet event” layer.