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Legacy Habitat Suitability of eastern oysters (Crassostrea virginica) in Louisiana: a prelude to Mississippi River Delta freshwater diversions

Tasia MV Denapolis
University of New Orleans, tdenapolis@gmail.com

Legacy Habitat Suitability of eastern oysters (*Crassostrea virginica*) in Louisiana: a prelude to Mississippi River Delta freshwater diversions

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Abstract

The Louisiana oyster industry is greatly impacted by freshwater and sediment diversions that are part of the effort to restore the state's coastline. A habitat suitability index (HSI) proposes species-habitat relationships that can be instrumental in creating impact assessments and suitability predictions for management as new diversions are implemented. An oyster (*Crassostrea virginica*) HSI was developed using three variables crucial to oyster sustainability: average annual salinity, minimum monthly salinity, and average salinity during the spawning season. These Legacy HSI visualizations show annual fluctuations in the distribution of zones suitable for oyster cultivation prior to proposed diversions in Pontchartrain and Barataria Basins from 1967 to 2016. Modeling suitability based upon these variables can provide crucial information for timing the use of diversions to lessen harmful effects upon the oyster industry as well as indicate new potentially suitable areas that the diversions may create.

Key Words: oyster, habitat suitability, HSI, C. virginica, habitat modeling, suitability assessment

Introduction

Threats to the coastal zone of Louisiana necessitate the use of Mississippi River sediment and freshwater diversions to restore the receding wetlands of the Pontchartrain and Barataria basins. The increased volume of sediment and fresh water will shift the suitable zone for oyster cultivation down estuary towards the Gulf of Mexico. Suitable zones for oyster cultivation from 1967 to 2016 were characterized using an oyster Habitat Suitability Index (HSI). Assessment strategies of the past evaluated suitability using only salinity ranking strategies (Chatry et al. 1983), or salinity and substrate (Cake 1983, Soniat & Brody 1988) but did not include temperature effects. This new HSI incorporates temperature, and the synergistic effects of temperature and salinity to further refine suitability assessments. Legacy HSI visualizations show annual fluctuations in the distribution of zones suitable for cultivation of *Crassostrea virginica* oysters that are subject to the effects of diversions.

Habitat Suitability Index Model

"Habitat quality can only be defined as the capability of a site to support oysters." (Soniat & Brody 1988). A habitat suitability index model (HSI) is "a hypothesis of species-habitat relationships" (Cake 1983) that does not account for every component of oyster fitness nor demonstrate causation of observed effects. Nonetheless, it can be useful in management and understanding oyster growth and survival, and to detect areas that will be impacted by freshwater diversions (Cake 1983, Volety et al. 2008, Soniat et al. 2013). The HSI approach is a tool to be used in habitat evaluation procedures (HEP) for management of a particular habitat unit (HU) and the species within it. It is defined as an aggregation of multiple suitability indices, each representing a specific habitat component that is integral to the target species survival or reproduction, and results in a ratio from 0.0 to 1.0 that expresses the range of habitat conditions (USFWS 1980). To effectively enhance prospective management decisions, a baseline must be established as a basis for same species comparisons of different HU's or single species comparisons for a single HU over time (USFWS 1980). The usefulness of a HSI depends on the quality of the modeling data, and consideration of life history and seasonal variations of the target taxon (Brooks 1997).

The Eastern Oyster (*Crassostrea virginica*)

The eastern oyster, *Crassostrea virginica* (Gmelin), is an asymmetrical bivalve mollusk native to intertidal and subtidal estuarine areas ranging from Canada, southward along the eastern and south eastern coasts of North America into the Gulf of Mexico to the coasts of Brazil (Buroker 1983). It has been introduced on the west coast of North America, Hawaii, Japan, Australia and Great Britain (Ahmed 1975, Stanley & Sellers 1986). Oysters are a keystone species that affect water quality, provide food and habitat for multiple organisms within their environment, and function as ecosystem engineers. (Barnes et al. 2007, NOAA 2007) A single oyster can filter 34 liters of water per hour, and in doing so removes phytoplankton, sediments, organic carbon and other small organisms from the water column (Bushek & Allen 1996, Barnes et al. 2007). Their pseudofeces is a food source for fish and benthic organisms (Luckenbach et al. 1999, Barnes et al. 2007) and oysters themselves are an important food source for stone crabs, black drum, rays, oyster drills, gastropod mollusks and many other aquatic creatures (Cake 1983, McGuire 2006, Banks et al. 2016). Oyster reefs provide habitat for shrimp, crabs and fish (Chapman & Underwood 2011, Banks et al. 2016) and also protection against coastal erosion (NOAA 2007). In addition to their ecological role, oysters support commercial fishery. Nationwide, the industry peaked in the late 1800's to early 1900's, producing up to 160 million pounds of oyster meat in a single year (MacKenzie & Wakida-Kesunoki 1997), but has since declined due to over fishing, hypoxia and habitat destruction (Luckenbach et al. 1999); annual harvest was about 25 million pounds in 2015 (NOAA 2017). According to Shumway (1996) the synergistic effects of temperature and salinity almost certainly have a profound effect on *C. virginica* and other estuarine species. Although oysters can tolerate a wide range of temperatures (Cake 1983), optimal temperature for adult oysters is 20-30ºC and ideal salinity between 14 and 28, (Stanley & Sellers 1986) although this fluctuates according to geographic location (Shumway 1996).

In Louisiana, *C. virginica* is predominantly subtidal (Banks et al. 2016) and most productive at salinities between 5 and 15. At moderate salinities oysters avoid osmotic and reproductive failure associated with low salinity and parasitic infections and predators that prefer higher salinity environments (Ray 1954, Chatry et al. 1983, Craig et al. 1989, NOAA 2007, LaPeyre et al. 2009, LaPeyre et al. 2013). Typically for *C. virginica*, spawning ensues when temperature is above 20^{o}C and salinity above 10 however, in the northern Gulf of Mexico spawning ensues as temperatures near 25^{o}C with salinities closer to 15. **(**NOAA 2007, LaPeyre et al. 2013**)**. The spawning season for *C. virginica* in the northern Gulf of Mexico can occur from May to June and again in September **(**Cake 1983). The larval forms are motile and temporarily planktonic which assists in dispersal to permanent benthic settling locations (Stanley & Sellers 1986). They require clean, hard substrate to settle upon (Newell 1988). Adults exhibit phenotypic plasticity relating to shell shape and thickness, dependent upon the type of habitat substrate (Eble & Scro 1996, NOAA 2007). Among the many predators and parasites that attack oysters, dermo disease caused by the protozoan *Perkinsus marinus* (Mackin 1951, Soniat 1985, NOAA 2007**)** is one of great concern. The higher salinity and long warm seasons (above 20^{o}C for more than 6 months per year) in northern Gulf waters provide a favorable environment for the proliferation of *P. marinus* (Mackin 1951, Menzel & Hopkins 1955, Soniat et al. 2006, WORMS 2011).

Genetic differences have been identified amongst oyster populations ranging from the American Northeastern coast, Florida and westward across the Gulf of Mexico to Texas (Bushek & Allen 1996, NOAA 2007). Genotypes have been selected and cultivated to improve survival and growth (Allen et al. 1993). Culturing specific oyster lineages with genetic resistance to Dermo and MSX (an oyster disease caused by a haplosporidian parasite), is a common practice in oyster aquaculture (Allen et al. 1993). Another approach is to induce triploidy, and while it has not been shown to confer disease resistance to Dermo or MSX, it renders oysters sterile which allows them to allocate energy to growth instead of reproduction. In ideal conditions, triploidy allows oysters to evade disease long enough to reach harvest size before succumbing to severe infections (Allen et al. 1993, Degremont et al. 2012).

Salinity and temperature are key factors in oyster reproduction, growth, and mortality (LaPeyre et al. 2015, Lowe et al. 2017). *C. virginica* exhibit protandric hermaphroditism, starting out as male and changing to develop female gonads as they age. Warmer springtime temperatures initiate gametogenesis and further increasing temperatures (near 25^{o}C.) of late spring and summer prompt spawning (Stanley & Sellers 1986, Lorio & Malone 1994). Oysters release gametes into the water column that are suspended in the water column until settling on firm, clean substrate (Stanley & Sellers 1986). There is evidence of at least two races of *C. virginica*: one occupying the Atlantic coast and the other in the Gulf of Mexico, with a transitional zone along the eastern Florida coast (Loosanoff & Nomejko 1951, NOAA 2007). These races vary in gonadal maturation time depending on each race’s optimal temperature, and each has a specific spawning temperature ranging from 15^{o}C - 25^{o}C (Loosanoff & Nomejko

1951, Stanley & Sellers 1986). This suggests that predictive habitat suitability modeling should be population and location specific. The combination of reduced salinities of 10.7–16.1 and higher temperatures between 20°C–26.3°C have recently been shown to be ideal for optimal growth of spat, seed and sack oysters in southern Louisiana however, local adaptations dictate the most effective salinity and temperature for each reef and size class (LaPeyre et al. 2013, Lowe et al. 2017). Oysters close their valves as a defense to freshwater disturbances but this behavior poses a tradeoff between defense and feeding, resulting in reduced growth (LaPeyre et al. 2013). Short episodes of low salinity do not significantly impact oyster mortality or growth; however, extended freshet events are fatal, especially those combining low salinity with high temperatures (Cake 1983, Soniat & Brody 1988, LaPeyre et al. 2013, Wang et al. 2017). Higher salinities and warm temperatures are favorable for the perseverance of *P. marinus* that causes Dermo disease and marine predators such as the gastropod *Stramonita haemastoma* (Soniat 1985, Bushek & Allen, 1996, Luckenbach et al. 1999, Turner 2006). A positive effect of short freshening events is the reduction of marine predators and diseases that affect oyster growth and survival (Gunter 1955, Soniat 1985, LaPeyre et al. 2009).

Barataria and Pontchartrain Basins

The Pontchartrain Basin is located east of the Mississippi river, bounded by the state of Mississippi in the north, Pearl River on the east and the Chandeleur Islands in the south, and includes the Biloxi marsh and Breton Sound. It is a watershed encompassing 10,000 square miles of Louisiana land that drains into rivers, bayous, swamps and lakes that connect with the Gulf of Mexico, and includes forests, wetlands and marshes crucial to the cultural and commercial economy of southern Louisiana (LPBF 2017). Barataria Basin is just over 2,445 square miles of forest, swamps, and marshes, bounded on the north and east by the Mississippi River, the west by Terrebonne Basin and opening to the south to barrier islands and the Gulf of Mexico (Conner et al.1987, CWPPRA 2017). Coastal areas of southern Louisiana are subject to fluctuations including hurricanes, floods, droughts and diversions (Chesney et al. 2000, Lopez 2003). Gunter (1955) correlated land loss with saltwater intrusion and oyster mortality by mapping erosion of portions of the barrier islands from Grand Island to Last Island. Navigation canals like the Mississippi River Gulf Outlet (MRGO), the Intercoastal Waterway (ICW) and Inner Harbor Navigational Canal (IHNC) provide channels for saltwater intrusion into the surrounding wetlands (Lopez 2003, Shaffer et al. 2009). The three waterways together effectively connected brackish Lake Pontchartrain to the higher saline waters of the Gulf of Mexico. Barataria Basin is divided by the Gulf Intracoastal Waterway (GIWW) that extends from the Mississippi River to the Gulf of Mexico, the Barataria Bay Waterway that reaches from Grand Isle to the GIWW, and the Empire-Gulf Waterway which connects the Gulf of Mexico to the Mississippi River (CWPPRA 2017).

Storms and droughts

Storms entering the Gulf of Mexico (Table 1) can influence the salinity of coastal Louisiana (Conner et al. 1989, Weather Research Center 2002, Lopez 2003, Gurung 2014, NOAA 2018). Wind events caused by storms often push saline water and sediments inland causing anoxic conditions in estuarine habitats, and depending on frequency, duration and severity of the events, heavy rains associated with storms can dilute salinity (Michener et al. 1997, Mulholland et al. 1997, Sallenger 1997). Damage to habitat from storm surge and winds (storms above category 3) also affect oyster abundance by siltation of oyster reefs and alteration of salinity. Gulf of Mexico storms of category 3 or above near the Louisiana coastline occurred in the years 1969-71, 1974-75, 1977, 1979, 1983, 1985, 1992, 1995, 1998, 2002, 2004-05, and 2008, often causing extensive damage to the coastline (Roth 2010, NOAA 2018). Recent Louisiana droughts occurred in 1998 and 2000, however, droughts in the Mississippi River watershed can also reduce freshwater input (NOAA 2018).

Diversions

Freshwater and sediment diversions from the Mississippi River are in place to offset effects of the navigation canals and correctly utilized, enhance the Louisiana oyster industry (Viosca 1927, Meffert & Good 1996). Freshwater diversions reduce salinity of inland waters forcing suitable oyster habitat more seaward (CWPPRA 1993, Lopez 2003, Soniat et al. 2004 & 2013) and sediment diversions designed to reduce land loss in the marshes also affect salinity (Caffey & Schexnayder 2002). Diversions east of the Mississippi River such as the Bonnet Carré Spillway, Mardi Gras Pass, Caernarvon Diversion and the structures at Fort St. Philip affect wetlands from Breton Sound to Mississippi Sound, including Lakes Pontchartrain and Borgne (Lopez 2003, USACE 2010, Teal et al 2012). West bank diversions such as Davis Pond, The siphons at Naomi and West Pointe a la Hache and the West Bay diversion impact Barataria Basin (USACE 2010, Teal et al 2012). Some of the main diversions are summarized (Table 1).

Table 1.

Important Diversions, Storms, Floods and Droughts.

Name	Year	Event Type	Affected Area	Source
Bonnet Carré Spillway	1937, 1950, 1973, 1975, 1979, 1983, 1997, 2016	Freshwater Diversion	Lakes Pontchartrain and Borgne, Mississippi Sound	Roberts et al. 1992, Lane et al. 2001, Lopez 2003, Turner 2006, USACE 2010, Teal et al. 2012, Gurung 2014, Banks et al. 2016
Caernarvon Diversion	1991-present	Freshwater and Sediment Diversion	Upper Plaquemines, St. Bernard wetlands, Delacroix/Big Mar Pond, Bayou Mandeville, Lake Leary	Roberts et al. 1992, Meffert & Good 1996, Lane et al. 2001, Caffey & Schexnayder 2002, Lopez 2003, Snedden et al. 2007, LADWF 2010, SLFPAE 2010, USACE 2010, Teal et al, 2012, Janasie 2013, Gurung 2014, LPBF 2014, Smith et al. 2015, Banks et al. 2016
White's Ditch Diversion	1963-present	Freshwater and Sediment Diversion	Breton Sound Basin, Phoenix between Mississippi River and River aux Chenes	USACE, 1984, Meffert & Good 1996, Caffey & Schexnayder 2002, SLFPAE 2010, USACE 2010, Teal et al. 2012, Janasie 2013, USACE 2013, Gurung 2014
Violet Siphon	1957-present	Freshwater Diversion	St. Bernard, Bayou Lamoque, (connects Mississippi River and California Bay near Empire)	Roberts et al. 1992, Caffey & Schexnayder 2002, Teal et al. 2012, Janasie 2013, Gurung 2014
Bohemia Spillway	1924-present	Freshwater and Sediment Diversion	Southwestern Breton Sound Estuary, South of Pointe a la Hache	Roberts et al. 1992, USACE 2010, Gurung 2014, Lopez et al. 2014, Smith et al. 2015
Mardi Gras Pass	2011-present	Freshwater Diversion	Bohemia Reach, Breton Sound	Teal et al. 2012, Lopez et al. 2014
Ostrica Lock	1880's, 1940, 1953, 2011-present	Freshwater Diversion	Breton Sound (south of Bohemia Reach), Ostrica, Plaquemines	USACE 1984, Teal et al. 2012, Janasie 2013
Channel Armor Gap Crevasse	1997-present	Sediment Diversion	Venice, Delta National Refuge, Mary Bowers Pond, Pilottown, southern Mississippi River Delta	Rodrigue 2003, Teal et al. 2012

Table 1.

Important Diversions, Storms, Floods and Droughts.

Name	Year	Event Type	Affected Area	Source
Bayou Lamoque Structures	1955 and 1978- present	Freshwater and Sediment Diversion	Breton Sound, Black Bay	USACE 1984, Roberts et al. 1992, Meffert & Good 1996, Caffey & Schexnayder, 2002, USACE 2010, Teal et al. 2012, Janasie 2013, Gurung 2014, Banks et al. 2016
Davis Pond	2001- present	Freshwater Diversion	Barataria Basin, Lake Cataouatche	Roberts et al. 1992, Caffey & Schexnayder 2002, USACE 2010, Teal et al. 2012, Janasie 2013, Gurung 2014, Banks et al. 2016
Naomi Siphon	1993- present	Freshwater Diversion	Barataria Basin, Plaquemines	Roberts et al. 1992, USACE 2010, Teal et al. 2012, Janasie 2013
West Pointe a la Hache Siphon	1993- present	Freshwater and Sediment Diversion	Barataria Basin, Plaquemines	Roberts et al. 1992, Caffey & Schexnayder 2002, USACE 2010, Teal et al. 2012, Janasie 2013, Gurung 2014
West Bay Diversion	2003	Sediment Diversion	Barataria Basin, Venice	USACE 2010, Teal et al. 2012, Gurung 2014 Smith et al. 2015
Old River Control Structure	1963-present	Freshwater and Sediment Diversion	Prevents Mississippi River from diverting into Atchafalaya Basin	Roberts et al. 1992, Teal et al. 2012
Hurricane Camille	8/14/1969 Ms.	Storm (CAT5)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Celia	8/31/1970 Tx.	Storm (CAT3)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Edith	1971	Storm (CAT5)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Carmen	8/29/1974 La.	Storm (CAT4)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Eloise	9/13/1975 Al.	Storm (CAT3)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Babe	1977	Storm (CAT1)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Anita	8/29/1977 Mexico	Storm (CAT5)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018

Table 1.

Important Diversions, Storms, Floods and Draughts.

Name	Year	Event Type	Affected Area	Source
Hurricane Frederic	8/29/1979 Al.	Storm (CAT4)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Claudette	1979	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Bob	1979	Storm (CAT1)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Alicia	8/15/1983 Tx.	Storm (CAT3)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Elena	8/28/1985 Fl./La.	Storm (CAT3)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Juan	1985	Storm (CAT2)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Florence	1988	Storm (CAT1)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Andrew	1992	Storm (CAT5)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Opal	9/27/1995 Fl.	Storm (CAT4)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Josephine	1996	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Coastal Flooding	1996	Flood	Parishes: Jefferson, Lafourche, Plaquemines, St. Bernard, Orleans	Weather Research Center 2002, NOAA 2018
Hurricane Danny	7/17/1997 La.	Storm (CAT1)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Hermine	9/17/1998 La.	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Frances	9/9/1998 La.	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Earl	9/1/1998 La.	Storm (CAT2)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Georges	9/26/1998 La.	Storm (CAT4)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Drought	1998	Drought	Southern Louisiana	Weather Research Center 2002, NOAA 2018

Table 1.
Important Diversions, Storms, Floods and Draughts.

Name	Year	Event Type	Affected Area	Source
Tropical Storm Harvey	1999	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Nine	2000	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Helene	2000	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Drought	2000	Drought	Southern Louisiana	Weather Research Center 2002, NOAA 2018
Tropical Storm Allison	6/5/2001 La./Tx.	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Barry	2001	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Hanna	9/14/2002 La./Ms./Al.	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Fay	2002	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Bertha	8/4/2002 La.	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Edouard	2002	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Isidore	9/25/2002 La.	Storm (CAT3)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Claudette	2003	Storm (CAT1)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Bill	6/30/2003 La.	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Henri	2003	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Lili	9/21/2002 La.	Storm (CAT4)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Erika	2003	Storm (CAT1)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Grace	2004	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018

Table 1.

Important Diversions, Storms, Floods and Draughts.

Name	Year	Event Type	Affected Area	Source
Hurricane Lili	9/21/2002 La.	Storm (CAT4)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Erika	2003	Storm (CAT1)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Grace	2004	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Matthew	10/9/2004 La./Ms.	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Bonnie	2004	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Ivan	9/2/2004 Al./Fl.	Storm (CAT4)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Cindy	7/5/2005 La.	Storm (CAT1)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Katrina	8/23/2005 La./Ms.	Storm (CAT5)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Rita	9/18/2005 Tx./La.	Storm (CAT5)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Coastal Flooding	2006	Flood	Parishes: Jefferson, Lafourche, St. Tammany	Weather Research Center 2002, NOAA 2018
Tropical Storm Erin	2007	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Humberto	9/13/2007 Tx./La.	Storm (CAT1)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Fay	2008	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Edouard	8/3/2008 La.	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Dolly	2008	Storm (CAT2)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Gustav	9/1/2008 La.	Storm (CAT4)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Ike	9/12/2008 Tx./La.	Storm (CAT4)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018

Table 1.

Important Diversions, Storms, Floods and Draughts.

Name	Year	Event Type	Affected Area	Source
Tropical Storm Claudette	2009	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Ida	11/9/2009 La./Ms.	Storm (CAT2)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Coastal Flooding	2009	Flood	Parishes: Lafourche	Weather Research Center 2002, NOAA 2018
Tropical Storm Five	2010	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Bonnie	2010	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Tropical Storm Lee	9/2/2011 La.	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Drought	Jan-Dec. 2011	Drought	Louisiana	NOAA 2018
Drought	Jan-Mar. 2012	Drought	Louisiana	NOAA 2018
Tropical Storm Debby	2012	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Hurricane Isaac	8/28/2012 La.	Storm (CAT1)	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Drought	Aug-Oct. 2013	Drought	Louisiana	NOAA 2018
Tropical Storm Karen	2013	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Coastal Flooding	2013	Flood	Parishes: Orleans, St. Tammany	Weather Research Center 2002, NOAA 2018
Drought	Aug-Oct. 2015	Drought	Louisiana	NOAA 2018
Tropical Storm Bill	2015	Storm	Gulf of Mexico	Weather Research Center 2002, NOAA 2018
Coastal Flooding	2015	Flood	Parishes: Jefferson, St. Tammany, St. Bernard, Orleans	Weather Research Center 2002, NOAA 2018
Drought	Oct-Dec. 2016	Drought	Louisiana	NOAA 2018

"Name" indicates the diversion that was implemented or the event that took place that may have affected the HSI. "Year" specifies when it took place, "Event Type" specifies the category, and "Affected Area" indicates the general extent of impact.

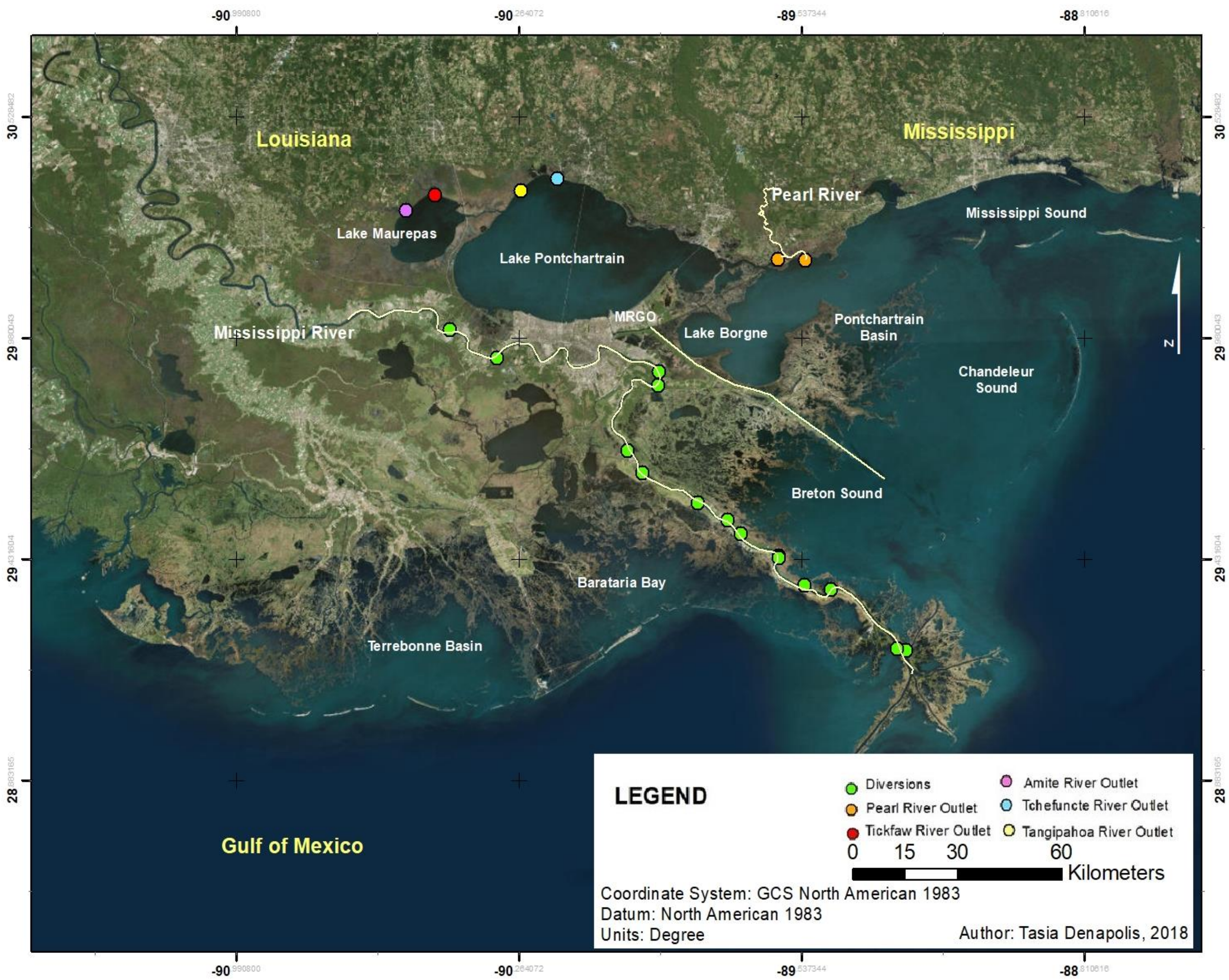

Figure 1. Area of Study

Map displays area of study in southeastern Louisiana, its boundaries, diversions & major freshwater sources. (Sources: Esri, HERE, Garmin, OpenStreetMap contributors, DigitalGlobe, GeoEye, Earthstar Geographics, CNESArbus DS, USDA, USGS, Aerogrid, IGN, Google Maps, & the GIS User Community)

and the area of Rigolets Pass. The Tangipahoa and Tchefuncte rivers empty into Lake Pontchartrain, which joins to Lake Borgne through the Chef Menteur and Rigolets passes nearby. The Tickfaw and Amite rivers discharge into Lake Maurepas, which flows directly into Lake Pontchartrain adding to the fresh water incursion (Guntenspergen 1992, McAnally & Berger 1997).

Historic Habitat Suitability Index Models

Cake's (1983) HSI model for the eastern oyster was founded on practices and guidelines used by U.S. Fisheries and Wildlife Services in 1981 to formulate management strategies and impact assessments of the Gulf of Mexico's subtidal estuarine habitat. His HSI integrated both pre-settlement (larval) and post-settlement (seed, spat and adult) life phase suitability indices into a single final value that indicated the potential of an area to support a *C. virginica* reef. His pre-settlement SI had three variables: cultch coverage, mean summer salinity and mean abundance of living oysters (Table 2).

Table 2.

Eastern Oyster Habitat Suitability Index (Cake 1983).

Name	SI Type	Variable	Description	SI Equivalency
V_1	Pre-settlement HSI1/HSI2	Cultch .Coverage (<50% unsuitable)	Clean, solid material such as shells, rocks, gravel or shell hash	0% cultch SI =0.0, 20% cultch SI =0.4, 40-100% cultch SI =1.0
V_2	Pre-settlement HSI1/HSI2	Larval Settling: Mean Summer Salinity	Ideal=18-22	Salinity 0.0SI =0.0, Salinity 5.0 SI =0.0, Salinity 10.0-30.0 SI =1.0, Salinity 35.0 SI = 0.5 and Salinity 40.0 SI =0.0
***V_3**	Pre-settlement HSI1/HSI2	Sociable Settling Factor: Mean Abundance of Living Oysters	Ideal abundance established was ≥25/m²	0/m² SI=0.0, 10/m² SI =0.4, 20/m² SI =0.8, 25-100/m² SI = 1.0
V_4	Post-settlement HSI1/HSI2	Historic Mean Salinity	Ideal = 10.0-20.0	Salinity 0.0 SI =0.0, Salinity 10.0-20.0 SI =1.0, Salinity 25.0 SI =0.7, Salinity 35.0 SI =0.2 and at Salinity 40.0 SI =0.0
V_5	Post-settlement HSI1/HSI2	Killing Flood Effect	Continuous Salinity ≤2.0 for several weeks is deadly to 50-100% of oysters	Salinity 0.0-1.0 SI =0.0, Salinity 2.0 SI =0.5, Salinity 3.0-5.0 SI =1.0
****V_6**	Post-settlement HSI1/HSI2	Mean Substrate Firmness (indicated by a penetrometer device)	Ideal firmness is ≥1.0kg/cm² with <80% sand, silt or clay composition	0.0 kg/cm² SI =0.0, 0.5 kg/cm² SI =0.5, 1.0-2.0 kg/cm² SI =1.0
*****V_7**	Post-settlement HSI2	Mean Predator Abundance (*S. haemastoma*)	≥1 drill (>4.0 cm size)/ m² as unacceptable	0.5 drills/m² SI =1.0, 0.4 drills/m² SI =0.5,0.8 drills/m² SI =0.2, 1.2 drills/m² SI =0.1 and >2.0drills/m² SI =0.0
***V_8	Post-settlement HSI2	Mean Disease Intensity (caused by the protozoan *P. marinus*)	Oysters infected at medium heavy/heavy levels (Quick 1972 appraisal technique) will not survive	levels 0-1 SI =1.0, level 2 SI =0.7, level 3 SI =0.5, level 4 SI =0.2, and levels 5-6 SI =0.0

*if V3=0.0 the pre-settlement SI is to be calculated as follows: $(V_1 * V_2)^{½}$
**if the substrate is composed of ≥80% sand then the composite post-settlement SI =0.0
*** V_7 and V_8 included for specific applications in oyster management "Name" indicates the notation used for a specific variable in the formula. "SI Type" categorizes the suitability indices into either pre- or post-oyster settlement stages. "Variable" describes the type and significance of the variable. "Description" explains the variable and "SI Equivalency" represents variable as suitability index value between zero and one.

When Cake (1983) calculated their HSI, the common rule was that if post-settlement SI < pre-settlement SI then HSI = post-settlement SI, or if post-settlement SI > pre-settlement SI, the HSI $=(\text{post} - \text{settlement SI} * \text{pre} - \text{settlement SI})^{1/2}$. The HSI was envisioned as a comparative approach to discern which of 2 or more habitats were most suitable to support a population of *C. virginica* in the subtidal estuarine areas of the northern Gulf of Mexico (Cake 1983).

Chatry et al. (1983) used historical data to examine the relationships relating salinity, spatfall and seed oyster (26-75 mm in size) production in Breton Sound (south of Terre aux Boeufs and east of the Mississippi River) (Table 1). They summarized data collected within a 10 year period (beginning in 1971) at three sites: Black Bay, Bay Gardene and California Bay. Their main focus was salinity for the months critical to spawning and settling (May through September). Weekly salinity values and spatfall were recorded (>20 seed/m^2 was considered the minimum desirable level). An analysis of the relationship between salinity and number of spat set indicated 20-22 as the ideal salinity. They also noted there was an inverse relationship of spat set and seed production such that lighter sets produced more seed oysters. When examining salinity and seed production they determined that ideal salinity was 12.2-17.4 however, inspection of data from the 8 highest oyster production years led them to conclude there was no single perfect salinity, but a salinity regime that was most conducive to oyster production. The optimal regime was intended to reflect a salinity profile most conducive to high seed oyster production.

Table 3.

Optimal Monthly Salinity Survey. Chatry et al. (1983) simplified the ideal salinity regime to average ideal salinities for each month.

Month	Ideal Salinity
January	16.4
February	14.4
March	11.6
April	8
May	7
June	12.5
July	12.7
August	15.7
September	17
October	16.8
November	16.1
December	15.7

"Ideal Salinity" refers to the approximate ideal salinity for a specific month during an oyster's life cycle.

"HSI models provide a standardized means for assessing habitat quality for particular species on a scale from 0 to 1, where 1 represents optimal habitat. Soniat & Brody (1988) tested the HSI created by Cake (1983) for *Crassostrea virginica*, which included the following variables: (1) percent cultch coverage, (2) mean summer salinity, (3) mean abundance of living oysters, (4) historic mean salinity, (5) killing flood effect, (6) mean substrate firmness, (7) mean predator abundance and (8) mean P. marinus infection. They decided that the third variable undesirably altered the HSI calculation when assessing commercially harvested reefs due to the artificial drop in abundance created by harvesting. They also noted that spat concentration showed a positive association with high salinity in spawning season and was inversely correlated with the harvest of the preceding season (which also bears on variable 3, thus lowering the final HSI). Their recommendation was to simplify the model by removing variable 3 thus eliminating circular dependency. In agreement with Allen et al. (1984), they found that HSI values were lowest at extreme salinities and highest at intermediate salinities, and as salinity values moved away from optimal, seed production decreased (Soniat & Brody 1988).

Starke et al. (2011) devised a Restoration Suitability Index (RSI) to identify areas in the lower Hudson River and New York Harbor suitable for *C. virginica* reef restoration (via construction). The project was motivated by a focus on substrate suitability, and reef height was noted to be of particular importance due to the turbidity of the river. The four main parameters taken into account were salinity, depth, sediment type and sedimentary environment. Several different weights were applied when testing calculations of the salinity component of the RSI to optimize results minimize errors and investigate multiple possible scenarios. The explored scenarios were: an Analytic Hierarchy Process/ mean salinity suitability, an even weighted scenario/ mean salinity suitability, salinity dominant/ mean salinity suitability, Analytic Hierarchy Process/mean minus uncertainty in salinity suitability, an even weighted scenario/ mean minus uncertainty in salinity suitability, and salinity dominant/ mean minus uncertainty in salinity suitability. The results showed that the salinity dominated weighted scenario was the most conservative and the best choice for determining placement of restorative projects.

Pollack et al. (2012) devised a Restoration Suitability Index model for *C. virginica* in the Mission-Aransas estuary on the coast of Texas (Table 4). It is similar to the RSI of Starke et al. (2011), by including salinity and depth as variables, but it added effects of temperature, turbidity, and dissolved oxygen. Areas with the lowest standard deviations from the normalized variable measurement values were assigned higher SI values as they indicated a more stable environment with less extreme variations. Infection was weighted by averaging the ranked infections (5 point modified version of the Mackin Scale). Higher values were assigned to higher turbidity, lower temperatures with lower standard deviations, lower incidences of low dissolved oxygen, and moderate salinities (15 being ideal). The RSI parameters were weighted where standard deviations were set at a weight of 1, all normalized environmental variables to 2 and salinity to 4. If any parameter had a suitability index of zero then the RSI was also equal to zero. $RSI = (\prod_{i=1}^{n} NEV_i^{wi})^{1/n}$ w_i is the relative weight of importance of the normalized environmental variables (NEV). It was noted that areas with a high RSI were often located on live oyster reefs, and areas with the lowest RSI were in the deepest areas of the study site.

Table 4.

Restoration Suitability Index (Pollack et al. 2012).

Variable Type	Value	SI Equivalency
Salinity	10 15 28	SI = 0.75 SI = 1.0 SI = 0.0
Salinity Standard Deviation	5 10	SI = 1.0 SI = 0.0
Frequency of Dissolved Oxygen < 4 mg/l.	0 7	SI = 1.0 SI = 0.925
Frequency of Dissolved Oxygen < 4 mg/l. Standard Deviation	1 to 2 0.5 to 1 and 2 to 3 <0.5 and >3	SI = 1.0 SI = 0.5 SI = 0.0
Turbidity	10 NTU 59 NTU	SI = 0.0 SI = 1.0
Turbidity Standard Deviation	10 75	SI = 1.0 SI = 0.0
Temperature	22 ºC 25.8 ºC	SI = 0.0 SI = 1.0
Temperature Standard Deviation	4.75 6.5	SI = 1.0 SI = 0.0
Depth	1-2 m. 0.5 – 1 m. and 2-3 m. <0.5 and >3 m.	SI = 1 SI = 0.5 SI = 0.0

"Variable" refers to the type of data used to calculate the RSI. "Value" indicates salinity measure of the corresponding variable type, and "SI Equivalency" is how each value translates on a scale from 0.0 – 1.0. All variable values were normalized with the exception of depth.

The appendix to the 2012 Coastal Master Plan included a HSI created by Dr. Tom Soniat for the Lower Breton Sound Diversion as a management tool to evaluate the effects of particular restoration plans on existing oyster reefs (Soniat 2012; Table 5). This HSI was calculated without weighting any of the component parameters as follows: $(V_1 * V_2 * V_3 * V_4 * V_5)^{1/5}$ and returned a HSI value for a single year. The limitations of this modified model were its failure to address temperature effects as well as possible benefits from recruitment from other reefs. A slightly adjusted version of his 2012 HSI was published the following year (Soniat et al. 2013; Table 5).

Table 5.

Revised Eastern Oyster Habitat Suitability Index. Comparison of Soniat 2012 & Soniat et al. 2013 HSI models.

Variable	Variable Type	Value	2012 SI Equivalency	2013 SI Equivalency
V_1	Cultch Coverage (<50% unsuitable)	0% cultch coverage	SI =0.0	SI =0.0
		10%	SI = 0.4	SI = 0.4
		20%	SI = 0.6	SI = 0.6
		30%	SI = 0.8	SI = 0.8
		40%	SI = 0.9	SI = 0.9
		50-100% cultch coverage	SI =1.0	SI =1.0
V_2	Mean Spawning Salinity (May-Sept)	Salinity 0-5 and 40	SI =0.0	SI =0.0
		Salinity 35	SI =0.1	SI =0.1
		Salinity 10 and 30	SI =0.3	SI =0.3
		Salinity 15	SI =0.6	SI =0.65
		Salinity 18-22	SI =1.0	SI =1.0
V_3	Minimum Annual Salinity (minimum mean monthly salinity within a year)	Salinity 0-2	SI =0.0	SI =0.0
		Salinity 4	SI =0.05	SI =0.05
		Salinity 6	SI = 0.5	SI = 0.5
		Salinity 8-10	SI = 1.0	SI = 1.0
V_4	Mean Annual Salinity	Salinity 0-5 and 40	SI =0.0	SI =0.0
		Salinity 35	SI = 0.05	SI = 0.05
		Salinity 30	SI = 0.1	SI = 0.1
		Salinity 25	SI = 0.3	SI = 0.25
		Salinity 20	SI = 0.6	SI = 0.6
		Salinity 10-15	SI = 1.0	SI = 1.0
V_5	Percent Land	Gradient from 0%-100%	SI =1.0-0.0 (correspondingly)	SI =1.0-0.0 (correspondingly)

"Variable" indicates the variable's abbreviation in the HSI formula. "Variable Type" is a description of the variable used to calculate the HSI while "Value" is a quantification of each variable type. "SI Equivalency" translates the values on a scale from 0.0 – 1.0 to calculate the HSI for the year indicated.

Swannack et al. (2014) revised the models of Cake (1983), Soniat & Brody (1988), Pollack (2012), and Soniat (2012) into a new RSI to characterize and compare the suitability of both the Chesapeake Bay and Western Mississippi Sound regions. The variables included were percent cultch, mean spawning season salinity, mean annual salinity and minimum annual salinity, and did not include temperature effects. All relationships were identical to Soniat (2012) except for percent cultch which was defined with the following equation: $SI_{\%\ Cultch} = 0.01 \times (\%\ Cultch)$ which produced a more conservative SI than the relationship used in Soniat's 2012 HSI, which designated >50% cultch coverage at a SI value of 1. The same relationships were used to define SI values in both geographical locations. The RSI was then calculated as the unweighted geometric mean of the variables categorized as low for values 0 – 0.25, low/medium for 0.25 – 0.55, medium/high for 0.55 – 0.85, and high for 0.85 – 1.0 and mapped using GIS (Swannack 2014).

Preau et al. (2016) compared the habitat suitability models of Chatry et al. (1983) and Soniat (2012), to evaluate their usefulness in the management and restoration of reefs east of the Mississippi River. They averaged bi-weekly surface salinity values from 2013-2015, and generated maps to visualize the results of the models for comparison. Chatry et al. (1983) focused their model on seed oyster production in Breton Sound, taking into account the relationships relating salinity, set and seed production. The data was derived directly from live oyster reefs that were considered to be in an ideal production environment for seed oysters (Chatry et al. 1983). Soniat (2012) had five suitability indices that characterized the effects of salinity on spawning and production, and expanded to include the percent land variable, and an additional substrate factor that required reefs to be self-sustaining. Overall the outcomes of both models were in accord displaying similar unsuitable HSI values in Lakes Pontchartrain and

Maurepas however, there were some differences in the areas more open to the Gulf of Mexico. Although regions considered optimal by both models overlap in all three years, the Soniat (2012) model consistently showed larger areas of the top three salinities and smaller unsuitable areas, with the largest differences at the extremes. Chatry et al. (1983) placed optimal areas higher in the estuary whereas the Soniat (2012) results were further towards the Gulf of Mexico. Noting that hypoxia (not included in the model) can be an important factor to oyster survival, model representations were overlaid onto maps of hypoxic areas revealing areas where the model's predictions might be less effective. Historic reefs and U.S. Army Core of Engineers target areas for oyster reef restoration projects were also added to the map to enable better educated decisions for management (Preau et al. 2016).

Present Work

Habitat Suitability Index models have potential as a management tool to determine optimal locations for oyster cultivation as freshwater diversions are implemented. This work uses historical salinity data to visualize legacy HSI conditions prior to proposed freshwater diversions and provides a framework for predicting the location of suitable habitat due to their implementation. The purpose of the present work is to expand on the Soniat et al. 2013 model. The focus area for the application of our habitat suitability model is the southern coastal estuarine area of Louisiana that is crucial to Louisiana's oyster industry – specifically the Barataria and Pontchartrain Basins (Roberts et al. 1992, Soniat et al. 2013). Legacy HSI visualizations show annual fluctuations in the distribution of zones suitable for cultivation of *Crassostrea virginica* oysters subject to freshwater and sediment diversions. Hydrographic models of the effects of future diversions on the distribution of salinity, coupled with the HSI, enable predictions of suitable locations for oyster cultivation post-diversion.

Methods

Study Area

The study area includes the southern coastal estuarine regions in the deltaic plains of Louisiana bounded by Bayou Lafourche to the west, and Pearl River and Mississippi Sound to the east. This shallow estuary is a wetland that contains a network of lakes, bayous and canals varying along a gradient from inland freshwater to saline offshore, governed by fresh riverine input, diversions, and the saline waters of the Gulf of Mexico (Chatry et al 1983, Lopez et al. 2003, LaPeyre et al 2015) . Frequent flooding and subsidence are converting the wetlands to open water and storms and diversions contribute to the dynamic salinity environment (Lopez et al. 2003, LaPeyre et al. 2015). Multiple diversions have been implemented to reduce wetland loss and enhance production in the oyster industry (Roberts et al. 1992, Soniat et al. 2013). The study incorporates both the current and past oyster reefs of Pontchartrain and Barataria Basins, and extends into the higher salinity waters of Chandeleur Sound that may be appropriate for supporting oyster farming should diversions be utilized (Sallenger 1997, Soniat et al. 2013, LDWF 2016).

Data Collection and Treatments

Over forty years of Salinity data was obtained from five sources: United States Geological Survey (USGS), Lake Pontchartrain Basin Foundation (LPBF), Louisiana Department of Wildlife and Fisheries (LDWF), National Oceanic and Atmospheric Administration (NOAA), and Coastwide Reference Monitoring System (CRMS) (Figures 6-10). All data were checked for errors, and uniformly formatted in Notepad++ and Microsoft Excel. Salinity data locations not taken in NAD1983 were converted using an online converter to the corresponding NAD1983 location for continuity when mapping (V-Datum 2018). Real-time data (high frequency of measurements taken in one location) was averaged to a weekly value for each location, then monthly averages. An algorithm was created to incorporate the equally weighted effects of temperature and salinity on spawning/reproduction, physiological ability/growth and mortality. Finally, all data were loaded into an online database where the algorithm was applied to derive the annual HSI value for each location. Streamflow data was procured from USGS for gages on tributaries to the study area to serve as a representation of fresh influx into the basins (USGS 2018). Oyster Stock Assessment data was provided by LDWF, and only years (2012-2016), and reefs with available data were analyzed using a generalized linear model statistical approach (Tables 6-8). Oyster abundance was sampled at 58 stations, (9 in Barataria Basin, 32 in Breton Sound, and 17 in the Biloxi Marsh wetlands (east of the MRGO between Chandeleur Sound and Lake Borgne) and classed by size (Table 9). Oyster stock assessment stations in the Biloxi Marsh wetlands included sites at Morgan Harbor, East and West Karako, Millenium and Cabbage Reefs, Shell Point, Grassy, Petit, Grand Banks, Johnson and Turkey Bayous, 3-Mile and the 3-Mile Pass 2013 Cultch Plant, Round Island 2011 Cultch Plant, Drum Bay and the Drum Bay 2013 Cultch Plant (Table 9, Figure 64). Oyster stock assessment stations in Breton Sound (between MRGO and the Mississippi River) included sites at Jessie, Wreck, Sunrise Point, Black Bay, North and South Black Bay, California Bay, North California Bay, California Bay 2011 Cultch Plant, Bay Gardene, East Bay Gardene, Telegraph, North and South Lake Fortuna, Lake Fortune 2012 Cultch Plant, Horseshoe and Battledore Reefs, Mangrove, Curfew, East and West Pelican, East Stone, Bays Lone and Crabe, East and West Bay Crabe, Lonesome and North Lonesome, Snake, Elephant Pass, and Bayou Lost (Table 9, Figure 64). Oyster stock assessment stations in Barataria Bay (between Terrebonne Bay and the Mississippi River) included sites located in lower, middle and upper Hackberry Bay, Hackberry 2014 Cultch Plant, 2004 North and South Hackberry Cultch Plants, 2008 Cultch Plant, 2012 Cultch Plant, and the 2004 Barataria Bay Cultch Plant (Figure 64).

HSI and SI Formulations

The present HSI is calculated as a geometric mean of unweighted values derived from the relationship between chosen variables and a Suitability Index (SI). Use of the geometric (rather than arithmetic) mean of suitability indices results in a HSI of 0.0 if any SI=0. Both HSI, and SI vary from 0 (unsuitable) to 1 (ideal) (Figures 2-5). The environmental factors of focus in the development of this HSI were temperature and salinity, however, month was used as a proxy for temperature. The temperature dependency is manifested in SI3 (minimum salinity) (Lowe et al. 2017).

Average Annual Salinity

Average annual mean salinity incorporates monthly salinity values for a full year as a historical component, and indicates the optimal salinity range where oysters may exist however, it does not guarantee their presence (Soniat et al. 2013). The inability of the gastropod predator *Stramonita haemastoma* and the parasite *P. marinus* to survive in salinities lower than 15 was a large factor in assigning suitability values as it represents partial mortality due to predators and disease (Craig et al. 1989, Soniat 1996). Salinity data from U.S.G.S., L.P.B.F., L.D.W.F., N.O.A.A., and C.R.M.S. was averaged into a monthly value for each sampling location, and then into an annual value. The relationship was: Salinities of 0.0, 5.0, 40.0, and above all had a SI value of zero. Salinities of 10.0 – 15.0 are SI of 1.0, 20.0 was SI of 0.6, 25.0 was 0.25, 30.0 was 0.1 and 35 was S.I of 0.05.

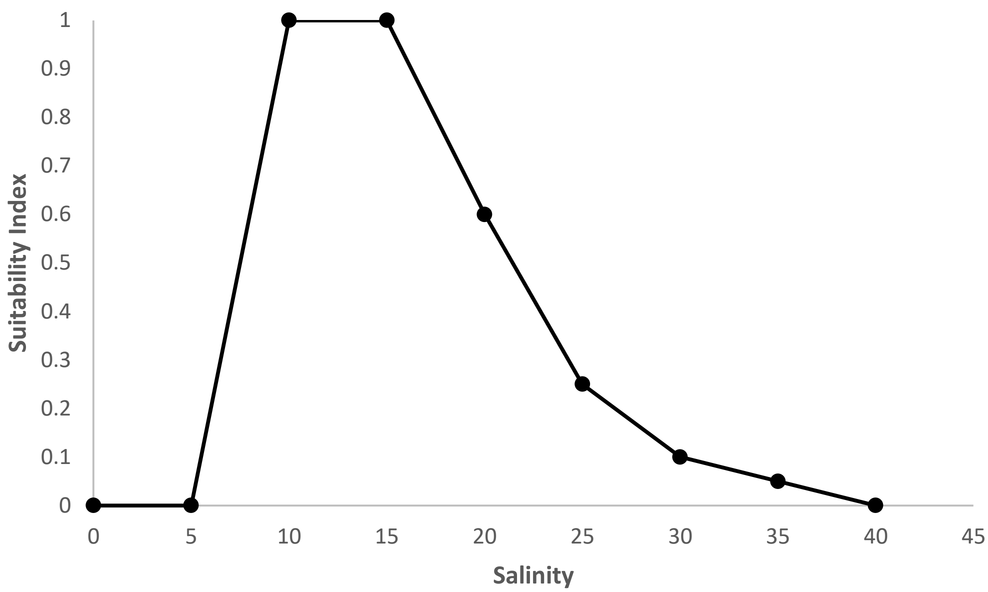

Figure 2. Suitability Index 1 - Average Annual Salinity

Mean Spawning Season Salinity

The warmer months of April-September are when spawning takes place for Louisiana's eastern oysters (Soniat et al. 2006, Soniat 2012, Soniat et al. 2013). The average spawning salinity suitability index differs from the annual mean salinity as it addresses the need for higher salinities that ensure successful spawning and larval survival. The relationship was: Salinities of 0.0 and 5.0 had a SI value of zero. Salinity of 10.0 had a SI of 0.3, 15.0 was SI of 0.65, 18.0-22.0 were 1.0, and 30.0 was SI of 0.3.

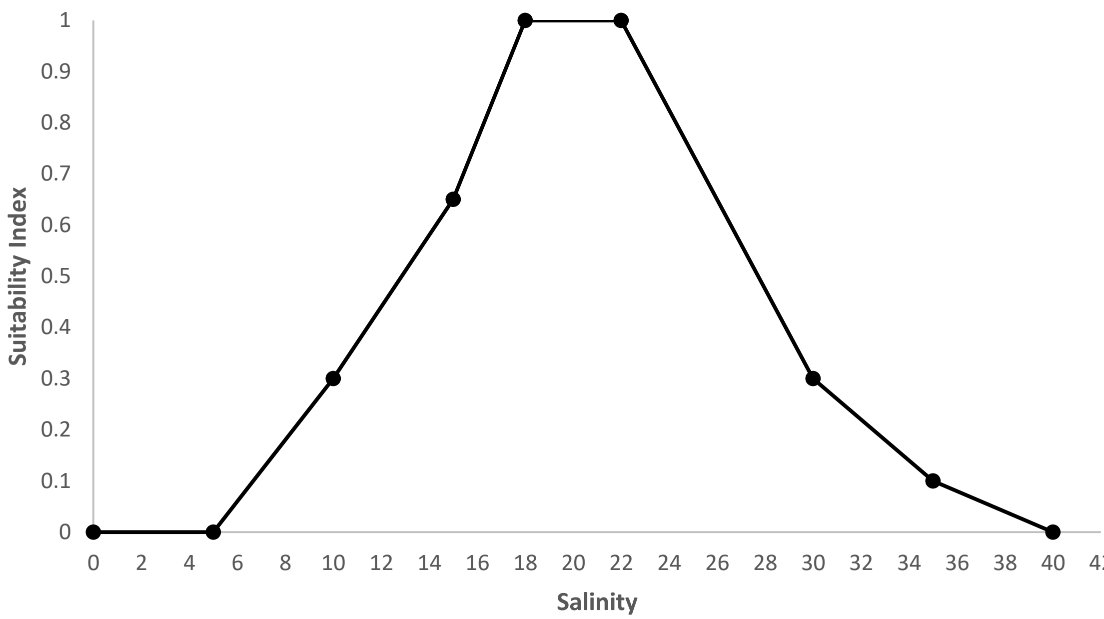

Figure 3. Suitability Index 2 - Mean Spawning Season Salinity

Minimum Salinity

The minimum salinity suitability index was the minimum mean salinity in any month during a year's time. It accounted for the synergistic effects of temperature and salinity on the physiology of the oysters and delineated the impacts of killing floods (Soniat et al. 2013). The relationships were: Warm months: Salinities of 0.0, 1.0, 2.0, 20.0, and above all had a SI value of zero. Salinity of 5.0 was SI of 0.1, 8 was SI of 1.0 and 15 was S.I of 0.2; Cool Months: Salinities of 0.0, 1.0, 20.0, and above all had a SI value of zero. Salinity of 5.0 was SI of 0.1, 8 was SI of 1.0 and 15 was S.I of 0.2. First the lowest mean monthly salinity for each year was identified. Month was used as a proxy for temperature; warm month and cold month relationships relating to minimum salinity, and minimum suitability index were developed and applied according to which month was being calculated.

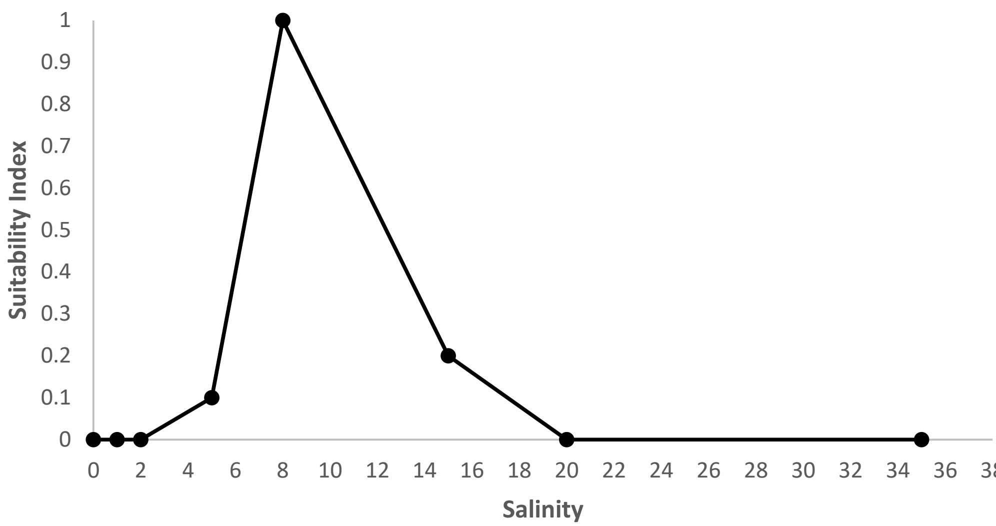

Figure 4. Suitability Index 3 – Minimum Average Salinity - Warm Months: April-September

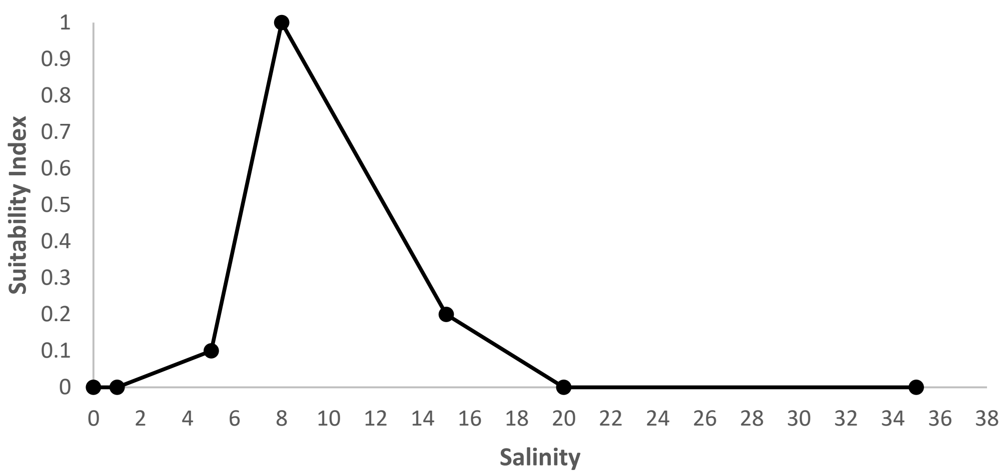

Figure 5. Suitability Index 3 – Minimum Average Salinity - Cool Months: October-March

Data capture was automated, and the HSI was calculated as an annual value for each sampling location, and a map was created for each year using ArcGIS ArcMap v. 10.3.1 (ESRI 2007) to visualize an overlay of the HSI onto a map of southern Louisiana. Color-coded polygons and iso-lines were created by interpolating HSI values using nearest neighbor for each

HSI. Finally, output from the models were uploaded on the Oyster Sentinel website (www.oystersentinel.org).

GIS

All mapping was done in ArcGIS ArcMap v. 10.3.1. (ESRI 2007) Water, and land maps were imported from the U.S. Census Bureau (LSU 2008, U.S. Census Bureau Tiger 2017a & 2017b). The 2008 Southeast Louisiana Parishes file was downloaded from Louisiana Department of Transportation and Development (Parker 2017). An additional Lake Pontchartrain map was imported from Esri online. Water maps were merged to create one continuous layer encompassing the waters of coastal, Southeastern Louisiana. The erase tool was used on the land map (which included waters) to remove the water and was then labeled “Land” for the sake of simplicity. All maps and data were in the NAD 1983 datum and coordinate system. The HSI data from January of 1967 to June 30th of 2017 was separated by year and basin (by selection on the GIS attribute table), and exported onto the map. The XY data were then plotted and the events exported as a shape files. The shape files were then clipped to the parish layer to remove offshore data points that could skew the final product and cause misrepresentation of suitable habitat. A triangular irregular network (TIN) layer was created from each clipped layer (3D-Analyst) interpolating the HSI values using nearest neighbor technique, and a color ramped raster (high to low values) was created from the TIN layer (3-D Analyst). Finally, contour lines were assigned to each 0.1 interval across the raster (Contour – Spatial Analyst) and labeled to display the HSI across the raster gradient.

Statistical Analyses

The oyster abundance dataset included repeated measures with unequal sample sizes, nested values, and non-normal distributions that did not respond to transformations hence, a generalized linear model was the best course for analysis. A generalized linear model was applied to each of three size class (spat, seed and sack) datasets in R using a quasi-Poisson distribution setting. The models were then reduced to minimum adequate models to explain variance in the response variable (oyster abundance). Factors included in the models were reef size, cultch quality, year, habitat suitability index (HSI), and the interactions between the variables. Reef size indicated the influence of gregariousness on spat set (Soniat & Brody 1988). Cultch quality was designated by the amount of brown (not buried by mud or sand) cultch present indicated by a value of 1 (high suitability =1000 g/m^2 and above) or zero (assigned to anything below 1000 g/m^2) (T. Soniat, personal communication). Year was included to account for stochastic events such as storms, droughts, floods. HSI accounted for the effects of temperature and salinity during oyster spawning, setting and growth (Lowe et al. 2017). Estimates are the coefficients of the predictors each with a significance value of effect on the response variable (abundance). Intercept values represent the grand mean for each variable in the model. Deviance is a measure of the unexplained variation after fitting the model and serves as a measure of goodness of fit (lower values indicate a better fit). Null deviance represents how well the response is predicted by the intercept alone. The dispersion parameter simplifies the relationship between the variance and the mean to a single number indicating how many times larger the variance is than the mean. A dispersion parameter below 1 indicates under-dispersion, and above 1 indicates over-dispersion (Lillis 2008).

Results

GIS Map Analysis

Heat maps generated from 1967-2016 show the HSI profile for each particular year however, statistical analysis was limited to years for which cultch and oyster stock assessment data were available (2012-2016). Upper Lake Borgne, near the Rigolets and Lake Pontchartrain outlet (Figure 1), displayed consistent HSI values below 0.5 (Figures 14-56, 58- 61, & 63) with the exception of tiny hot spots in 2015 (Figure 62) and intermediate values (HSI 0.5-0.7) in the year 2000 (Figure 57). There was no data for 1970 (Figure 17). The area of Lake Borgne nearest to the Caernarvon Diversion had low HSI values (< 0.5) from 1969 until the 1980s (Figures 16-27), and again in 1984 (Figure 31), and from 1999 (Figure 46), and 2006 (Figure 53). HSI values were low but approached intermediate in 1983 (Figure 30), 1987 (Figure 34), 1988 including a small hot spot (Figure 35), 1990-1998 (Figures 37-45), 2001-2005 (Figures 48-52), and 2007-2016 (Figures 54-63). The HSI was intermediate in 1967-1968 (Figures 14-15), 1981-1982 (Figures 28-29), 1985-1986 (Figures 32-33), 1989 (Figure 36) and 2000 (Figure 47).

The Biloxi Marsh wetlands had overall low HSI values in 1973 (Figure 20), 1976-1977 (Figures 23-24), 1981 (Figure 28), 1983 (Figure 30), 1992 (Figure 39), 1997-1998 (Figures 44-45), and low with hot spots in 1972 (Figure 19), 1974 (Figure 21), and 1979 (Figure 26). The years 1969 (Figure 16), 1988 (Figure 35), 1990 (Figure 37), 2010-2011 (Figures 47-48), 2013 (Figure 50) and 2016 (Figure 53) had a low to intermediate HSI gradient, with some years having hot spots including 1975-1977 (Figures 22-24), 1984 (Figure 31), 1987 (Figure 34), and 1999 (Figure 46). The years 1968 (Figure 15), 1980 (Figure 27), 1991 (Figure 38), 2000 (Figure 47), 2004 (Figure 51) and 2012 (Figure 59) had predominantly intermediate HSI values, while 1967 (Figure 14), 1989 (Figure 36), 1993 (Figure 40), 1996 (Figure 43), 2001-2002 (Figures 48-

49), 2005 (Figure 52), 2007 (Figure 54), 2009 (Figure 56) and 2015 (Figure 62) approached higher values. High HSI values (> 0.7) were observed in 1982 (Figure 29), and 1984-1986 (Figures 31-33). There was a low to high gradient in 1970 (Figure 17), 1994-1995 (Figures 41-42), 2003 (Figure 50), 2006 (Figure 53), 2008 (Figure 55), and 2014 (Figure 61). No data was available for 1970 and 1971 (Figures 17-18).

The region of Breton Sound immediately impacted by White's Ditch Diversion and the Violet Siphon were dominated by low HSI values in 1967 (Figure 14), 1973 (Figure 20), 1975 (Figure 22), 1978-1979 (Figures 25-26), 1990-1999 (Figures 37-46), 2002-2005 (Figures 50-53), and 2007-2016 (Figures 55-63). Intermediate HSI values were only prevalent in 1968 (Figure 15) and 1982 (Figure 29). There was a weak gradient from low to intermediate HSI approaching the Gulf of Mexico in 1967 (Figure 14), 1969 (Figure 16), 1974 (Figure 21), 1980-1981 (Figures 27-28), 1988-1989 (Figures 34-36), 2000-2001 (Figures 47-48) and 2006 (Figure 53), and a similar pattern of low to high HSI in 1970-1972 (Figures 17-19), 1976-1977 (Figures 23-24), and 1984-1987 (Figures 31-34).

The region of Breton Sound affected by the Bohemia Spillway and Mardi Gras Pass principally displayed low HSI values near the Mississippi River rising with distance from shore for the years 1974-1975 (Figures 21-22), 1978 (Figure 25), 1982 (Figure 29), 1984 (Figure 31), 1989-1990 (Figures 36-37), 1997 (Figure 44), 1999-2000 (Figures 46-47), 2006 (Figure 53), and 2011-2015 (Figures 58-62), and was mainly low in 1979 (Figure 26), 1983 (Figure 30), 1991 (Figure 38), 1993-1994 (Figures 40-41), 1998 (Figure 45), and 2010 (Figure 57). Intermediate HSI values were seen in 1970 (Figure 17), 1972 (Figure 19), 1976-1977 (Figures 23-24), 1980-1981 (Figures 27-28), and 1992 (Figure 39). The only years showing high HSI values were 1967-1969 (Figures 14-16), 1971 (Figure 18), 1973 (Figure 20), and 1985-1988 (Figures 32-35).

No data was available near the outfall areas for the years 1995-1996 (Figures 42-43), 2001-2005 (Figures 48-52), 2007-2009 (Figures 54-56) and 2016 (Figure 63).

The outfall areas of Bayou Lamoque and the Ostrica Locks displayed low HSI values in 1982-1983 (Figures 29-30) and in 2010 (Figure 57), and a low to intermediate gradient in 1975 (Figure 22), 1979-1980 (Figures 26-27), 1984 (Figure 31), 1994 (Figure 41), 1997-2000 (Figures 44-47), 2005-2006 (Figures 52-53), and from 2011-2016 (Figures 58-63). Intermediate values were observed in 1967-1969 (Figures 14-16), 1972 (Figure19), and 1981 (Figure 28), with a rising gradient to higher values in 1971 (Figure 18), 1974 (Figure 21), 1976-1978 (Figures 23-25), and 1992 (Figure 39). 1973 (Figure 20) was the only year with a high HSI, and there was no data for 1970 (Figure 17). The nearest available values to the region adjacent to the outfall area were intermediate for 2009 (Figure 56), with a rising gradient in 1985 (Figure 32), 1990 (Figure37), 1995-1996 (Figures 42-43), 2001 (Figure 48), and 2003-2004 (Figures 50-51). The years 1991 (Figure 38), 1993 (Figure 40), 2002 (Figure 49), and 2008 (Figure 55), saw a reversal in this trend, with a decline in HSI away from the Mississippi River. The region nearest to the Channel Armor Gap Crevasse and the structures at Fort St. Philip (including Little Coquille Diversion, Delta Management) displayed low HSI values for 1968 (Figure 15), 1977 (Figure 24), 1979 (Figure 26), 1982 (Figure 29), and 2010 (Figure 57), with a rising gradient near the diversions in 1974-1975 (Figures 21-22), 1978 (Figure 25), 1980 (Figure 27), 1983-1984 (Figures 30-31), 1994 (Figure 41), 1997-2000 (Figures 44-47), 2006 (Figure 54), and 2011-2016 (Figures 58-63). Intermediate values were observed in 1967 (Figure 14), 1969 (Figure 16), 1972 (Figure 19), 1976 (Figure 23), 1981 (Figure 28) and 1992 (Figure 39), with an increasing gradient to higher values in 1971 (Figure 18). 1973 (Figure 20) was the only year with an overall high HSI, and there was no data available for 1970 (Figure 17), 1985 (Figure 32), 1987-1991

(Figures 34-38), 1993 (Figure 40), 1995-1996 (Figures 42-43), 2001-2005 (Figures 48-52), 2007-2009 (Figures 54-56), and 1986 (Figure 33) (although nearby areas were approaching intermediate in 1986).

West of the Mississippi River, the general trend of low HSI values inland increased near the mouth of Barataria Basin, and declined nearer to the region of the West Bay sediment diversion. The region nearest the West Pointe a la Hache siphon had low HSI values in 1992-1999 (Figures 39-46), 2002-2005 (Figures 49-52), and 2007-2016 (Figures 54-63). Intermediate and high values were observed in 2000-2001 (Figures 47-48) and 2006 (Figure 53). There was no data available for 1967-1981 (Figures 14-28). The region of the Barataria Basin from Grande Isle to Bay Long was only dominated by low HSI values in 1976 (Figure 23), 1979 (Figure 26), and 1981 (Figure 28). Predominantly intermediate values were observed in 1968 (Figure 15), 1973-1975 (Figures 20-22), 1980 (Figure 27), 1982-1987 (Figures 29-34), 1991-1992 (Figures 38-39), 1994 (Figure 41), 1998-1999 (Figures 45-46), 2006-2007 (Figures 53-54), 2012-2013 (Figures 59-60), and 2016 (Figure 63). High HSI was seen in 1967 (Figure 14), 1970 (Figure 17), 1990 (Figure 37), 1995 (Figure 42), 1997 (Figure 44), 2001 (Figure 48), and 2010 (Figure 57). There was a gradient from high in the east declining westward across Grande Isle in 1971-1972 (Figures 18-19), and 2000 (Figure 47), and the opposite trend was observed in 1996 (Figure 43), 2002-2005 (Figures 49-52), 2008-2009 (Figures 55-56), and 2011 (Figure 58) and 2014-2015 (Figures 61-62). A variety of spotty values were seen in 1977-1978 (Figures 24-25), 1988-1989 (Figures 35-36), and in 1993 (Figure 40). The area immediately impacted by the West Bay sediment diversion showed low HSI values in 2010-2016 (Figures 57-63). While no other data was available for wetlands closest to the diversion, the region to the west had low values in 1998 (Figure 45), 2005-2007 (Figures 52-54) and 2009 (Figure 56), intermediate values in 2002-2004

(Figures 49-51), high in 1994 (Figure 41), 1999-2001 (Figures 46-48). No data was available for the West Bay sediment diversion region in 1967-1993 (Figures 14-40), 1995-1997 (Figures 42-44), and 2008 (Figure 55).

Statistical Analyses

Shapiro testing on spat, seed and sack abundance returned low p values (all <.001) and low W values (<0.99) indicating that none of the data was normally distributed (Tables 6-8). Tukey's transformation did not resolve the problem (Tables 6-8). All dispersion parameters were larger than one indicating over-dispersion of errors. A generalized linear model (GLM) for spat abundance resulted in a minimum adequate model that included: year ($p<0.001$), cultch quality ($p<0.001$), cultch quality x year ($p<0.001$), HSI ($p<0.01$), the interactions of HSI x cultch quality ($p<0.01$), HSI x reef size ($p<0.01$), HSI x year ($p<0.01$), HSI x cultch quality x year ($p<0.01$), and HSI x reef size x year ($p<0.01$), reef size ($p<0.05$), the interactions between reef size x cultch quality ($p<0.05$) and the interactions of reef size x year ($p<0.05$) (Table 6). The GLM for seed abundance resulted in a minimum adequate model that included: HSI ($p<0.001$), year ($p<0.001$), interactions between HSI x cultch quality ($p<0.001$) cultch quality ($p<0.01$), the interaction between cultch quality x year ($p<0.01$), reef size ($p<0.05$), the interaction between HSI x reef size ($p<0.05$), reef size x cultch quality ($p<0.05$), and HSI x reef size x cultch quality ($p<0.05$) (Table 7). The GLM for sack abundance resulted in a minimum adequate model that included: HSI ($p<0.001$), cultch ($p<0.01$), interactions between HSI x reef size ($p<0.01$) (Table 8). Reef size was not significant, but because its interactions with other variables were important it was kept in the model.

Table 6.

Spat Abundance: Statistical testing results of step reduction procedures run on the full generalized linear model for spat abundance resulted in a minimum adequate model that explained the variation in the sample set.

Variables	Estimate	Standard Error	t value	Significance Pr(>|t|)	Significance Code
(Intercept)	$3.183e^{+03}$	$9.508e^{+02}$	3.347	$8.660e^{-04}$	***
HSI	$-7.303e^{+03}$	$2.791e^{+03}$	-2.616	$9.112e^{-03}$	**
Reef Size	$1.373e^{-04}$	$6.043e^{-05}$	2.272	$2.342e^{-02}$	*
Cultch Quality	$-3.518e^{+03}$	$9.665e^{+02}$	-3.640	$2.960e^{-04}$	***
Year	$-1.580e^{-00}$	$4.724e^{-01}$	-3.344	$8.770e^{-04}$	***
HSI x Reef Size	$-3.867e^{-04}$	$1.434e^{-04}$	-2.697	$7.191e^{-03}$	**
HSI x Cultch Quality	$9.227e^{+03}$	$2.811e^{+03}$	3.282	$1.089e^{-03}$	**
HSI x Year	$3.625e^{-00}$	$1.386e^{-00}$	2.615	$9.150e^{-03}$	**
Reef Size x Cultch Quality	$1.365e^{-07}$	$6.781e^{-08}$	2.013	$4.454e^{-02}$	*
Reef Size x Year	$-6.825e^{-08}$	$3.002e^{-08}$	-2.274	$2.332e^{-02}$	*
Cultch Quality x Year	$1.746e^{-00}$	$4.801e^{-01}$	3.637	$2.990e^{-04}$	***
HSI x Cultch Quality x Year	$-4.581e^{-00}$	$1.396e^{-00}$	-3.281	$1.095e^{-03}$	**
HSI x Reef Size x Year	$1.920e^{-07}$	$7.121e^{-08}$	2.696	$7.205e^{-03}$	**

(Dispersion parameter for quasipoisson family taken to be 8.34903) Number of Fisher Scoring iterations: 6

Null deviance: 3475.1 on 616 degrees of freedom Residual deviance: 2977.9 on 604 degrees of freedom

Shapiro-Wilk Normality Test	**Post-Tukey's Transformation (^0.325) Shapiro-Wilk Normality Test**
W = 0.55115, p-value < 2.2e-16	W = 0.90138, p-value < 2.2e-16

glm formula = (abundance ~ hsi + reef size + cultch + year + hsi:reefsize + hsi:cultch + reefsize:cultch + hsi: year + reefsize:year + cultch:year + hsi: reef size: year + hsi: cultch: year, family = quasipoisson)

Deviance Residuals:

Min	1Q	Median	3Q	Max
-3.4562	-1.7035	-0.9579	0.3311	12.6540

"Variables" indicate the data types fed into the model. "Significance" is the specific probability of how frequently the variable would be found by chance (follows Student's t distribution) and "Significance Code" represents significance level as follows: "ns" is not significant, "***" is to 0.001, "**" is to 0.01, "*" is to 0.05.

Table 7.

Seed Abundance: Statistical testing results of step reduction procedures run on the full generalized linear model for seed abundance resulted in a minimum adequate model that explained the variation in the sample set.

Variables	Estimate	Standard Error	t value	Significance Pr(>|t|)	Significance Code
(Intercept)	$1.443e^{+03}$	$4.132e^{+02}$	3.493	$5.120e^{-04}$	***
HSI	$-6.938e^{+00}$	$1.967e^{+00}$	-3.527	$4.520e^{-04}$	***
Reef Size	$-5.465e^{-07}$	$2.285e^{-07}$	-2.392	$1.705e^{-02}$	*
Cultch Quality	$-3.518e^{+03}$	$9.665e^{+02}$	-3.640	$2.960e^{-04}$	***
Year	$-1.285e^{+03}$	$4.269e^{+02}$	-3.010	$2.723e^{-03}$	**
HSI x Reef Size	$1.293e^{-06}$	$5.769e^{-07}$	2.241	$2.542e^{-02}$	*
HSI x Cultch Quality	$7.086e^{+00}$	$2.013e^{+00}$	3.521	$4.630e^{-04}$	***
Reef Size x Cultch Quality	$5.281e^{-07}$	$2.352e^{-07}$	2.245	$2.511e^{-02}$	*
HSI x Year	$3.625e^{+00}$	$1.386e^{+00}$	2.615	$9.150e^{-03}$	**
Cultch Quality x Year	$6.372\ e^{-01}$	$2.120e^{-01}$	3.006	$2.758e^{-03}$	**
HSI x Reef Size x Cultch Quality	$-1.357e^{-06}$	$5.870e^{-07}$	-2.311	$2.114e^{-02}$	*

(Dispersion parameter for quasipoisson family taken to be 8.595051)

Null deviance: 3475.1 on 616 degrees of freedom

Residual deviance: 3475.1 on 616 degrees of freedom

Number of Fisher Scoring iterations: 6

Shapiro-Wilk Normality Test	**Post-Tukey's Transformation (^0.325) Shapiro-Wilk Normality Test**
W = 0.43509, p-value < 2.2e-16	W = 0.7862, p-value < 2.2e-16

Deviance Residuals:

Min	1Q	Median	3Q	Max
-3.1523	-1.6848	-0.9638	0.3294	12.0027

"Variables" indicate the data types fed into the model. "Significance" is the specific probability of how frequently the variable would be found by chance (follows Student's t distribution) and "Significance Code" represents significance level as follows: "ns" is not significant, "***" is to 0.001, "**" is to 0.01, "*" is to 0.05.

Table 8.

Sack Abundance: Statistical testing results of step reduction procedures run on the full generalized linear model for sack abundance resulted in a minimum adequate model that explained the variation in the sample set.

Variables	Estimate	Standard Error	t value	Significance Pr(>|t|)	Significance Code
(Intercept)	$-1.553e^{-01}$	$1.670e^{-01}$	-0.930	0.353	ns
HSI	$1.131e^{+00}$	$2.733e^{-01}$	4.137	$4.03e^{-05}$	***
Reef Size	$8.104e^{-08}$	$5.456e^{-08}$	1.485	$1.38e^{-01}$	ns
Cultch	$4.244e^{-01}$	$1.303e^{-01}$	3.257	$1.19e^{-03}$	**
HSI x Reef Size	$-3.447e^{-07}$	$1.301e^{-07}$	-2.650	$8.27e^{-03}$	**

(Dispersion parameter for quasipoisson family taken to be 2.010221)

Null deviance: 705.11 on 583 degrees of freedom

Residual deviance: 633.24 on 579 degrees of freedom

Number of Fisher Scoring iterations: 5

Shapiro-Wilk Normality Test	**Post-Tukey's Transformation (^0.375) Shapiro-Wilk Normality Test**
W = 0.40793, p-value < 2.2e-16	W = 0.66965, p-value < 2.2e-16

glm formula = (Abundance ~ HSI + Reef Size + Cultch Quality + HSI: Reef Size, Family = quasipoisson)

Deviance Residuals:

Min	1Q	Median	3Q	Max
-2.0674	-0.6073	-0.3739	0.1117	9.9277

"Variables" indicate the data types fed into the model. "Significance" is the specific probability of how frequently the variable would be found by chance (follows Student's t distribution) and "Significance Code" represents significance level as follows: "ns" is not significant, "***" is to 0.001, "**" is to 0.01, "*" is to 0.05.

Discussion

Although suitability studies have been focused on Louisiana and the Northern Gulf of Mexico, none have been applied to Barataria Basin (Cake 1983, Chatry et al. 1983, Soniat & Brody 1988, Starke et al. 2011, Pollack et al. 2012, Soniat et al. 2013, Swannack et al. 2014). Two studies focused on Breton Sound, Louisiana (Chatry et al. 1983, Soniat et al. 2013), one on the Hudson River and New York Harbor (Starke et al. 2011), two were applied to estuaries in Texas (Soniat & Brody 1988, Pollack et al 2012), and one compared suitability between Western Mississippi Sound and Chesapeake Bay (Swannack et al. 2014). All of the explored studies include cultch as a factor with the exception of the 1983 salinity only strategy employed by Chatry et al. (Cake 1983; Chatry et al. 1983; Soniat & Brody 1988; Starke et al. 2011; Pollack et al 2012; Soniat et al 2013, Swannack et al. 2014). The Soniat et al. 2013 and Swannack et al. 2014 models calculate an HSI for a year, whereas others calculate a single HSI based on multi-year data. (Cake 1983; Chatry et al. 1983; Soniat & Brody 1988; Starke et al. 2011; Pollack et al 2012; Soniat et al 2013, Swannack et al. 2014). The average and standard deviation of historic temperatures was included in the model by Pollack et al. (2012); Starke et al. (2011) only included temperatures taken from May through November when high temperatures were prevalent, and none of the other models were inclusive of temperature effects as SI variables. The current HSI model incorporates different SI relationships that account for the effects of salinity due to temperature variances, one for cool (applied to October-March) and one for warm temperatures (applied to April-September). It attempts to expand upon the previous designs by creating annual, salinity and temperature driven, index distributions that identify past regions suitable for *C. virginica.* The intended use for these historic annual distributions is to compare and correlate HSI with hydrographic events and serve as a baseline prior to the implementation of proposed freshwater and sediment diversions. This can be instrumental in the placement of reef restoration projects in both Barataria and Pontchartrain Basins as diversions are implemented.

All diversions were open during 2012-2016 (except for the Bonnet Carré spillway which was closed until its opening in 2016) allowing the discharge to be impacted by natural events (excessive rain/flood/storm/drought), or a lack thereof (Table 1). Freshwater influx from the Pearl River and tributaries flowing into Lakes Maurepas and Pontchartrain (USGS 2018; Table 10), in addition to Bonnet Carré spillway openings (Table 1) resulted in historically low HSI values in the Pontchartrain Basin, especially near upper Lake Borgne (Figures 14-63). The drought of 2011 that extended into March of 2012 (Table 1) is associated with high HSI values (0.9-1.0) nearer Chandeleur Sound that declined across Biloxi Marsh to 0.3 near the mouth of Lake Borgne (Figures 58-59). Tropical Storm Debby in late June of 2012 (Table 1) produced a storm surge of 1-5 feet with sustained winds up to 36 mph. (NASA 2018, NOAA 2018), and in late August, Hurricane Isaac landed east of the Mississippi Delta (Table 1) with 75 mph. sustained winds, over 20 inches of rain, and a storm surge of 8-13 feet, in Plaquemines and St. Bernard that extended into Lake Pontchartrain (NASA 2018). Increased fresh water flow from Lakes Maurepas, Pontchartrain, and the Pearl River outlet depressed HSI values near the Rigolets and in Lake Borgne (Table 10, Figure 59). Drought conditions occurred from August to October 2013, which likely contributed to the maintained high HSI values in Chandeleur Sound (Figures 60-61); during 2013 and 2014 no major storms occurred (NASA 2018; Table 1) (Figures 60-61). Pearl River flow in 2013 kept HSI values depressed near the Rigolets (Table 10, Figure 60), however a drop in cfs in 2014 and 2015 resulted in patchy areas of increased values (Table 10, Figure 61). August to October 2015 (Table 1) were characterized by drought conditions which maintained high HSI values near to Chandeleur Sound; the mouth of Lake Borgne showed low values (0.1-0.3) with only small patches of higher ones (Figure 62). The drought of 2016 did not come until later in October (NASA 2018) minimizing its effects on suitability, and there were no storms of high impact (storm surge) that year to push saline waters inland. The Pearl River had an increase in cfs from 2015 to 2016 which resulted in a gulfward shift of suitable areas, creating unsuitable areas in Lake Borgne, and only mid-range (0.4-0.5) in the wetlands leading to Chandeleur Sound (Table 10, Figure 63).

The salinity of inland northwest Breton Sound has been influenced by the Caernarvon Diversion since 1991, White's Ditch Diversion since 1963, and the Violet Siphon since 1957. Before implementation of the Caernarvon Diversion in 1991 (Table 1), the wetlands in upper Plaquemines, St. Bernard and Delacroix displayed HSI values from low (0.0-0.4) to intermediate (0.4-0.7) (Figures 11-38). Once the diversion was employed, HSI remained low through 2016, except in 2000 which may be attributed to drought conditions (Table 1, Figures 38-63). Fluctuations in water flow from the Caernarvon diversion correspond to the shift in HSI in Breton Sound from 2012-2016 (Table 10, Figures 59-63; USGS 2018). Down river from Caernarvon, the Bohemia Spillway (1924-present), Mardi Gras Pass (2011-present), Ostrica Lock (2011-present), Fort St. Philip crevasses (2006-present), Channel Armor Gap crevasse (1997-present), and Bayou Lamoque structures (1978-present) provide additional freshwater, nutrients and sediment to southern Breton Sound (Teal et al. 2012, Lopez et al. 2014). The droughts of 2011-2012 and 2015-2016 (Table 1) appear to have had no obvious impact upon HSI in the northeastern wetlands of Breton Sound as they and the areas directly east of the Mississippi River consistently saw low values of 0.0-0.1 (Figures 58-63). The HSI of Breton Sound sample stations (Figure 64) ranged from 0.1-0.7, rising nearer the MRGO possibly due to storm surge from Hurricane Isaac (NASA 2018, NOAA 2018; Figures 59-63). The lack of storms in 2013-2014 (Table 1) resulted in a slight shift of suitable HSI into Chandeleur Sound (Figures 60-61). During 2015 and 2016 conditions were similar, although the southern-most sample site (Battledore Reef) increased to mid-range values (0.4-0.5) (Figures 62-63). Barataria Bay has been subject to freshwater input from the northern location of Davis Pond (2001-present) which contributed to consistently low HSI values in the upper Barataria Basin assessment sites (North Hackberry Bay 2004 Shell Plant, 2008 and 2012 Cultch Plants, Hackberry Bay 2014 Cultch Plant, Mid and Upper Hackberry Bay) (Table 1, Figures 1 & 40-64). There was a roughly 50% decrease in cfs for the Davis pond diversion from 2011 to 2012 allowing storm surges to push saline water inland, raising the HSI near the upper Barataria Basin assessment sites from intermediate (0.5-0.6) to high levels (0.7-0.8); the cfs almost doubled in 2013, dropping the suitability below 0.4, dropped by about 55% in 2014 raising the suitability back up to 0.7, rose again by about 60% dropping suitability back to 0.3, and returned to very near the 2014 value again in 2016 however the suitability remained low (0-0.1) (Figures 59-64, Tables 7 & 8). The mouth of Barataria Bay (spanning from western Grand Isle to Bay Long), is subject to more saline gulf waters which likely explain the general gradient of HSI 0.4 in the eastern marshes (near Port Sulphur, between the West Pointe a la Hache and West Bay Diversions) to 0.8 in the west (Caminada Bay), that spanned all 5 study years (Figures 1 & 59-63). The droughts of 2011 - 2013, and storm surges from Hurricane Isaac and Tropical Storms Lee, Debby and Karen, correlate with the spread of intermediate to high HSI areas across the mouth of Barataria Basin from 2011-2013 explaining the intermediate to high values for the South Hackberry 2004 Shell Plant (0.8-0.6), and Barataria Bay 2004 Cultch Plant (0.6-0.7) (Tables 1 & 8, Figures 59-64). There were no impactful storms to force saline water inland, nor was there a drought in 2014 (Table 1). Combined with coastal flooding in 2013 and 2015, this may have resulted in restoration of freshwater flow levels at the West Pointe a la Hache and West Bay diversions thus reducing the HSI in the wetlands between them from 0.4 in 2012 and 2013, to 0.3 in 2014 nearing 0.0 in 2015 (Table 1, Figures 1 & 59-63). The influence was minimal for the Barataria Bay 2004 Cultch plant which fluctuated from 0.5-0.7 through 2015 (Figures 60-62). The small rise in suitability to 0.7 at the South Hackberry Shell Plant site correlated with the drop in flow at Davis Pond in 2014 and the drop to 0.5 the following year to the 2015 rise in flow (Table 10, Figures 61-62). The drought in 2016 and drop in cfs at the Davis Pond diversion correlate with the expansion of suitable habitat across the mouth of Barataria Basin from a narrow more western area in 2015, to a broader (and more inland) area in 2016 (Table 1, Figures 62-63), however the lower HSI values at both the South Hackberry Shell Plant and the Barataria Bay 2004 Cultch Plant are inexplicable unless there is a time lag to the effect (Figures 62-64).

Generalized linear modeling indicated that year, quality cultch, and the interaction between year and quality cultch were the most significant factors influencing oyster spat abundance ($p<0.001$), followed by HSI and the interactions of HSI and reef size, HSI and quality cultch, HSI and year, HSI with reef size and year, and HSI and cultch quality with year ($p<0.01$), reef size, the interaction of reef size with cultch quality, and the interaction of reef size with year ($p<0.05$) (Table 6). In any given year stochastic events may occur that affect salinity-- such the droughts of 2011-2013 and 2015-2016, coastal flooding in 2013 and 2015, storms in 2011-2013 and 2015, and the opening of the Bonnet Carré spillway in 2016 (Pollack et al. 2011, Kennicutt II 2017; Table 10). Year is thus a partial proxy of annual variations in salinity which affect HSI. Years with greatest spat abundance should correspond to years with suitable spawning salinities between 20 and 22; however, spat are more tolerant than larger size classes of low salinity (Chatry 1983, Kennicutt 2017, Lowe et al. 2017). "Year" also subsumes stochastic events that are independent of annual salinity variation. For example, storms can deposit re-suspended sediment on reefs thus reducing cultch quality or, in other cases, sweep buried reefs clean of sediment and create a new suitable bottom (Conner et al. 1989). The importance of quality cultch to settling of spat has been incorporated into HSI models (Cake 1984, Soniat and Brody, 1988, Starke et al. 2011). Reefs with higher relief are less subject to sedimentation and hypoxia, and provide more areas of refuge for spat (Chatry et al. 1983, Roegner & Mann 1995, Brown 1996, Lenihan & Peterson 1998, Luckenbach et al. 1999, Soniat et al. 2004, LaPeyre et al. 2009). The interaction between year and quality cultch is not surprising in that year is a partial proxy for salinity. The relationship between spat abundance and HSI indicates that the model captures the salinity requirements of reproduction, spat set, and initial spat survival. The interaction between HSI and reef size suggests that larger reefs with quality cultch likely have more spawning adults that initiate setting via waterborne chemical (Zimmer-Faust & Tamburri 1994). The interaction between HSI and quality cultch is indicative of the need for suitable salinity and quality substrate for successful spat set. The interaction of HSI and year implies that events independent of the HSI such as storms, droughts and diversion enactments affect the salinity suitability. The combined importance of HSI, year and reef size indicates the interactive importance of proper salinity (as incorporated into the HSI) without damaging events, and a sufficient reef footprint in promoting spat settlement. The interaction between HSI, year and cultch quality indicates the significance of the effects of stochastic events upon salinity and amount of quality cultch available to settling spat. The relationship of reef size to spat abundance may be related to the increased possibility of larval encounter with a hard bottom (O'Beirn et al 2000). The interaction of reef size and cultch quality points to a need for an adequate amount of suitable cultch upon a reef to enhance the possibility of spat set. The importance of the combined effects of reef size and year could indicate that some events fragment habitat by destroying it (ie: wave action) or changing its suitability by uncovering or burying it.

HSI, year, and the interaction between the HSI and cultch quality, were the most important factors influencing oyster seed abundance ($p<0.001$) (Table 7). The amount of quality cultch, and the interaction between year x cultch quality ($p<0.01$), reef size, the interactions of HSI and reef size, reef size x quality cultch, and HSI x reef size x quality cultch were also significant ($p<0.05$) (Table 7). The contribution of many of the above factors to seed abundance may be simply be due to the requirements of spat which survive and grow to seed size – amount of quality cultch, the interaction of HSI with reef size and year, and the HSI x cultch quality interaction are examples. For instance, it is not surprising that the interaction of HSI with quality cultch is also a significant factor in seed abundance. However, quality cultch and the interaction of cultch and year may further promote seed abundance through enhanced survival on quality reefs with suitable salinity and a lack of harmful stochastic events within a year (Luckenbach et al. 1999, O'Beirn et al. 2000, Soniat et al. 2004).

HSI was the most influential variable for sack oyster abundance ($p<0.001$), followed by the presence of quality cultch, and the interaction of HSI with reef size ($p<0.01$) (Table 8). Suitable salinity, an integral component of the HSI, limits mortality due to predators and disease, and mortality due to freshets (Ray 1954, Chatry et al. 1983, Soniat 1985, Stanley and Sellers 1986, Craig et al. 1989, Bushek & Allen, 1996). The significance of quality cultch to sack oyster abundance tracks the requirement for spat set, and spat and seed survival (Brown 1996, Lenihan & Peterson 1998, Soniat 2004). Quality cultch, however, may be directly related to sack oyster abundance. Quality cultch provides a firmer substrate to support growing oysters (Cake 1983). Furthermore, it is difficult to determine cause and effect in the relationship between sack abundance and reef quality. Quality cultch provides substrate for setting larvae that grow into large oysters, and an abundance of large oysters upon death in place supply cultch. The significant interaction of HSI with reef size suggests that sack oysters are more abundant when salinity and temperature are suitable where habitat fragmentation is minimal (Lenihan et al. 1999).

The current HSI responds positively to mid-range salinities and negatively to salinity extremes, with the magnitude of the response influenced by temperature at low salinities. The model delineates areas suitable for oyster cultivation in the past and can predict the effects of freshwater diversions on the future distribution of oysters. An increased flux of sediment and fresh water from proposed diversions will shift the suitable zone for oyster cultivation down-estuary. Legacy HSI visualizations show annual fluctuations in the distribution of zones suitable for oyster cultivation prior to the proposed diversions. Hydrographic models of the effects of future diversions on the distribution of salinity, coupled with the HSI, enable predictions of suitable locations for oyster cultivation post-diversion. A caveat of the present model is the assumption that all non-modeled conditions are within suitable ranges. While some factors (e.g. annual mean temperature, minimum and maximum annual temperature) are clearly within the suitable ranges, it is uncertain if others (e.g., dissolved oxygen) are. Because of insufficient data on dissolved oxygen, it was not included in the HSI. Increased freshwater from diversions will push the suitable zone for oyster cultivation seaward toward existing hypoxic areas. Incorporation of dissolved oxygen into future models will more precisely delineate the optimal zone for future oyster cultivation.

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Appendix

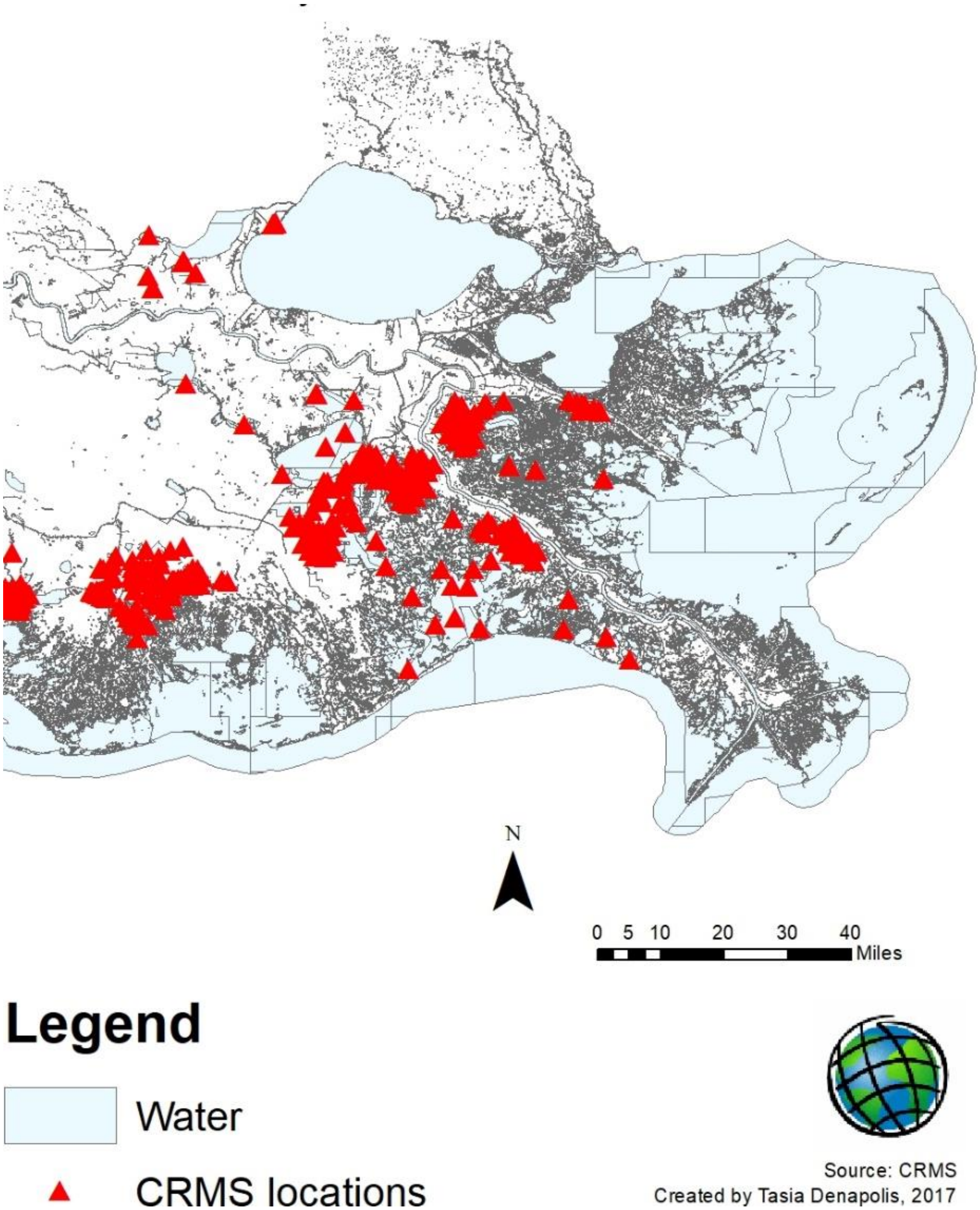


Figure 6: Coastwide Reference Monitoring Service (CRMS)
Salinity Data Collection Stations

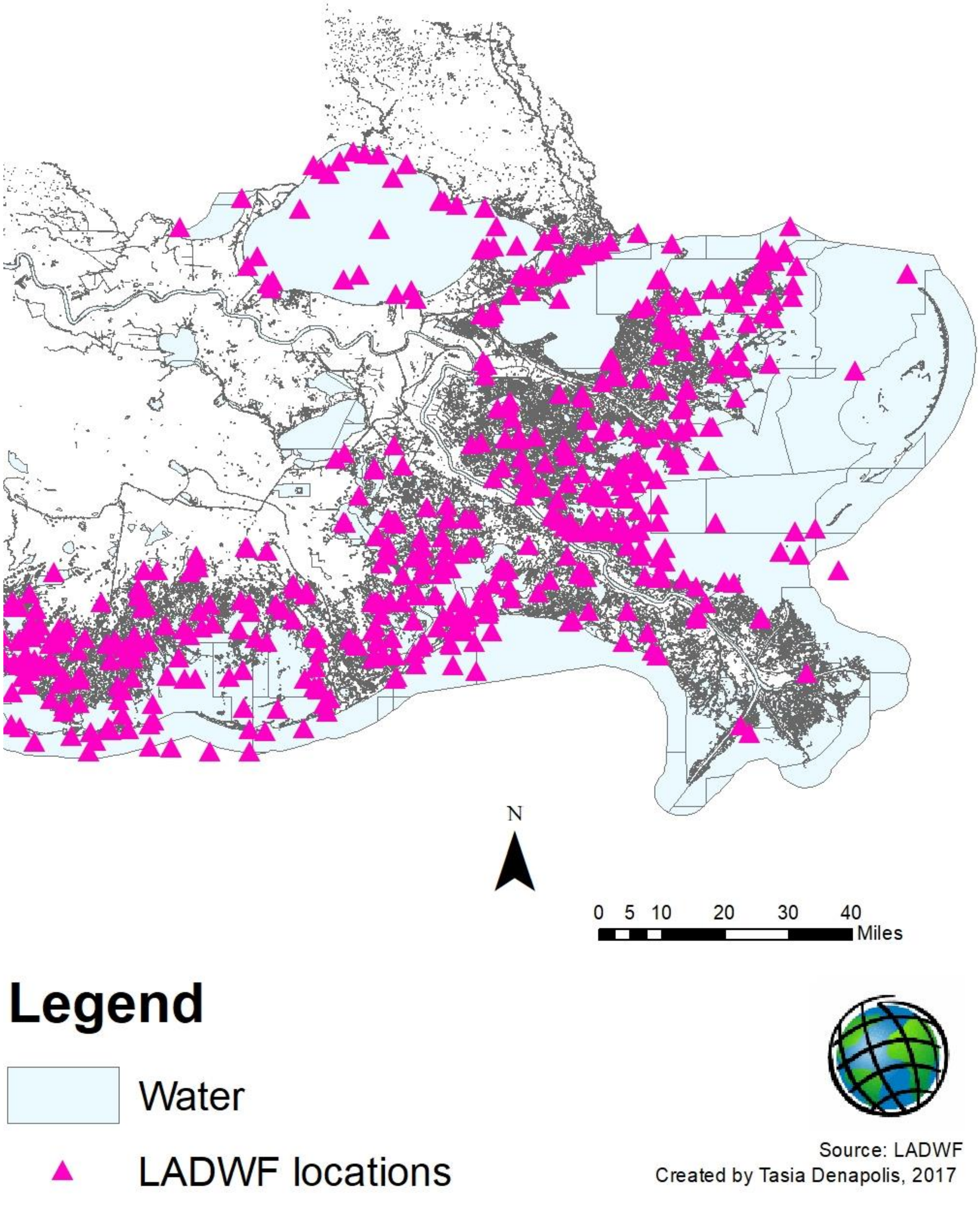


Figure 7: Louisiana Department of Wildlife and Fisheries (LDWF)
Salinity Data Collection Stations

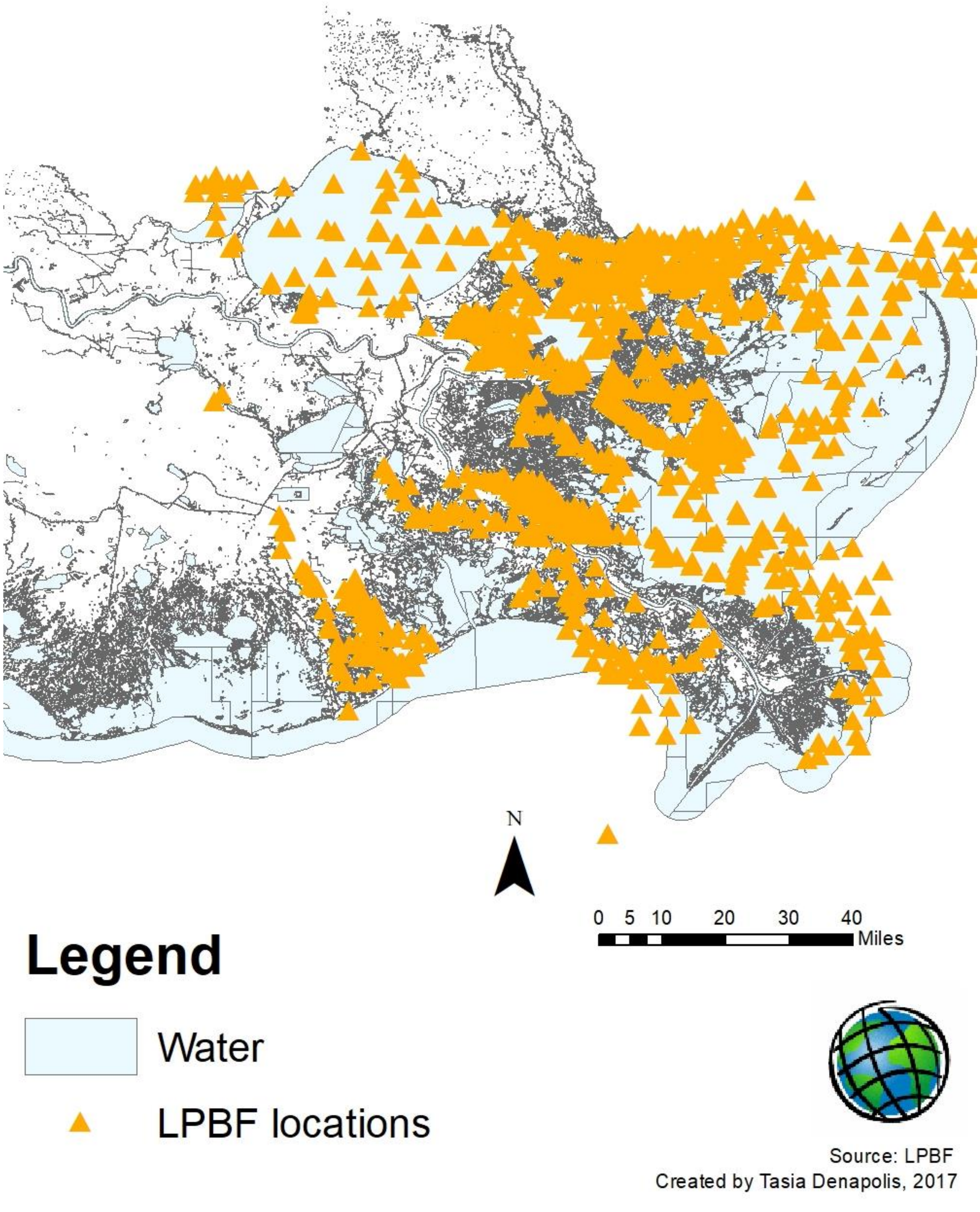


Figure 8: Lake Pontchartrain Basin Foundation LPBF)
Salinity Data Collection Stations

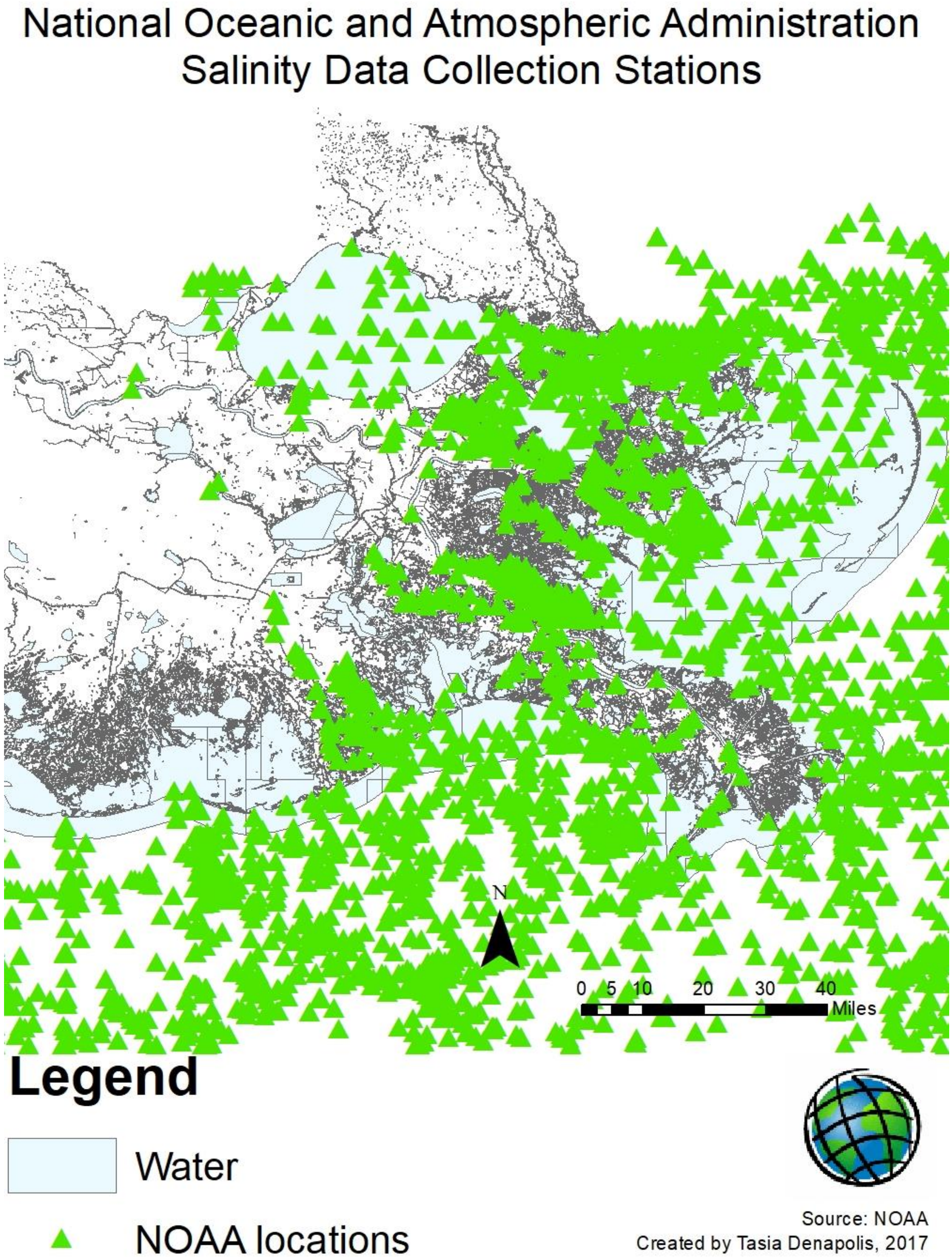


Figure 9: National Oceanic and Atmospheric Administration (NOAA)
Salinity Data Collection Stations

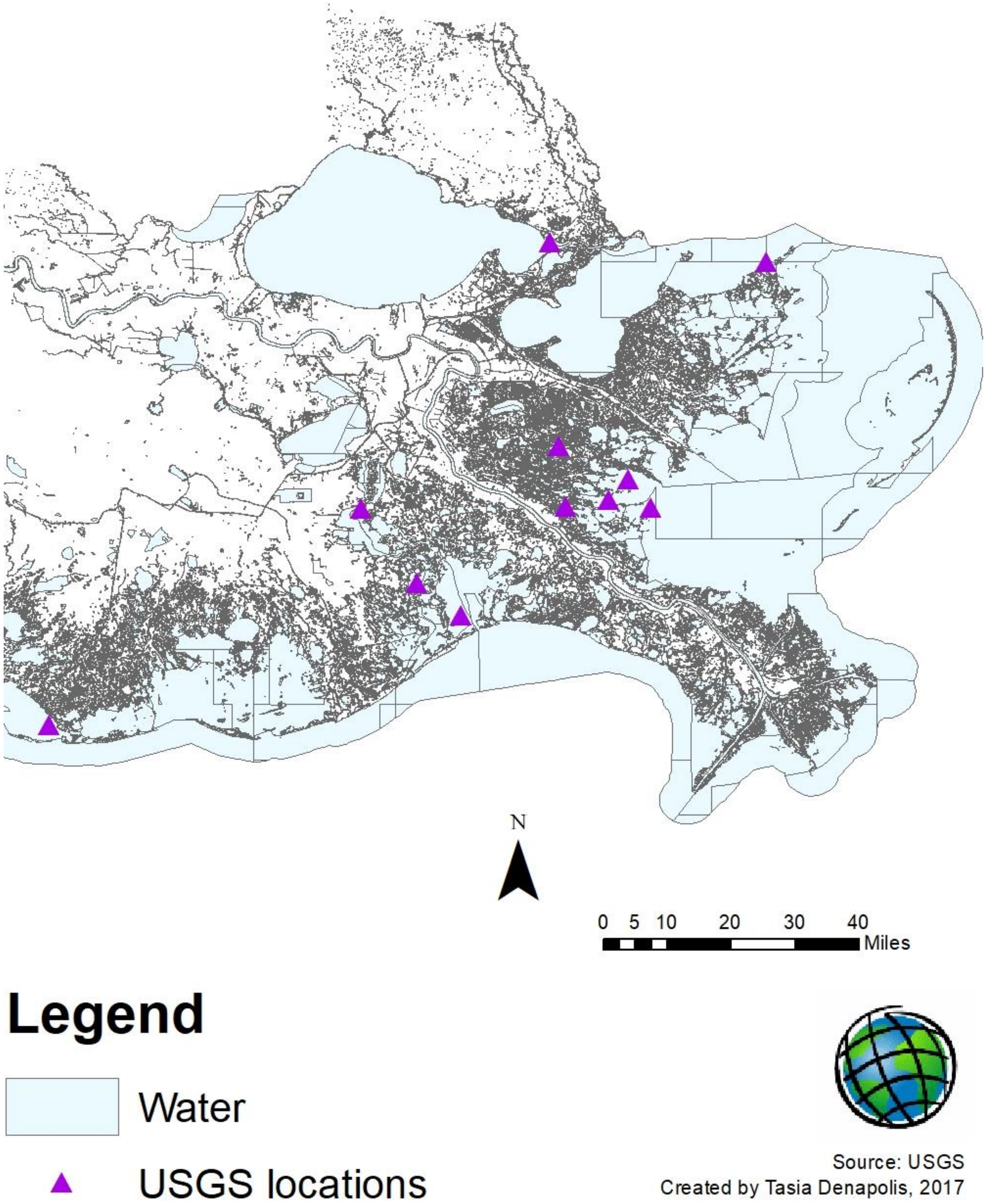


Figure 10: United States Geological Survey (USGS)
Salinity Data Collection Stations

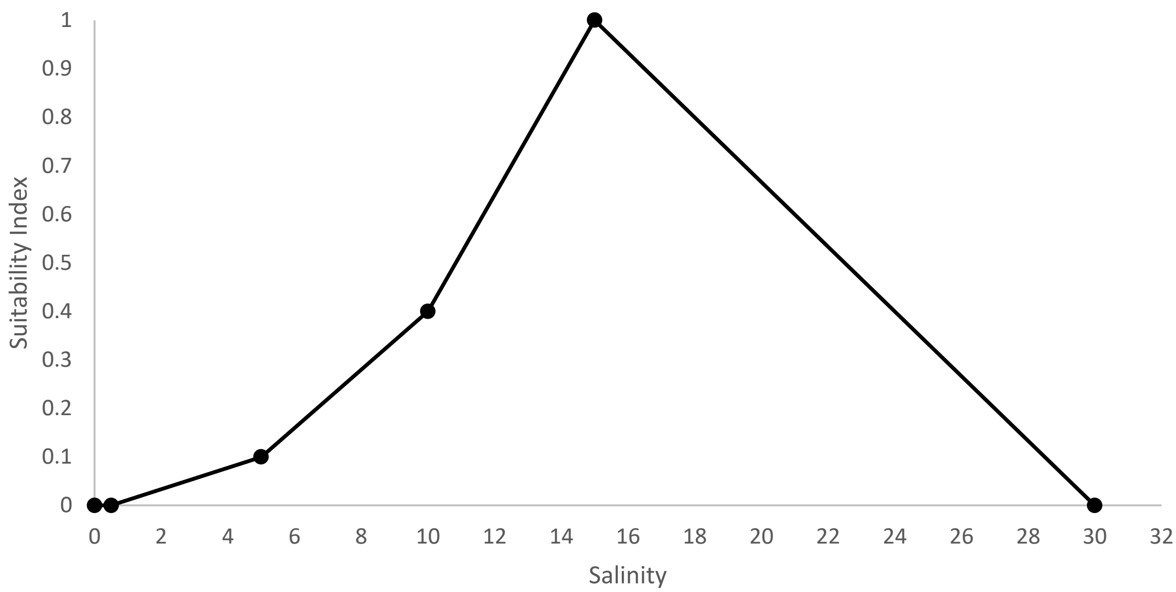


Figure 11: Original Minimum Monthly Salinity Relationships

Suitability Index 3: Cool months (Oct-Mar) relationship original definition:

Salinity	SI
0	0
0.5	0
5	0.1
10	0.4
15	1
30	0

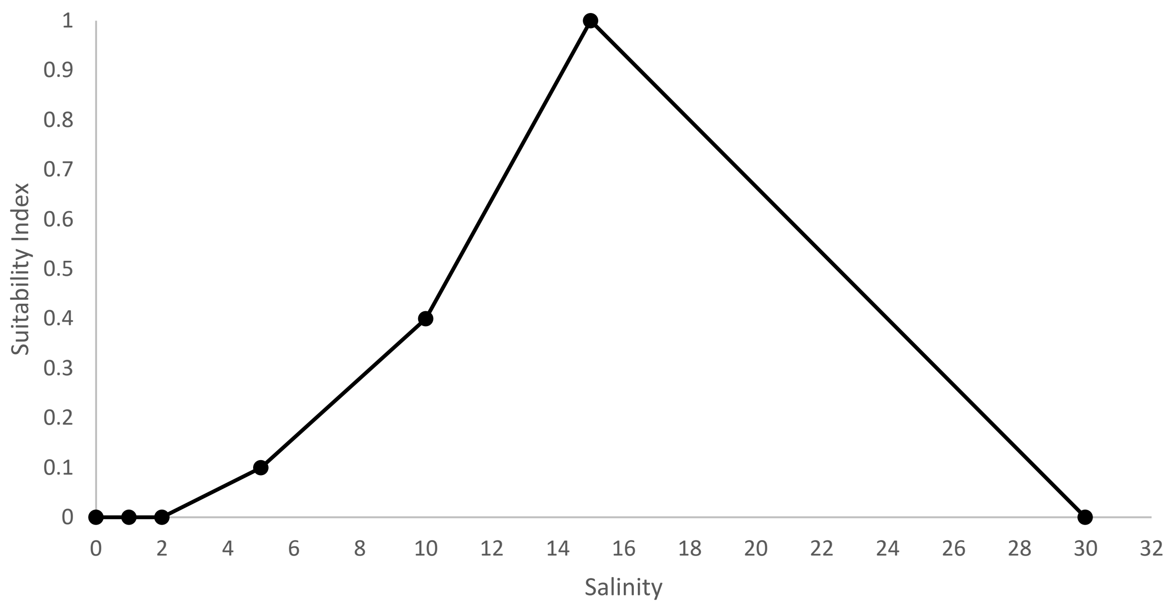


Figure 12: Original Minimum Monthly Salinity Relationships:
Suitability Index 3: Warm months (Apr-Sept) relationship original definition:

Salinity	SI
0	0
1	0
2	0
5	0.1
10	0.4
15	1
30	0

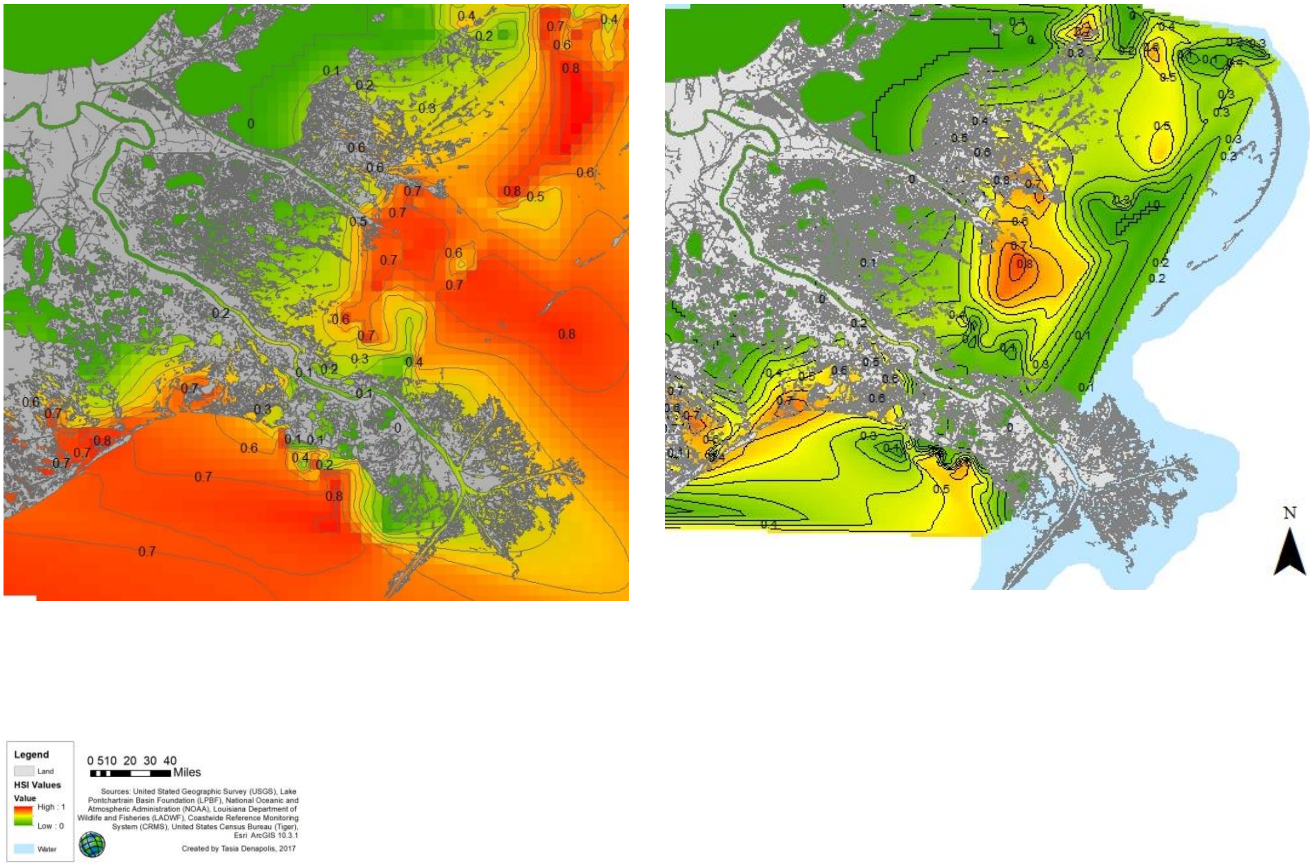


Figure 13: 2016 H.S.I. maps: before (left) and after (right):
The change in the relationship corrected false high H.S.I. values in high salinity offshore locations thus improving the accuracy of the new H.S.I. as evidenced by the example above.

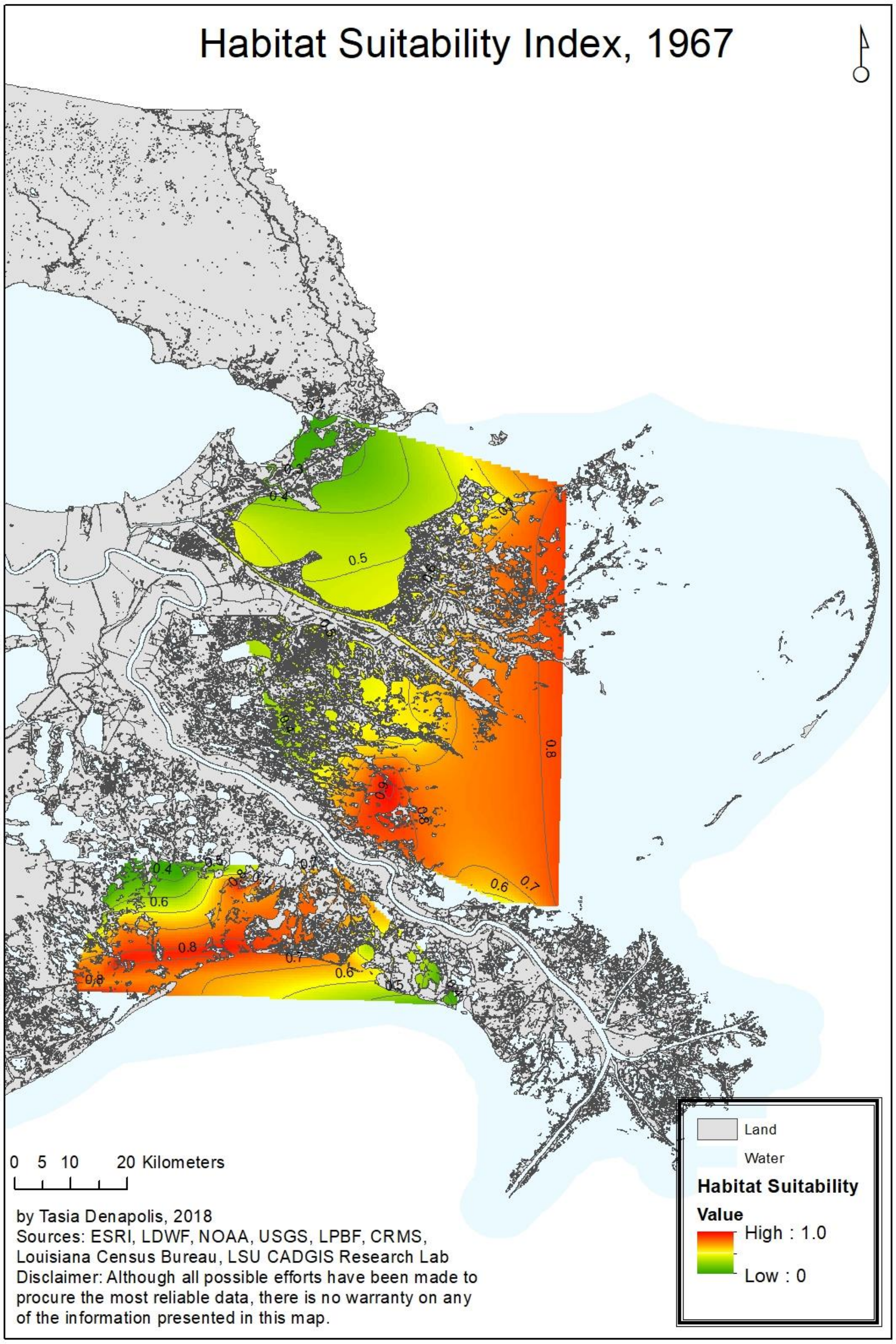


Figure 14 : Habitat Suitability Index (HSI) 1967

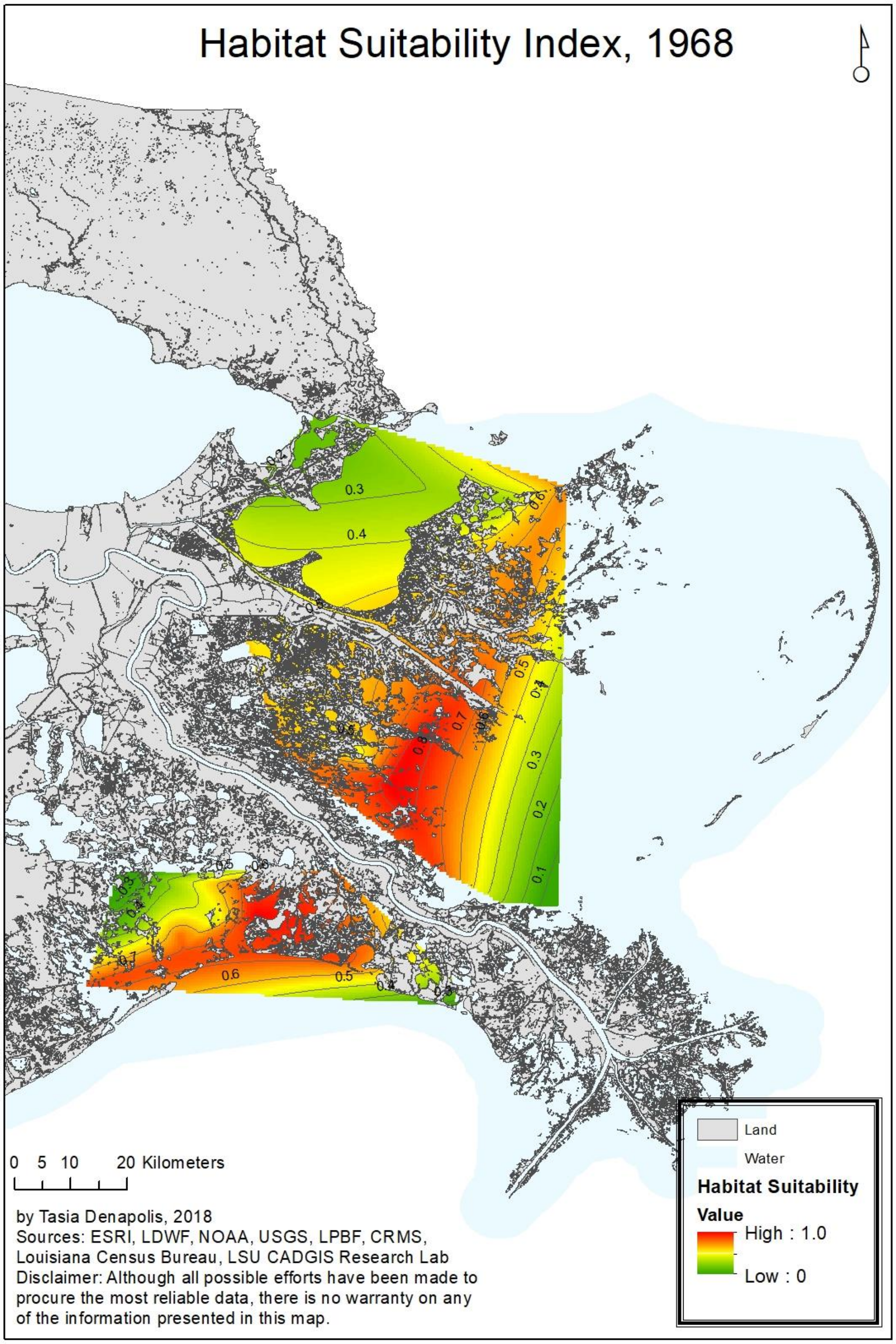


Figure 15 : Habitat Suitability Index (HSI) 1968

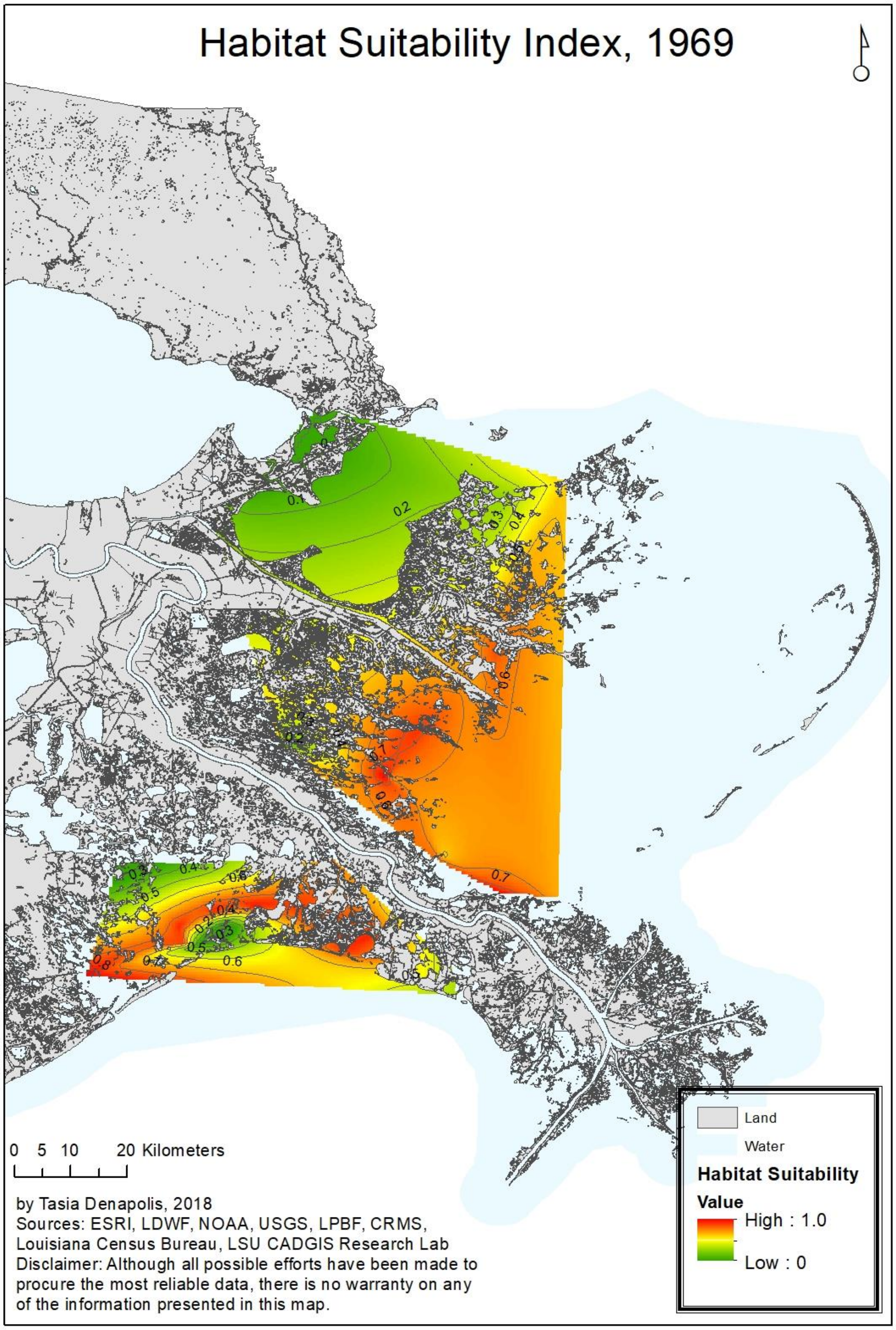


Figure 16 : Habitat Suitability Index (HSI) 1969

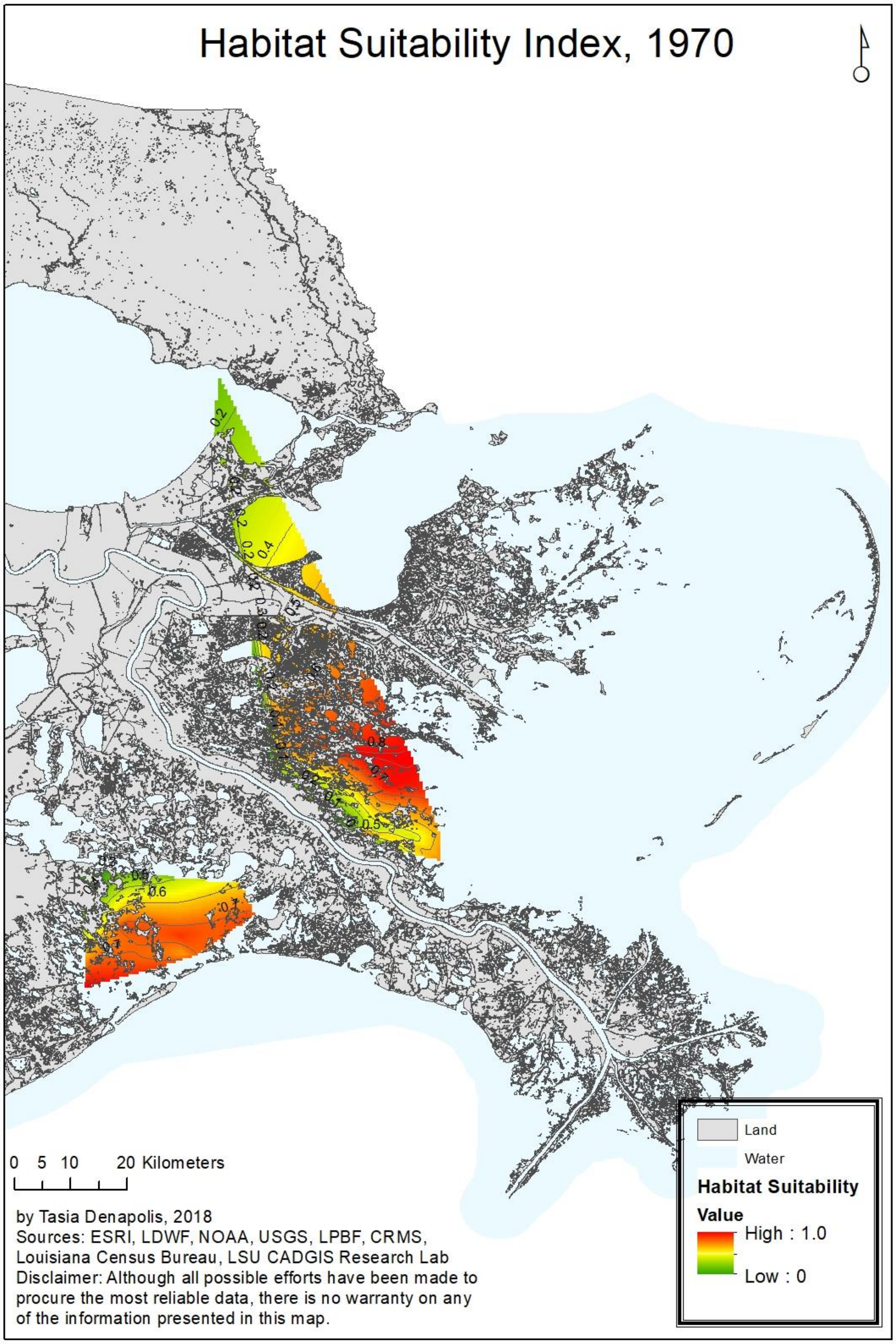


Figure 17 : Habitat Suitability Index (HSI) 1970

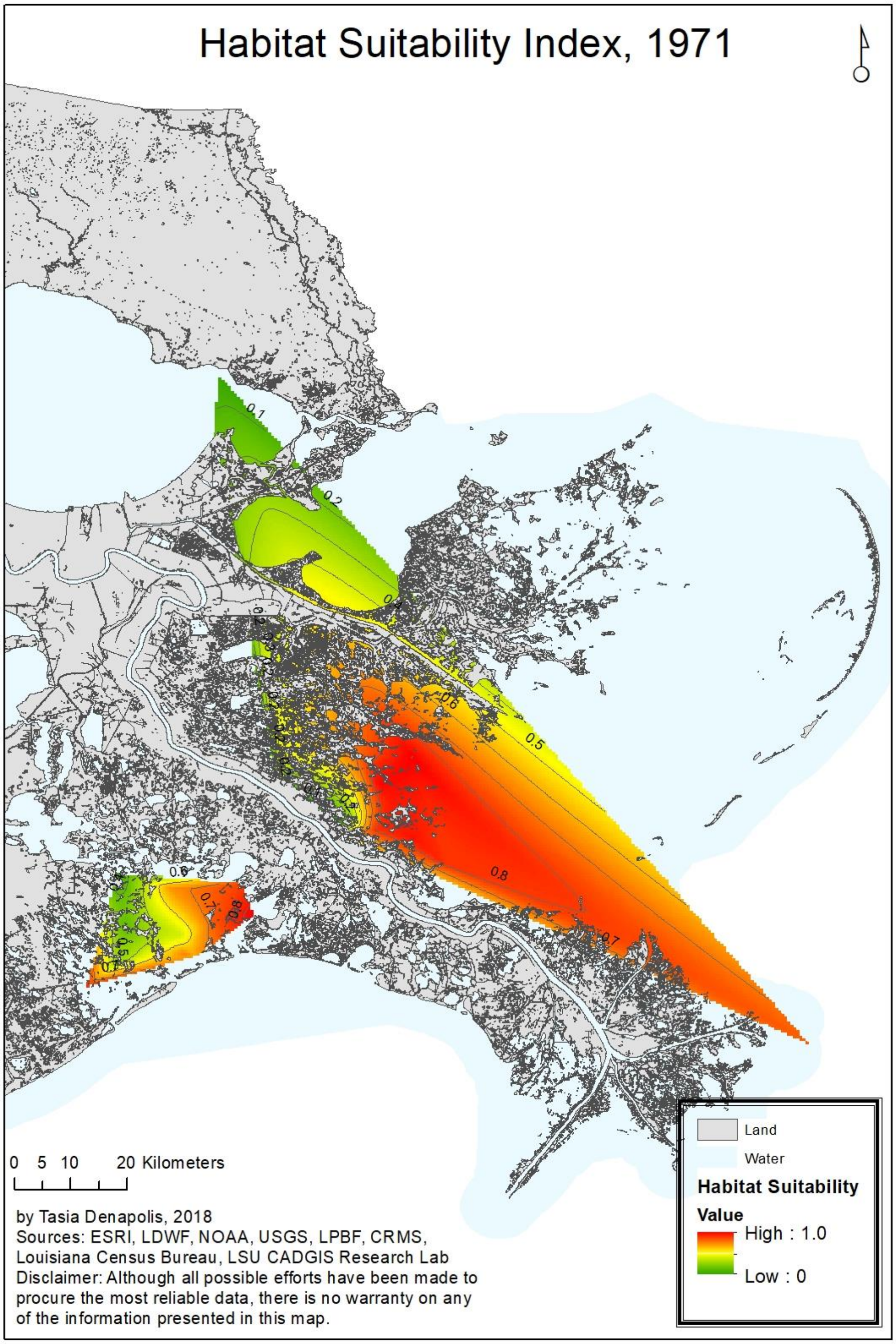


Figure 18 : Habitat Suitability Index (HSI) 1971

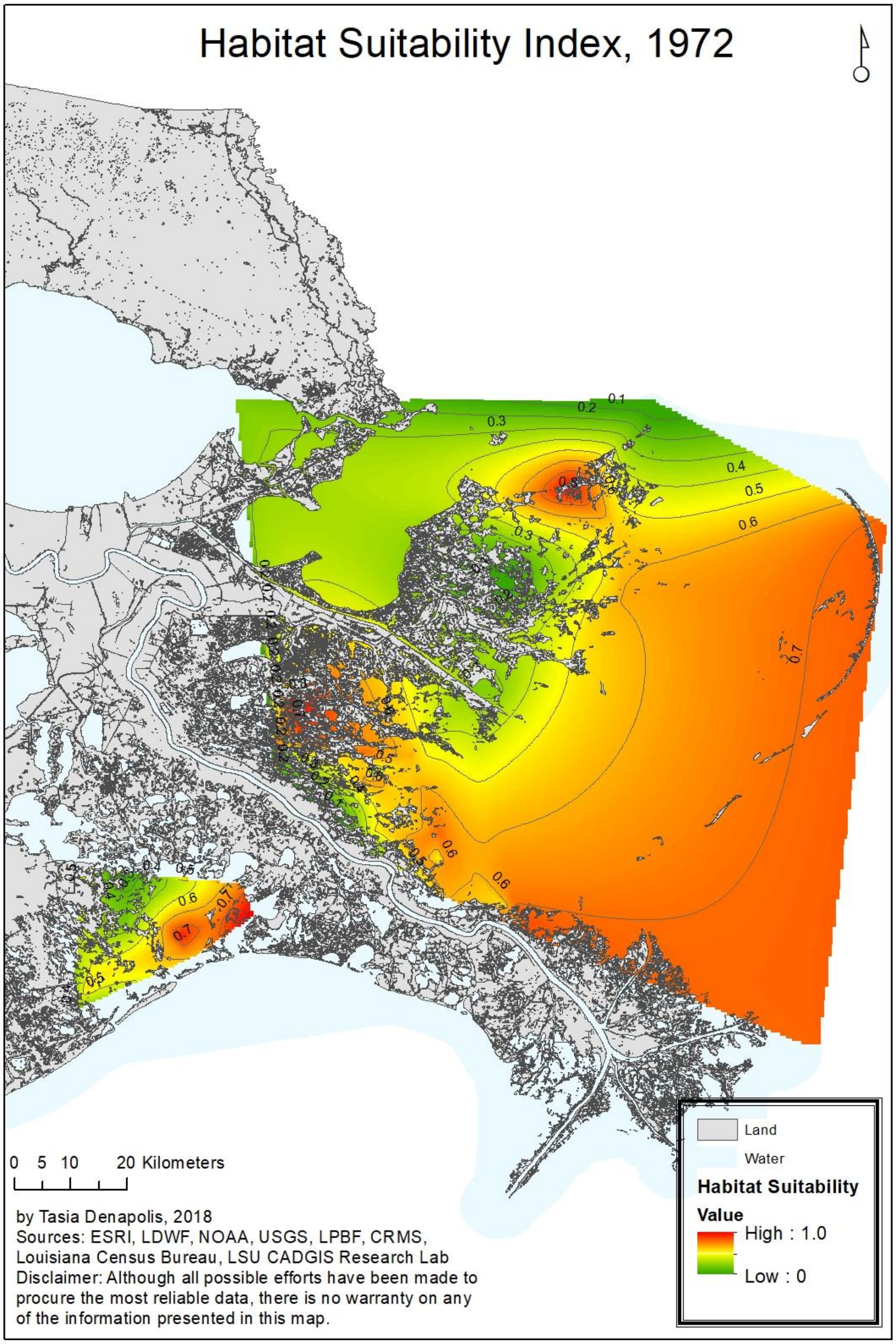


Figure 19 : Habitat Suitability Index (HSI) 1972

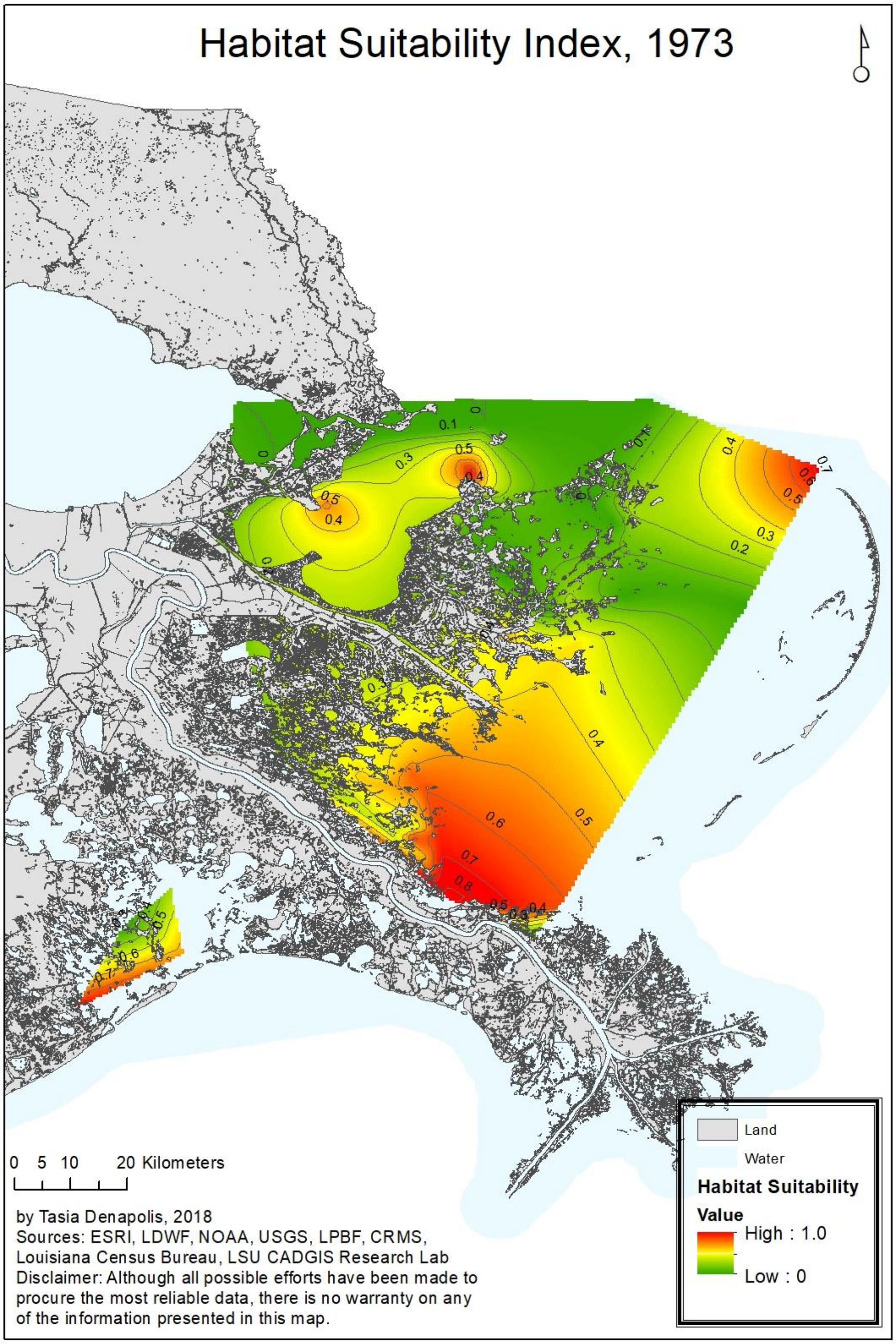


Figure 20 : Habitat Suitability Index (HSI) 1973

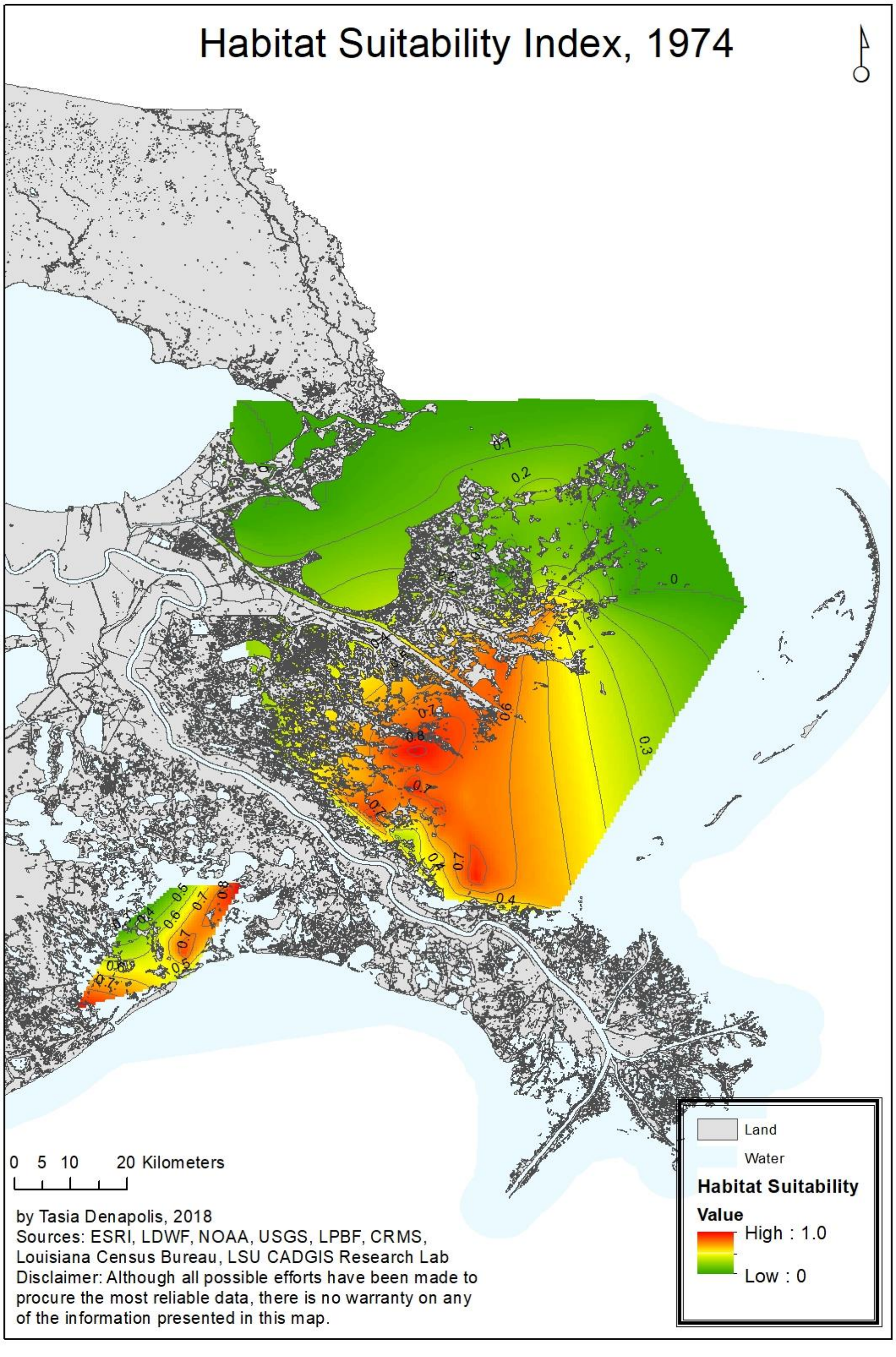


Figure 21 : Habitat Suitability Index (HSI) 1974

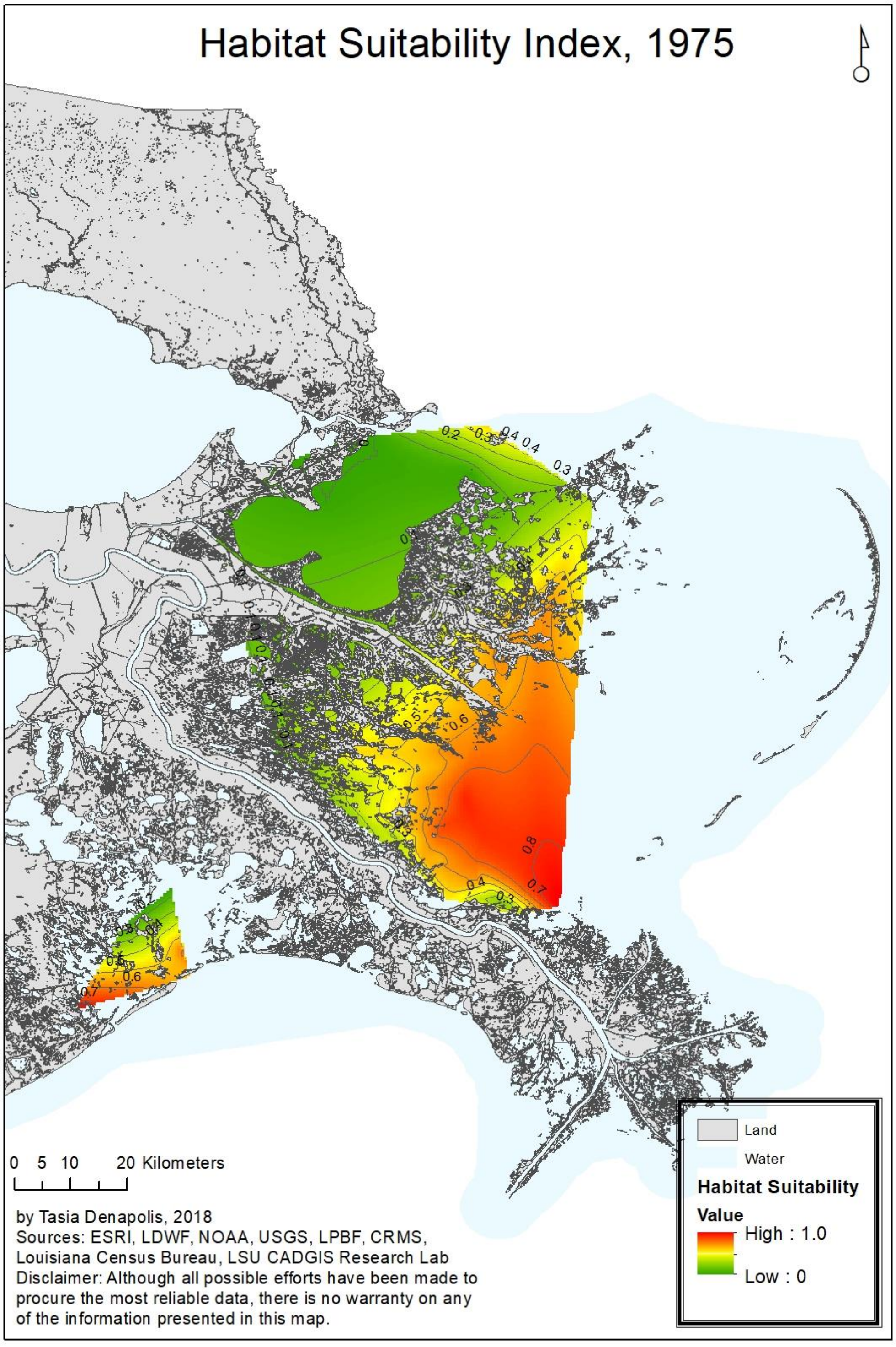


Figure 22 : Habitat Suitability Index (HSI) 1975

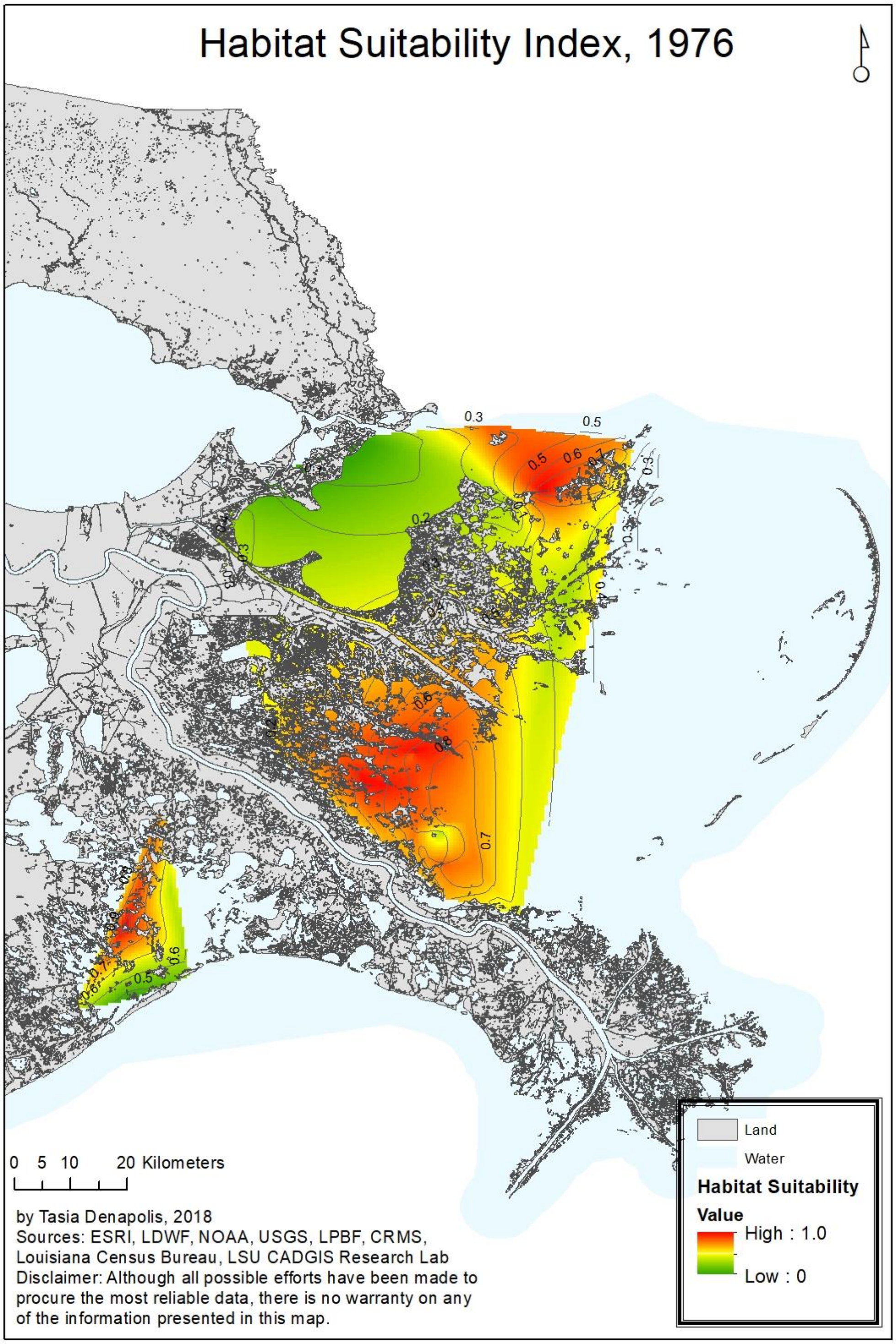


Figure 23 : Habitat Suitability Index (HSI) 1976

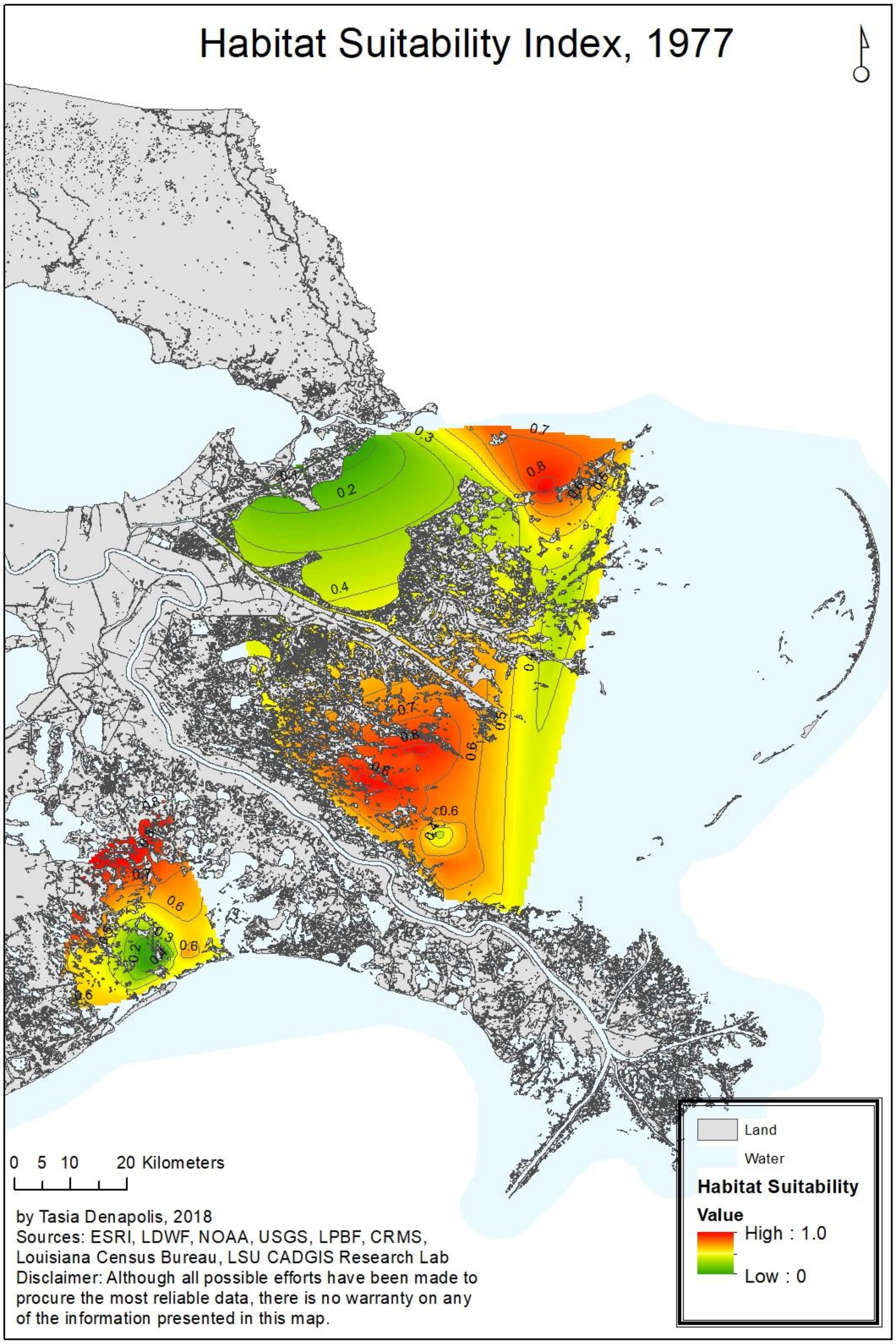


Figure 24 : Habitat Suitability Index (HSI) 1977

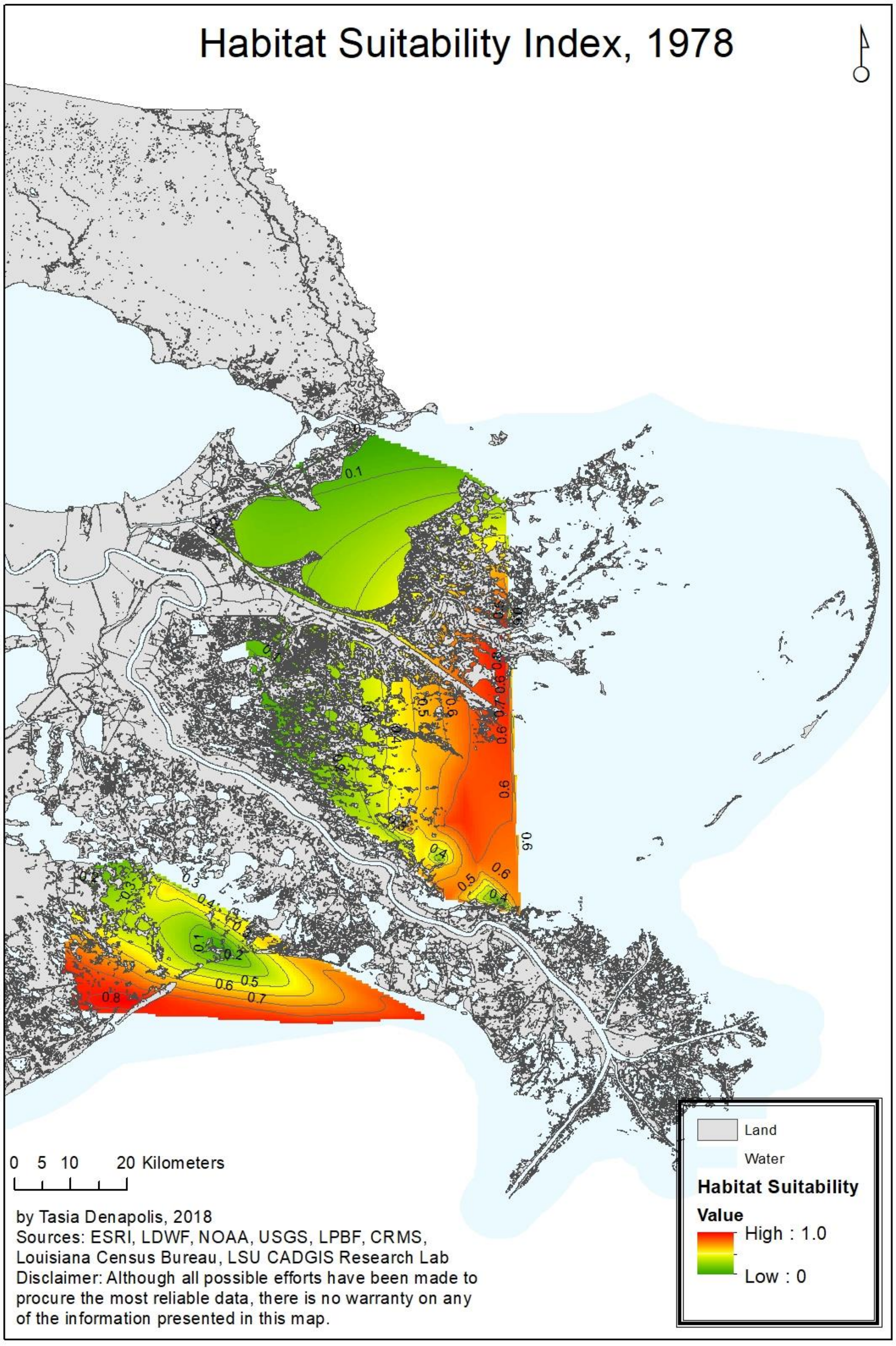


Figure 25 : Habitat Suitability Index (HSI) 1978

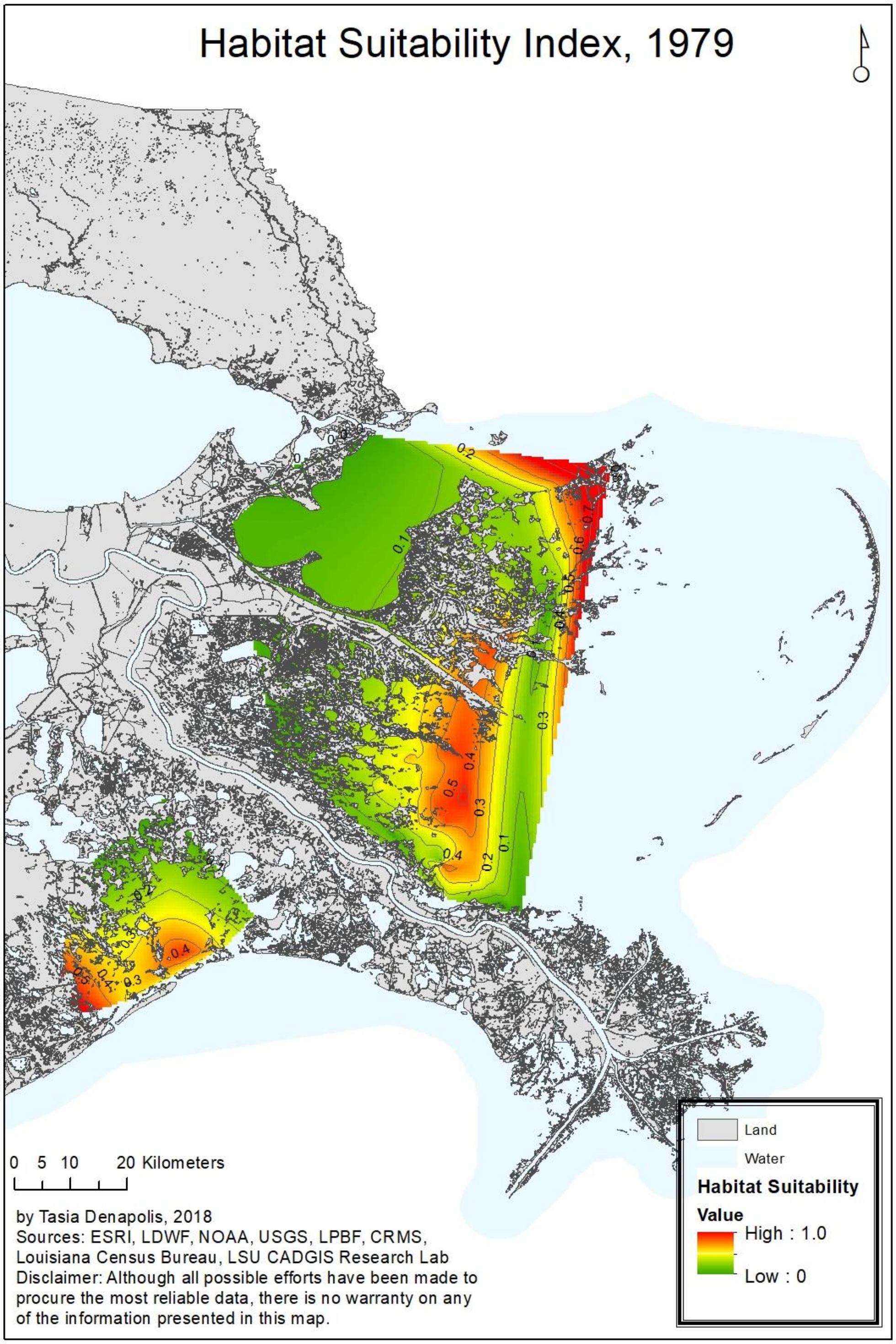


Figure 26 : Habitat Suitability Index (HSI) 1979

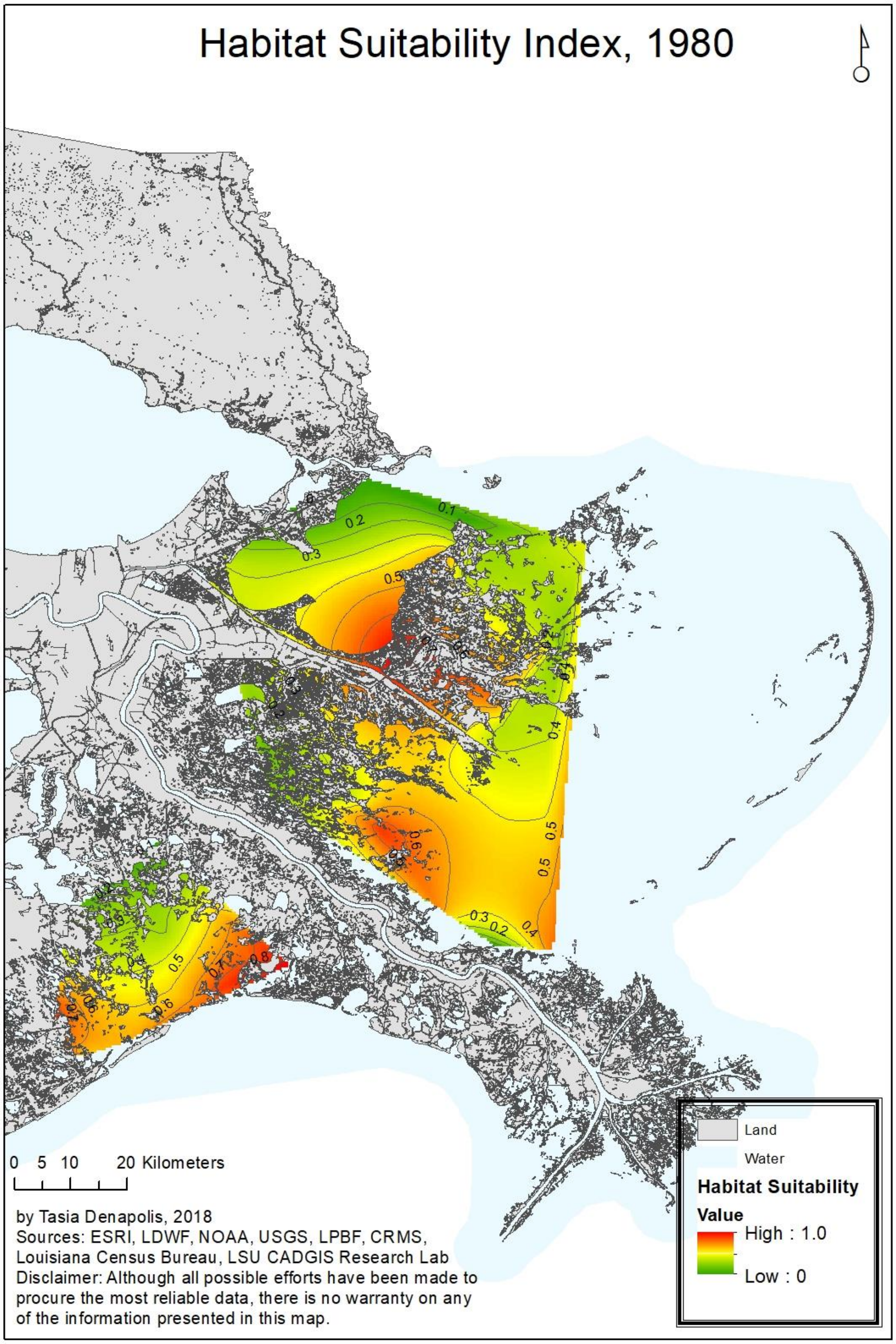


Figure 27 : Habitat Suitability Index (HSI) 1980

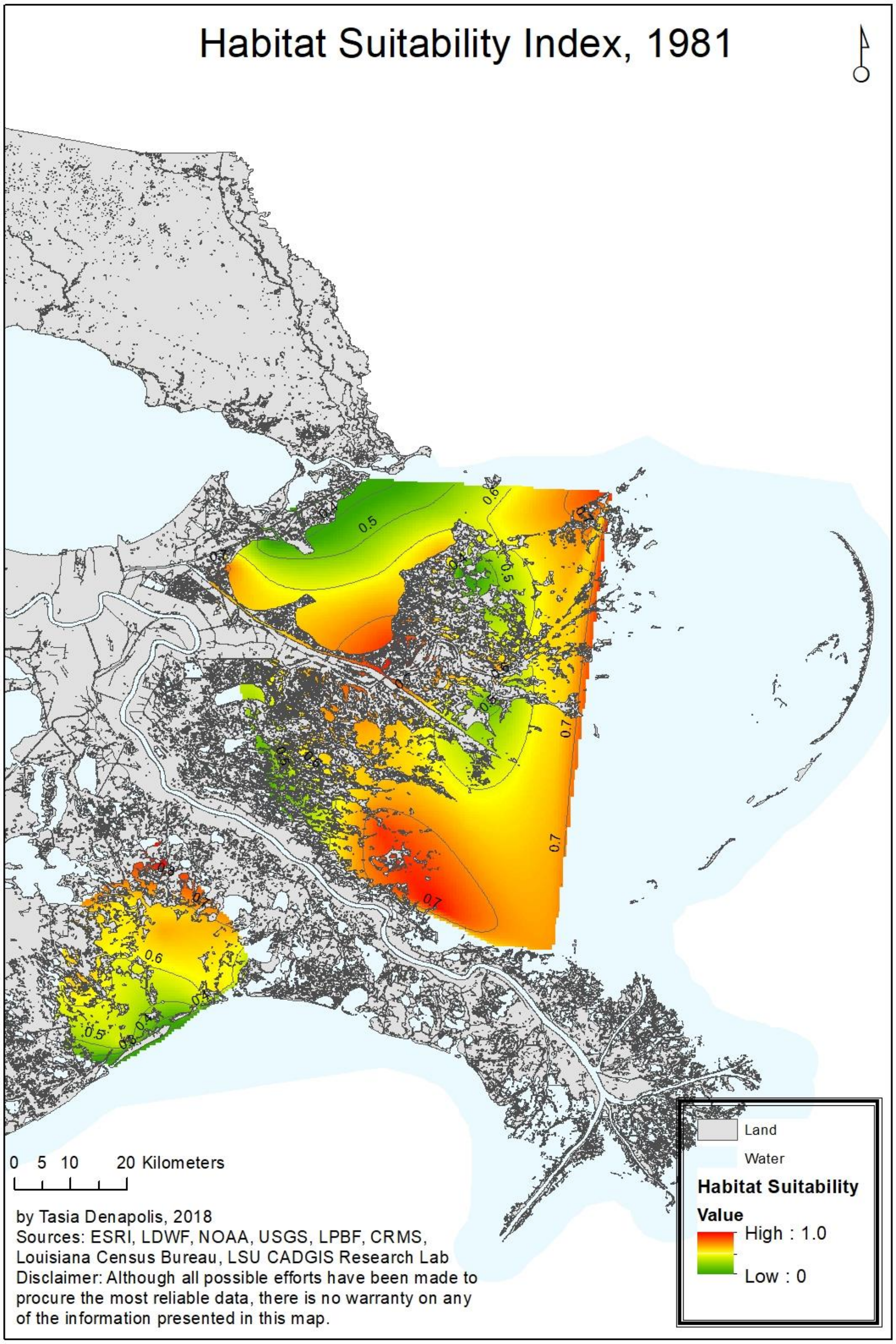


Figure 28 : Habitat Suitability Index (HSI) 1981

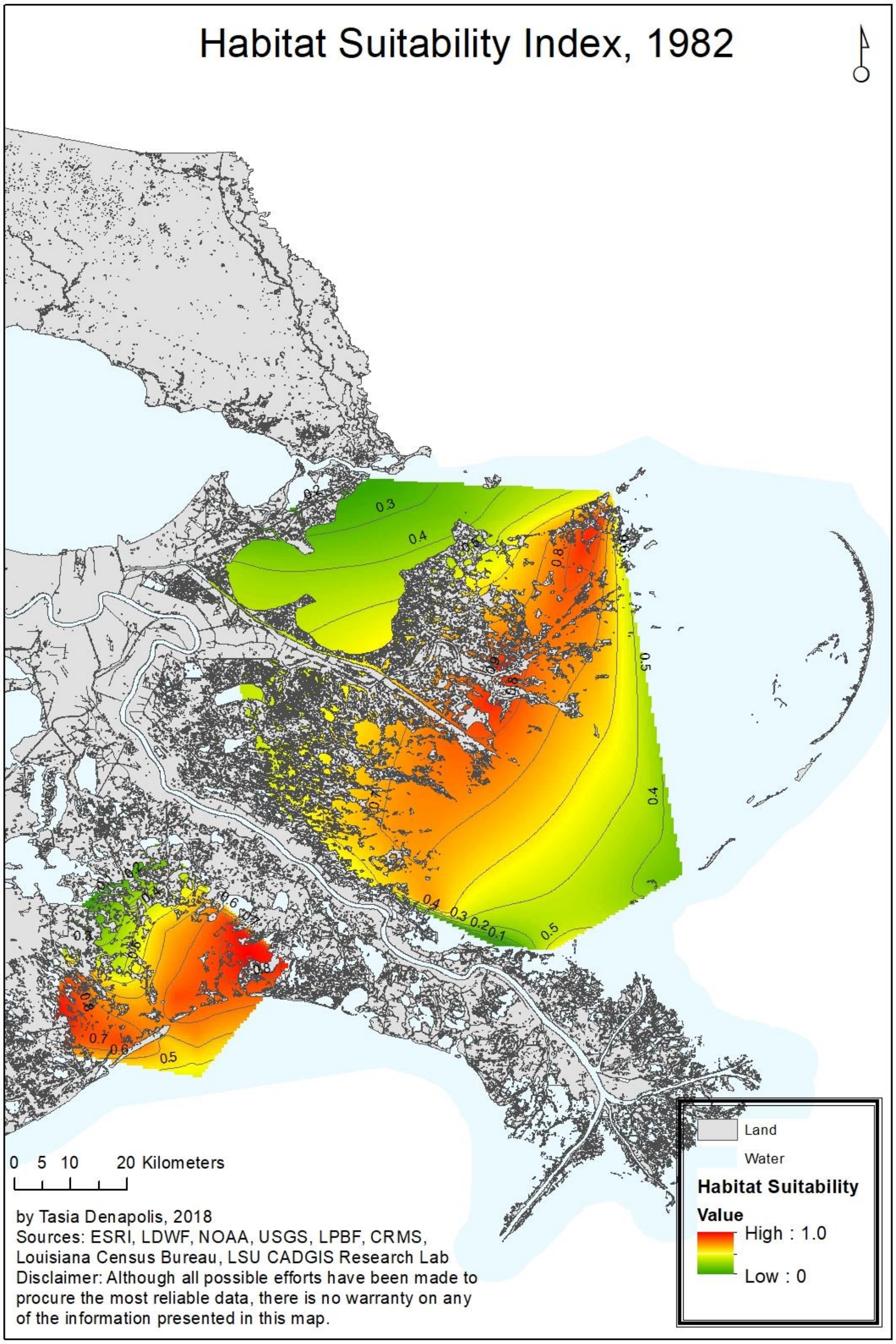


Figure 29 : Habitat Suitability Index (HSI) 1982

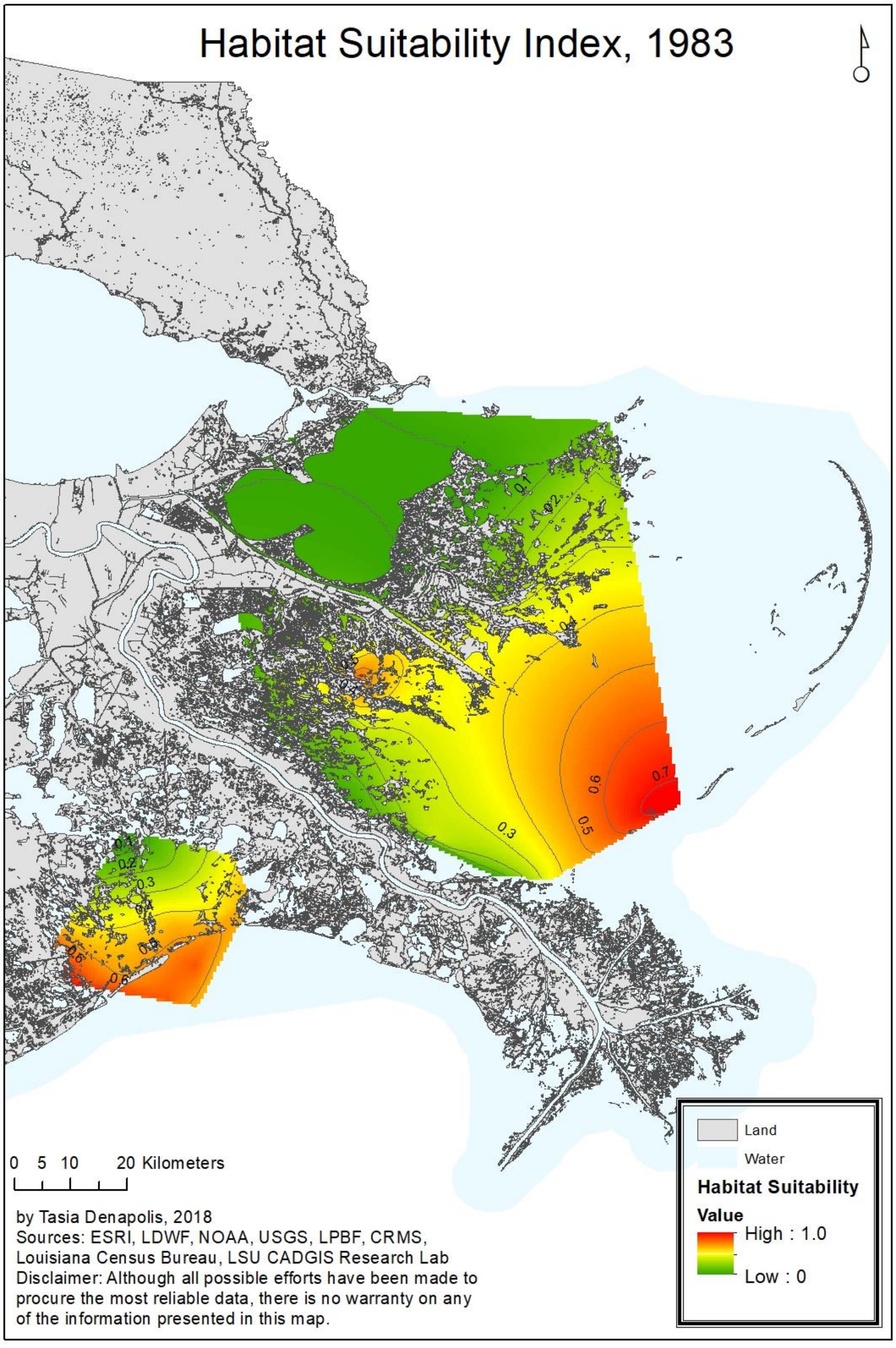


Figure 30: Habitat Suitability Index (HSI) 1983

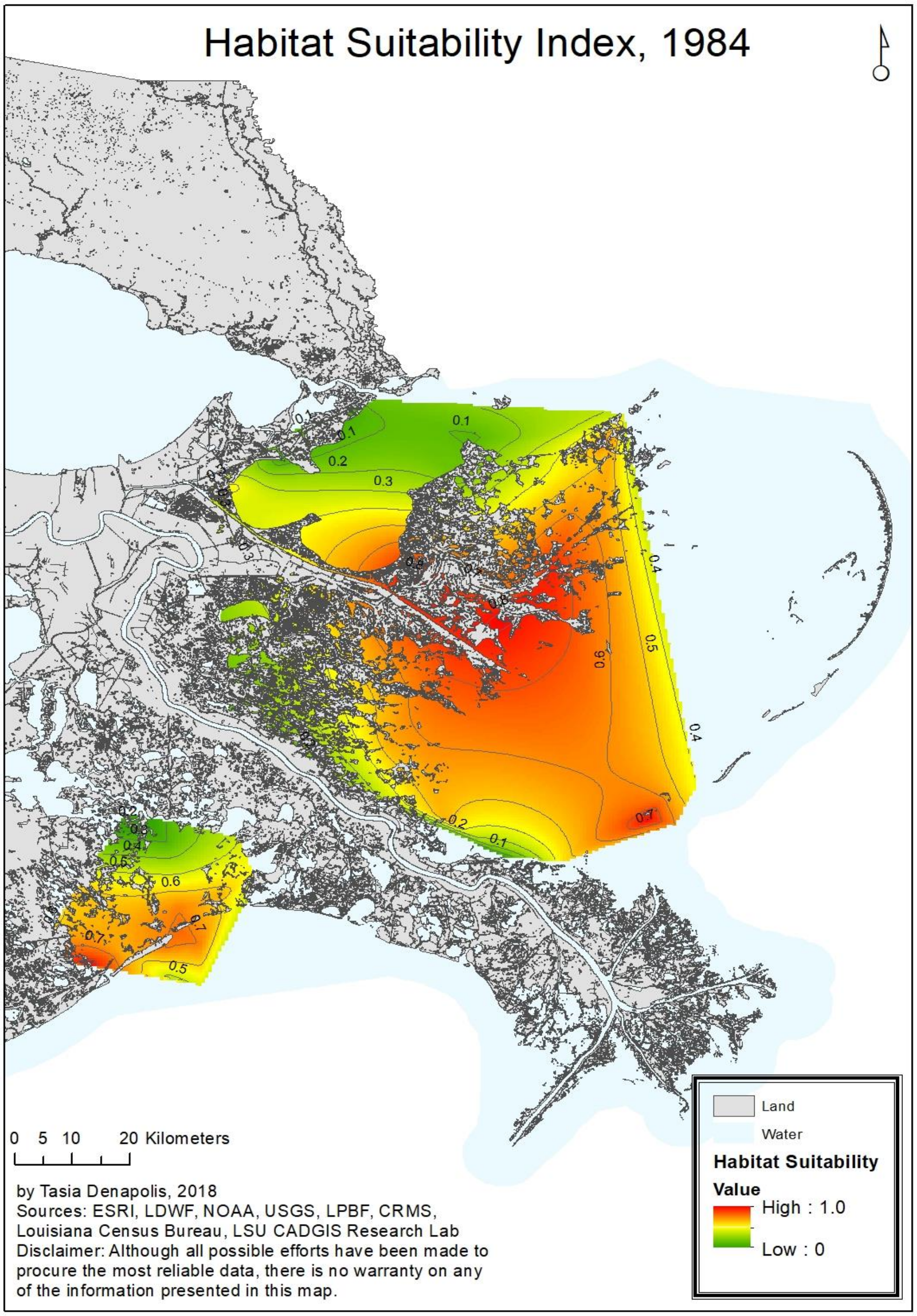


Figure 31: Habitat Suitability Index (HSI) 1984

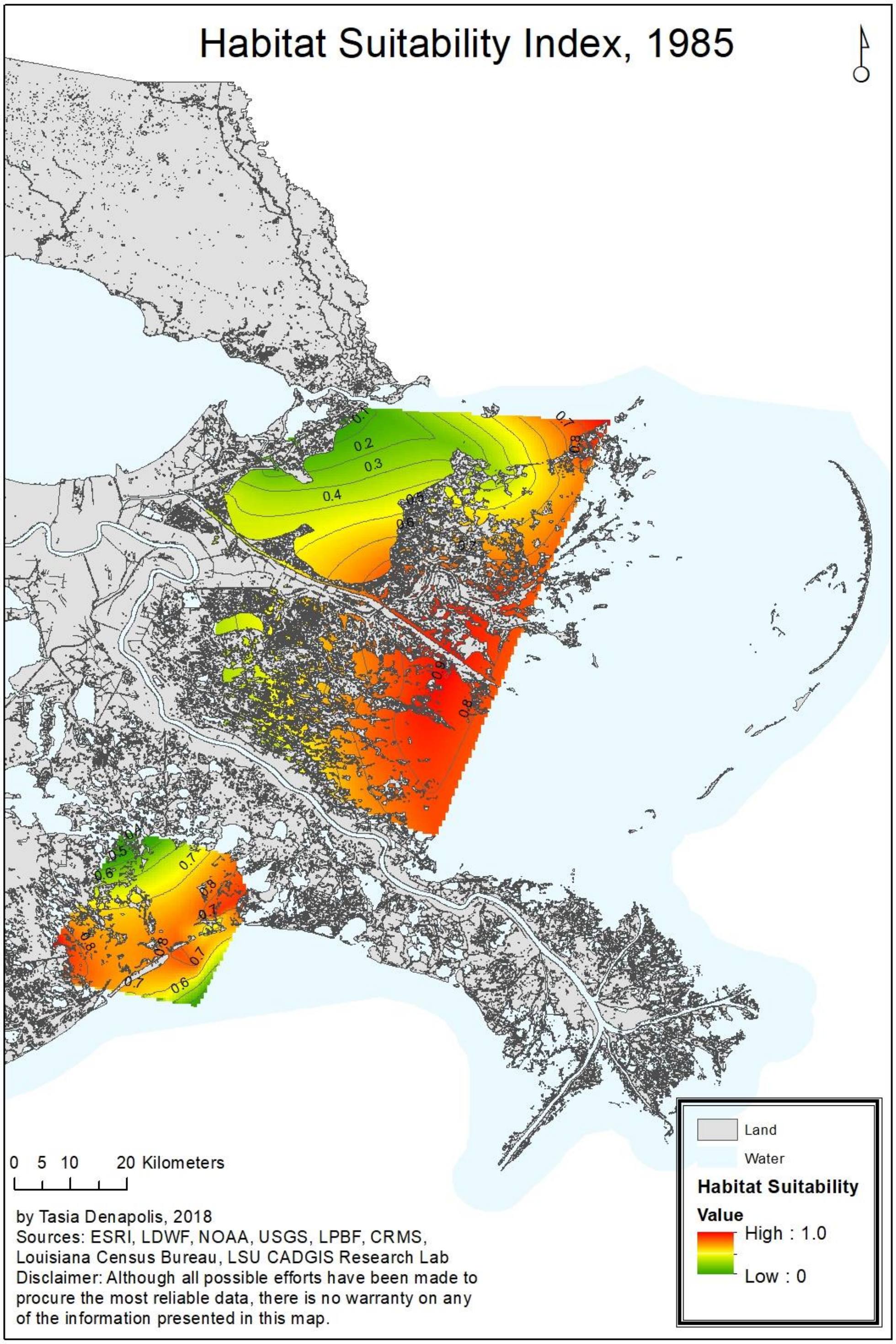


Figure 32: Habitat Suitability Index (HSI) 1985

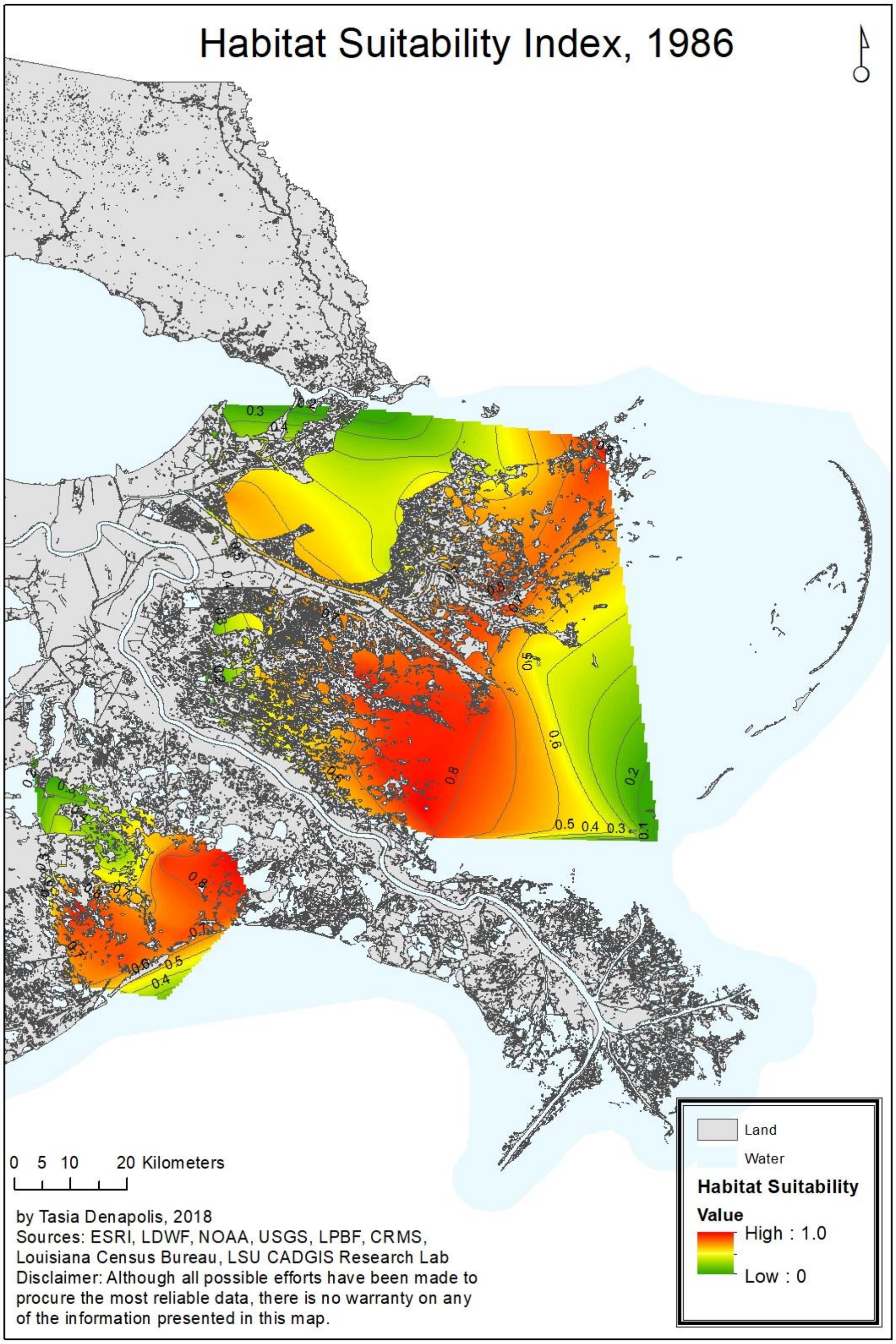
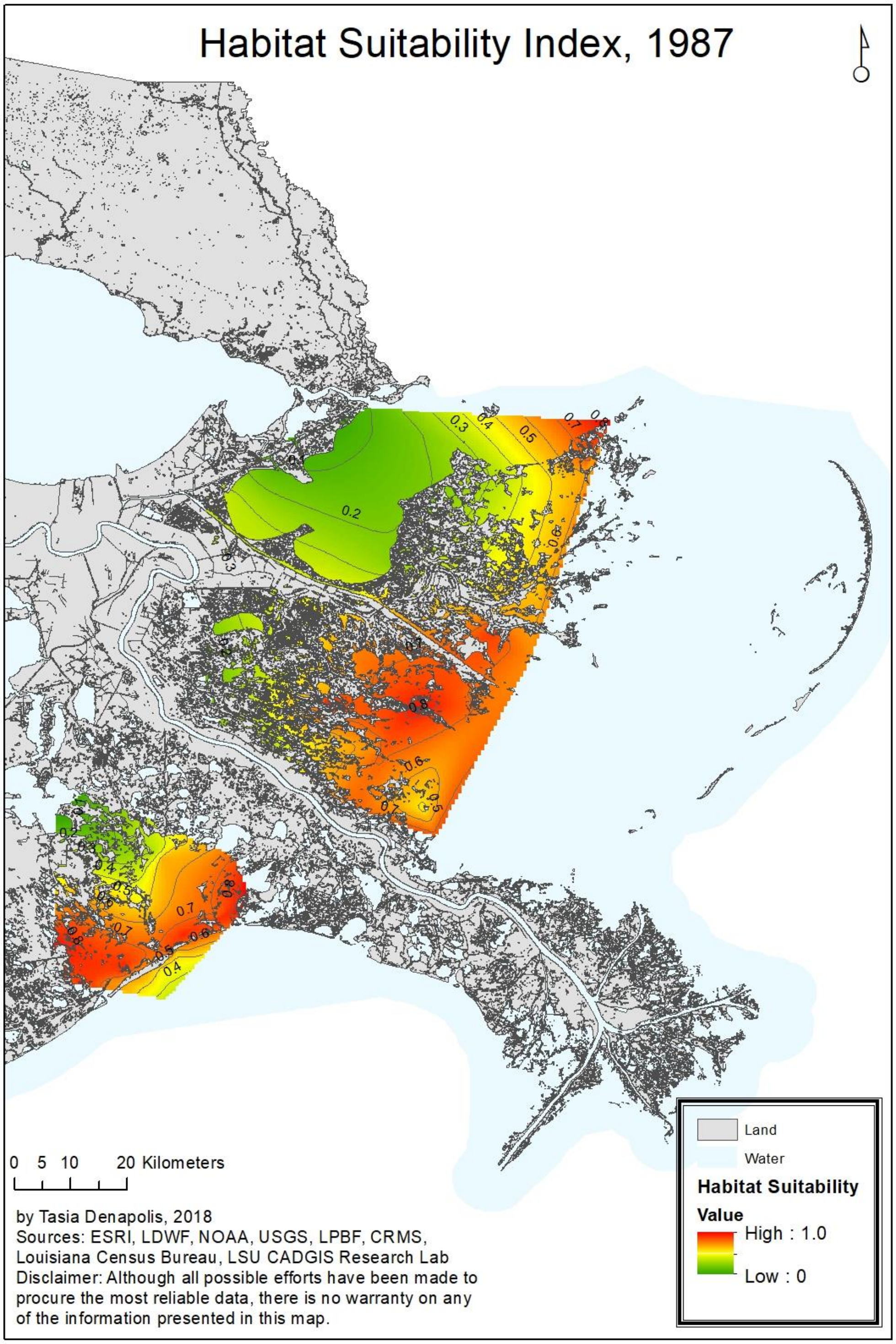


Figure 33: Habitat Suitability Index (HSI) 1986



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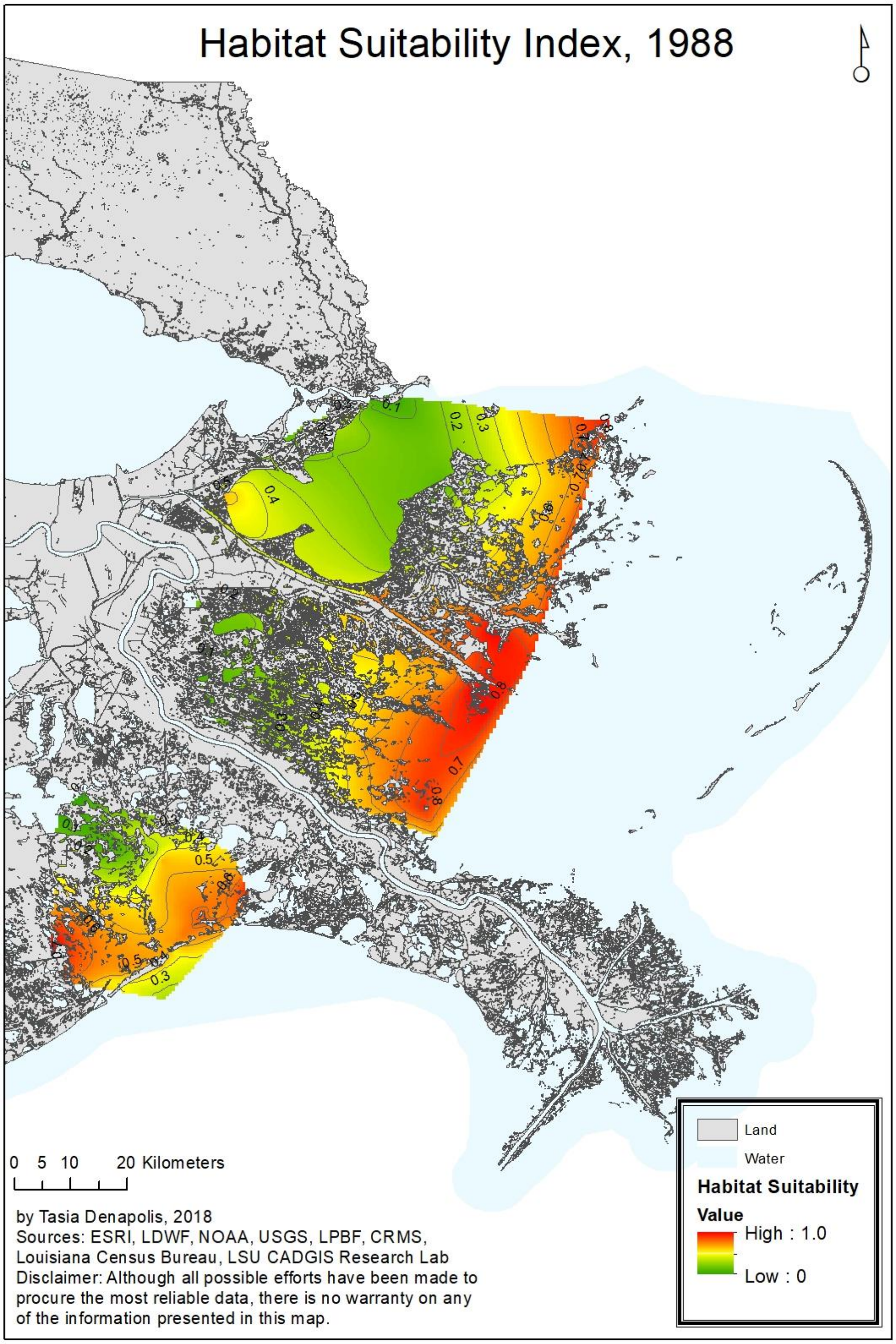
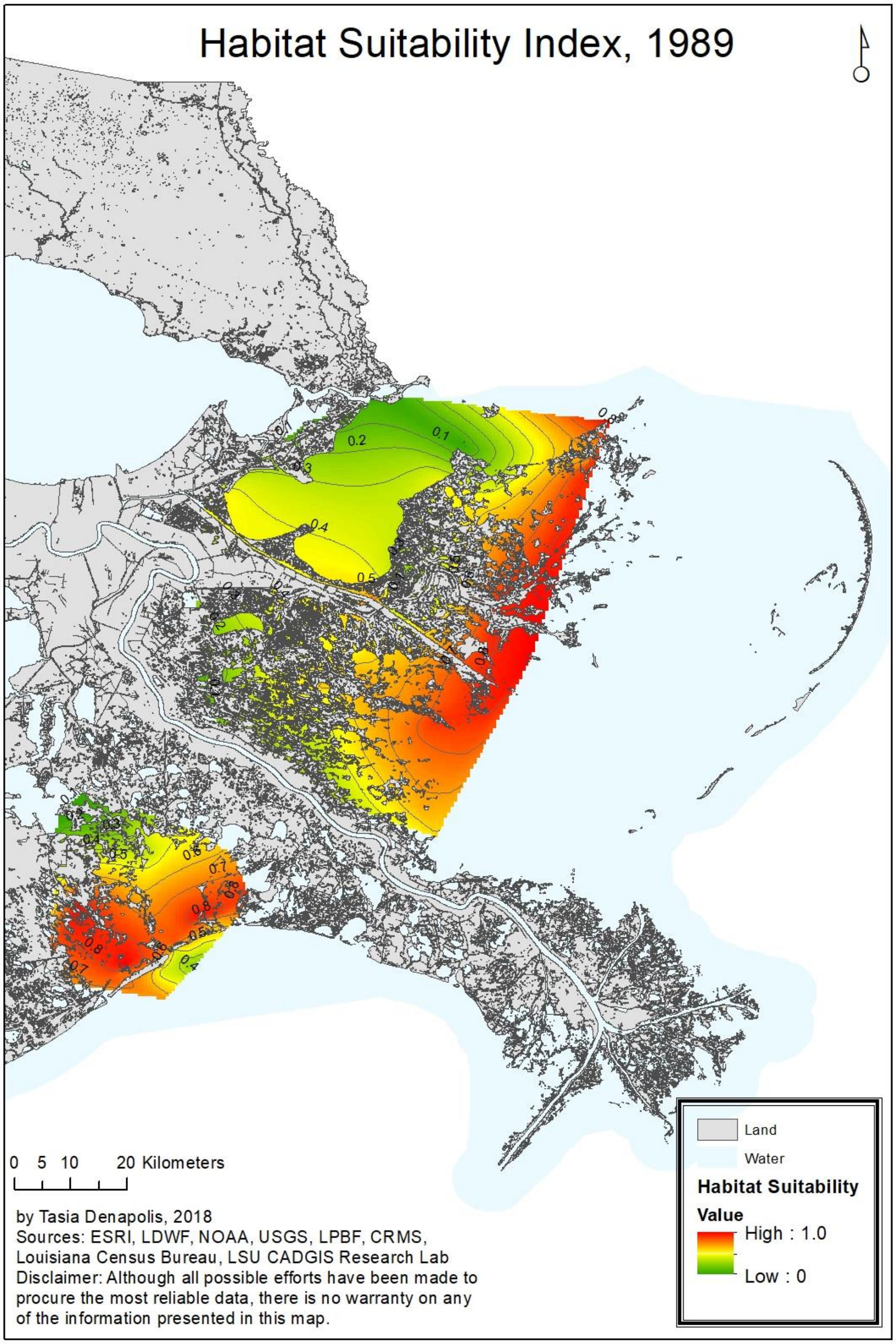


Figure 35: Habitat Suitability Index (HSI) 1988



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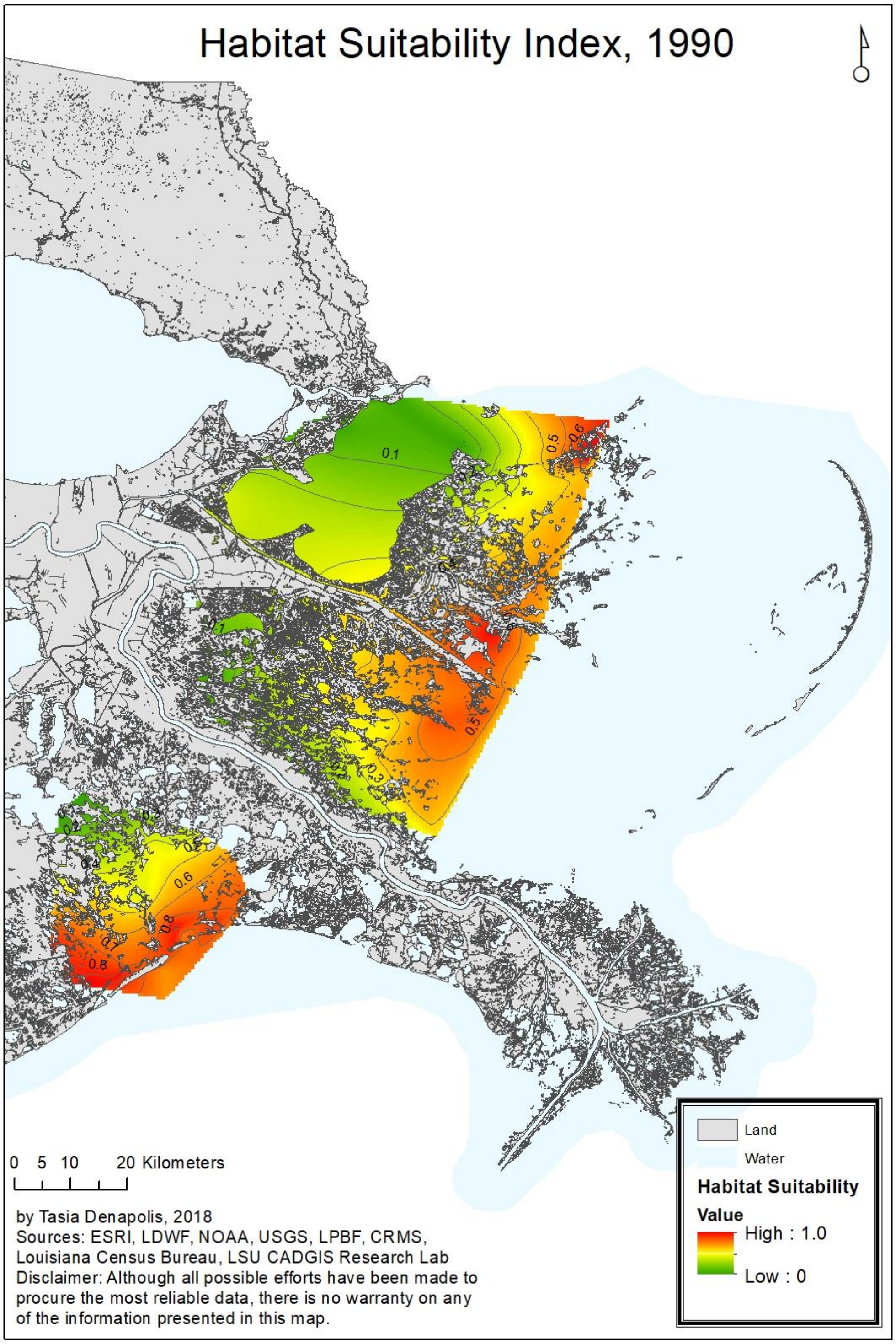

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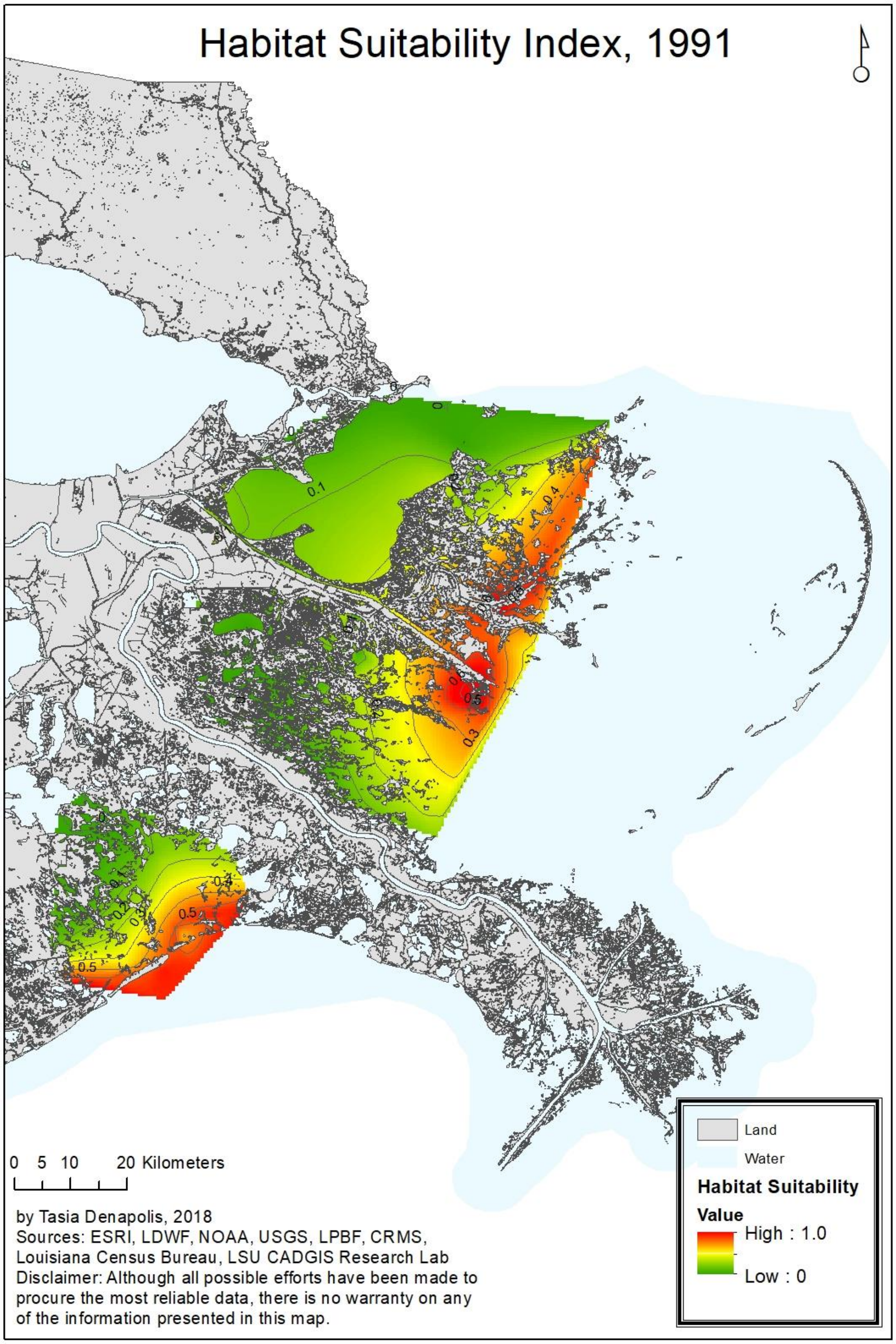

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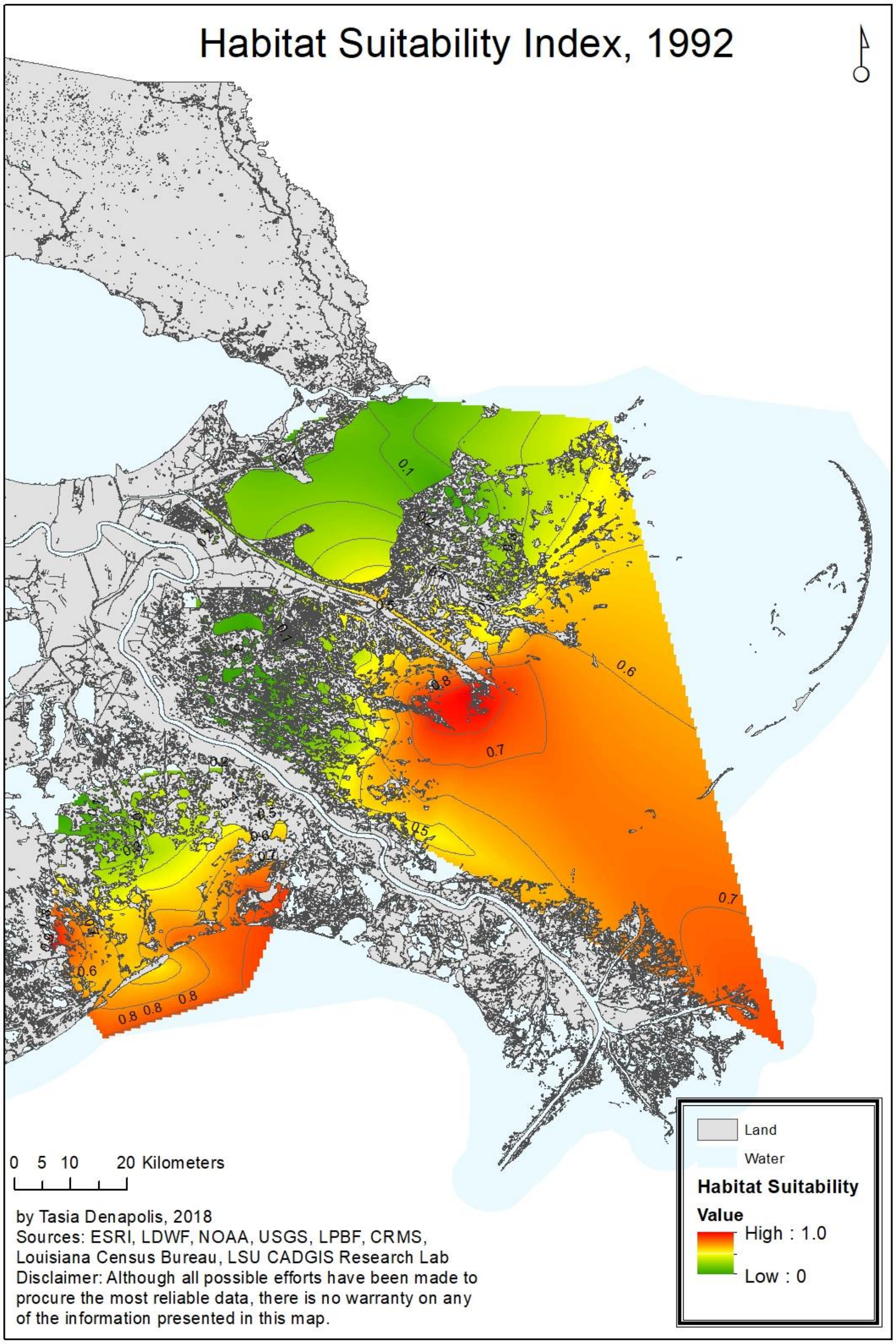

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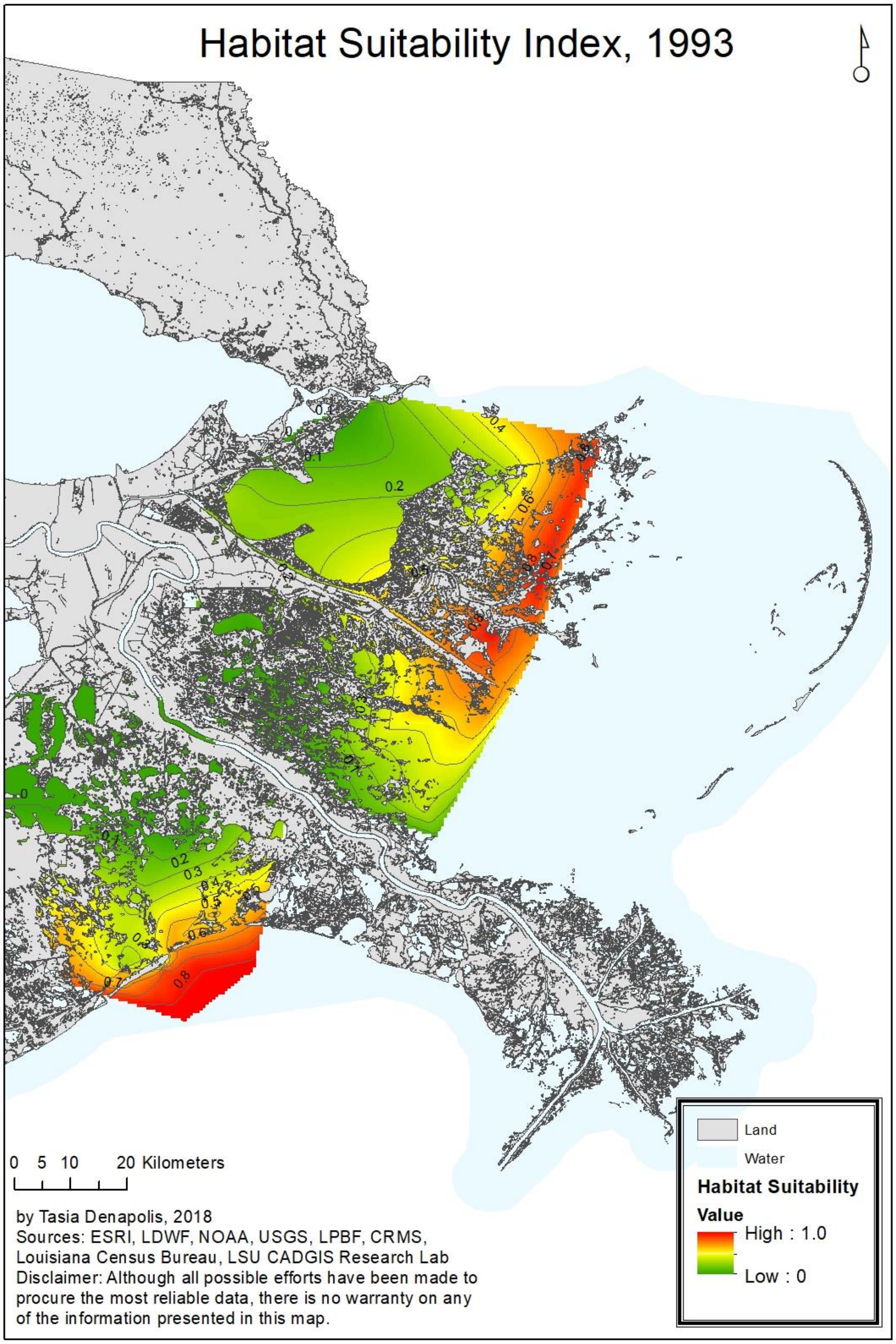

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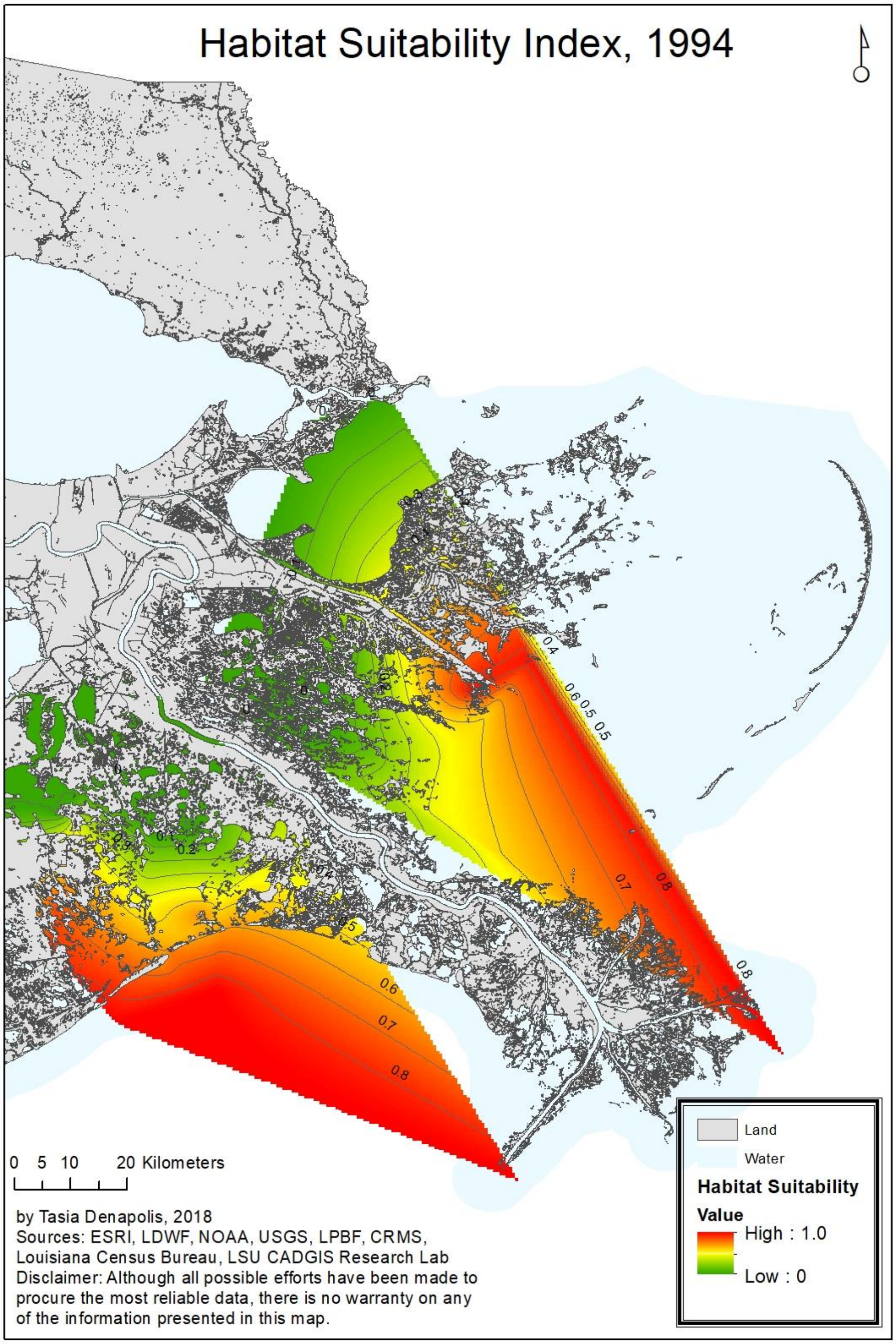
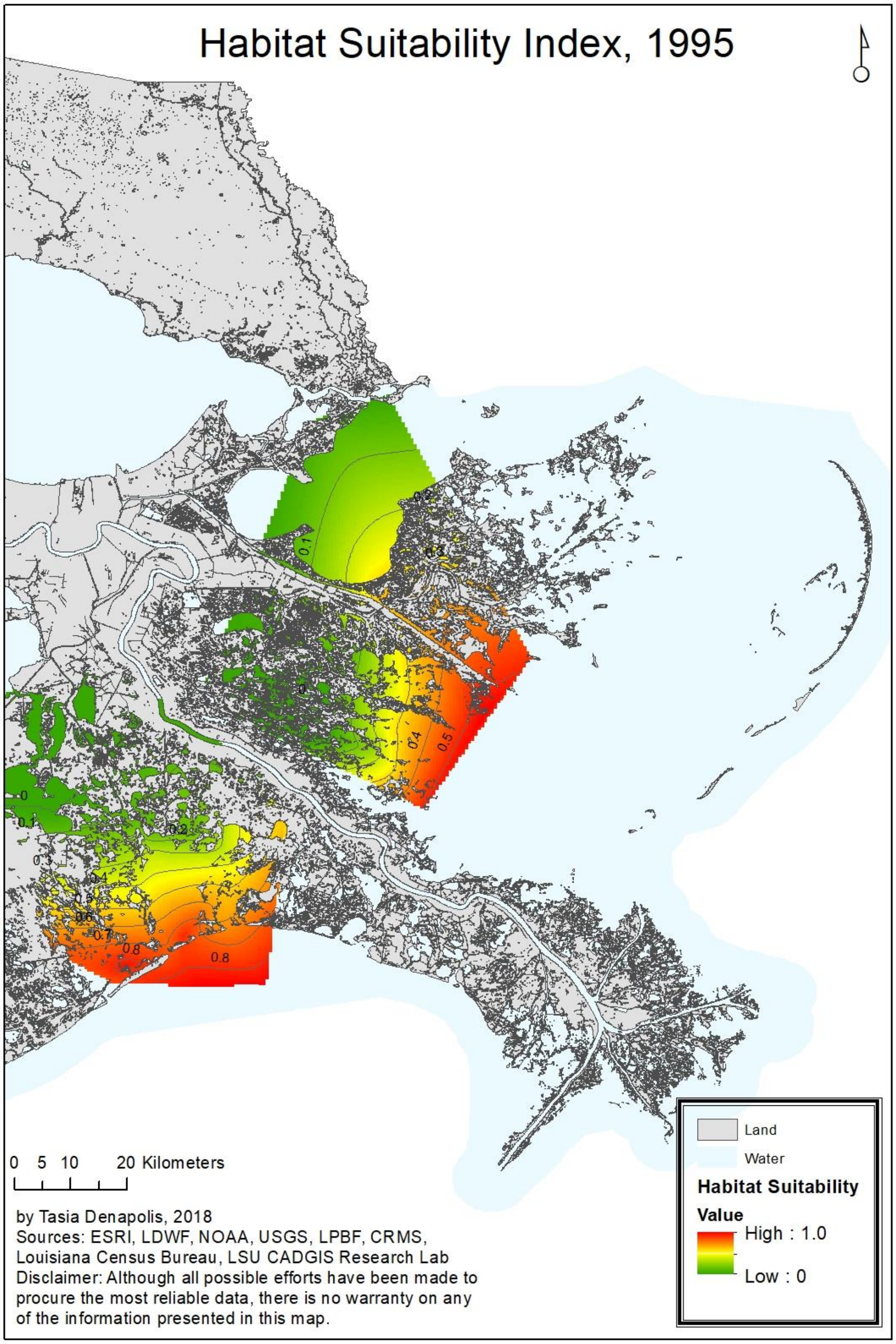


Figure 41: Habitat Suitability Index (HSI) 1994



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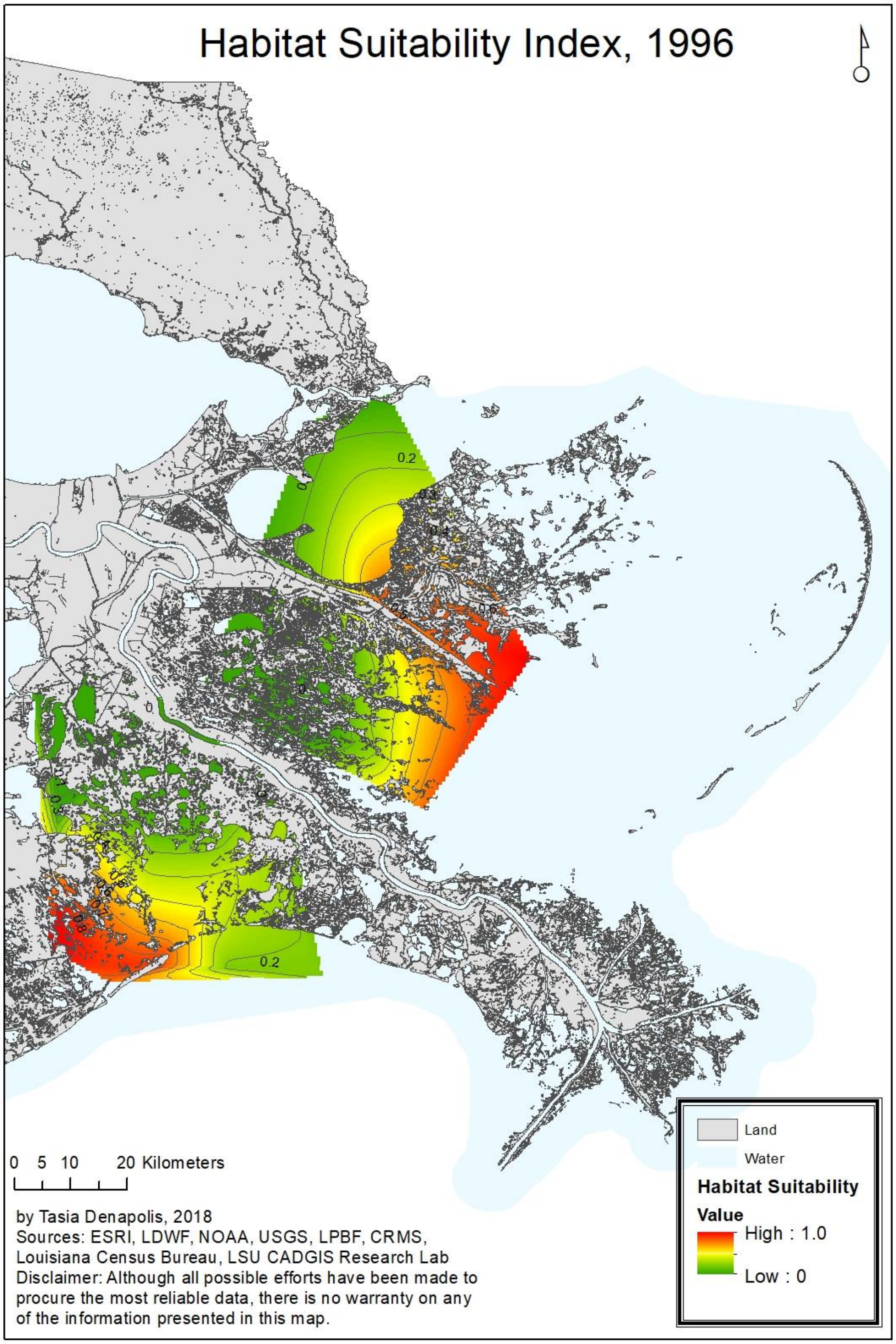
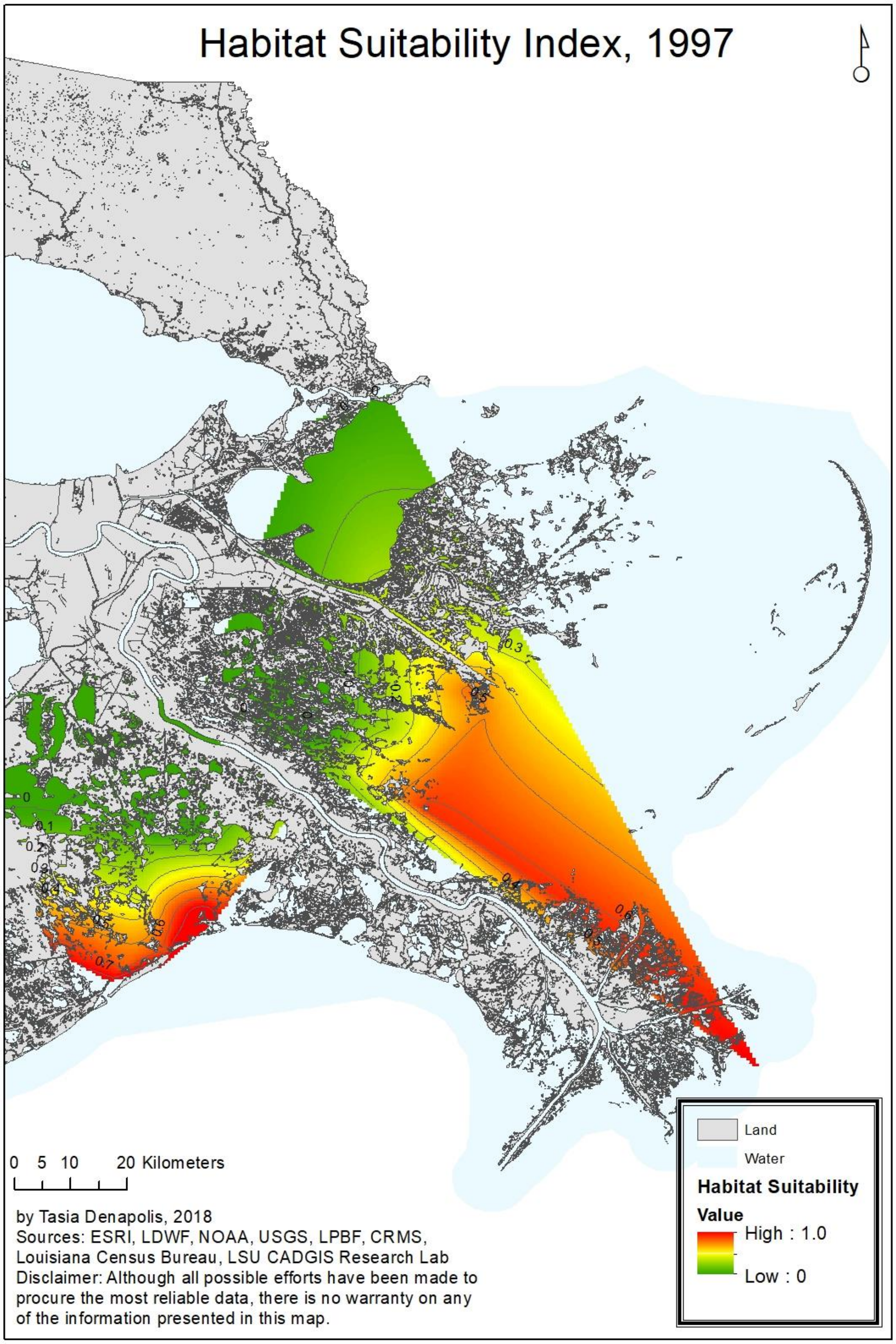


Figure 43: Habitat Suitability Index (HSI) 1996



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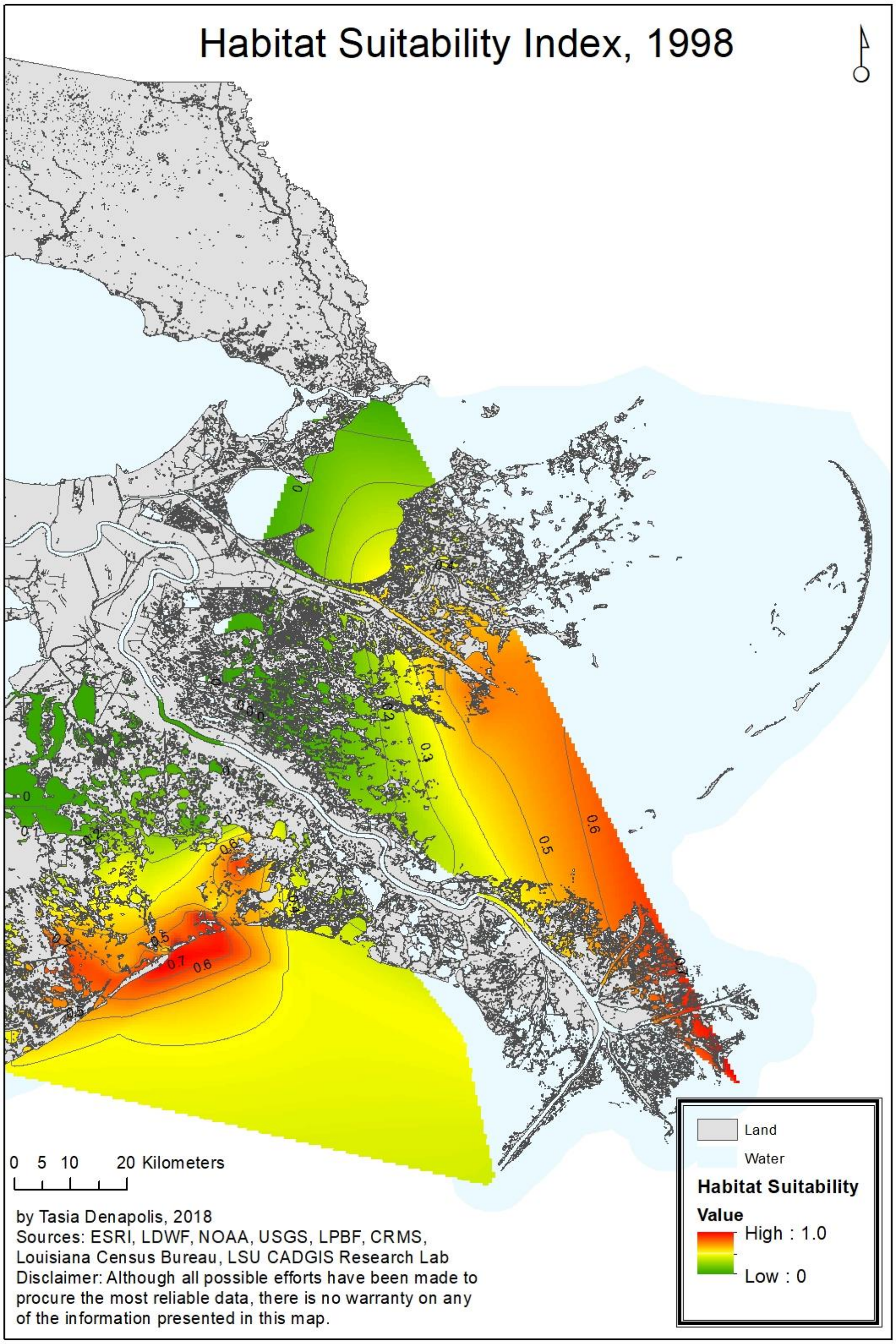

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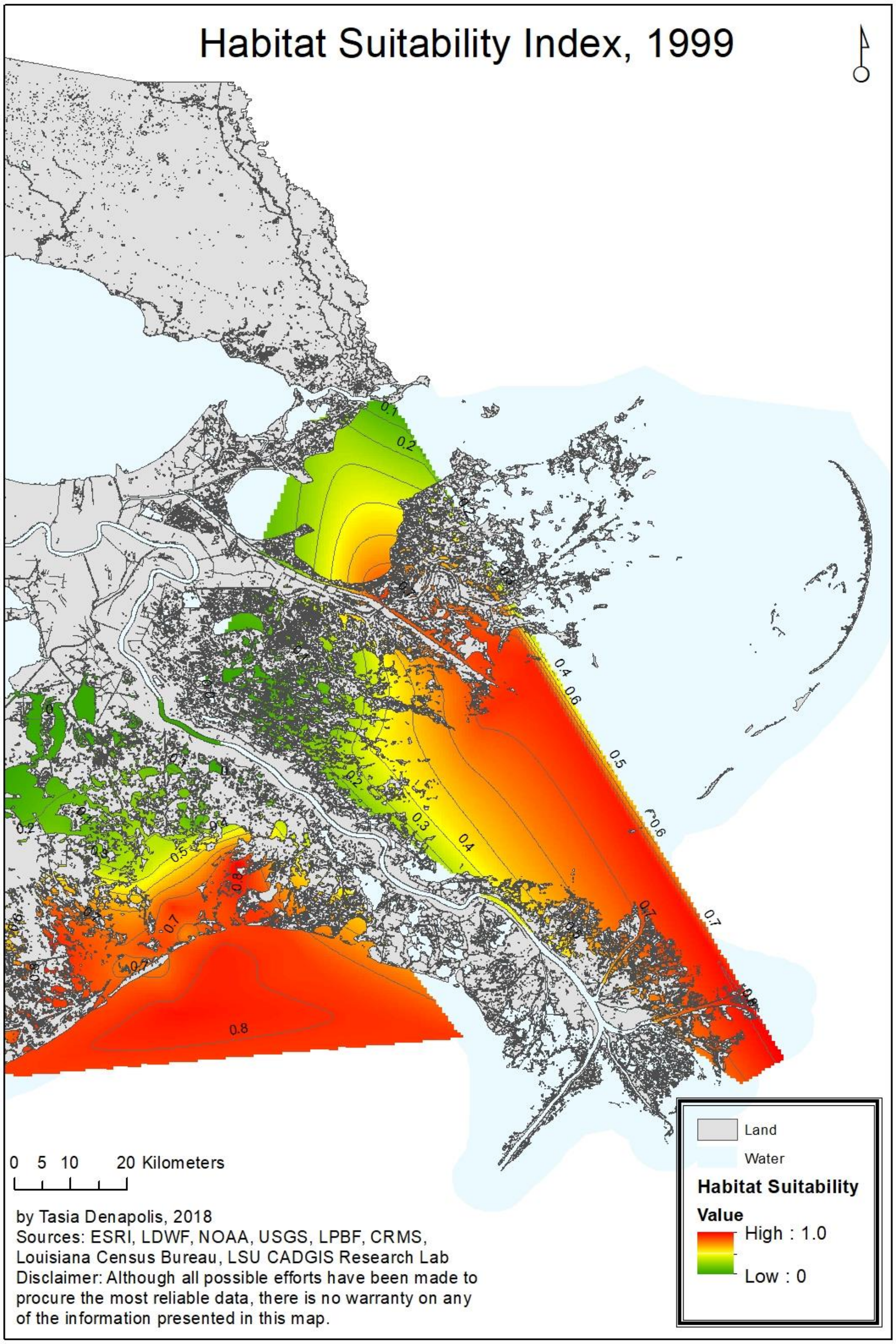

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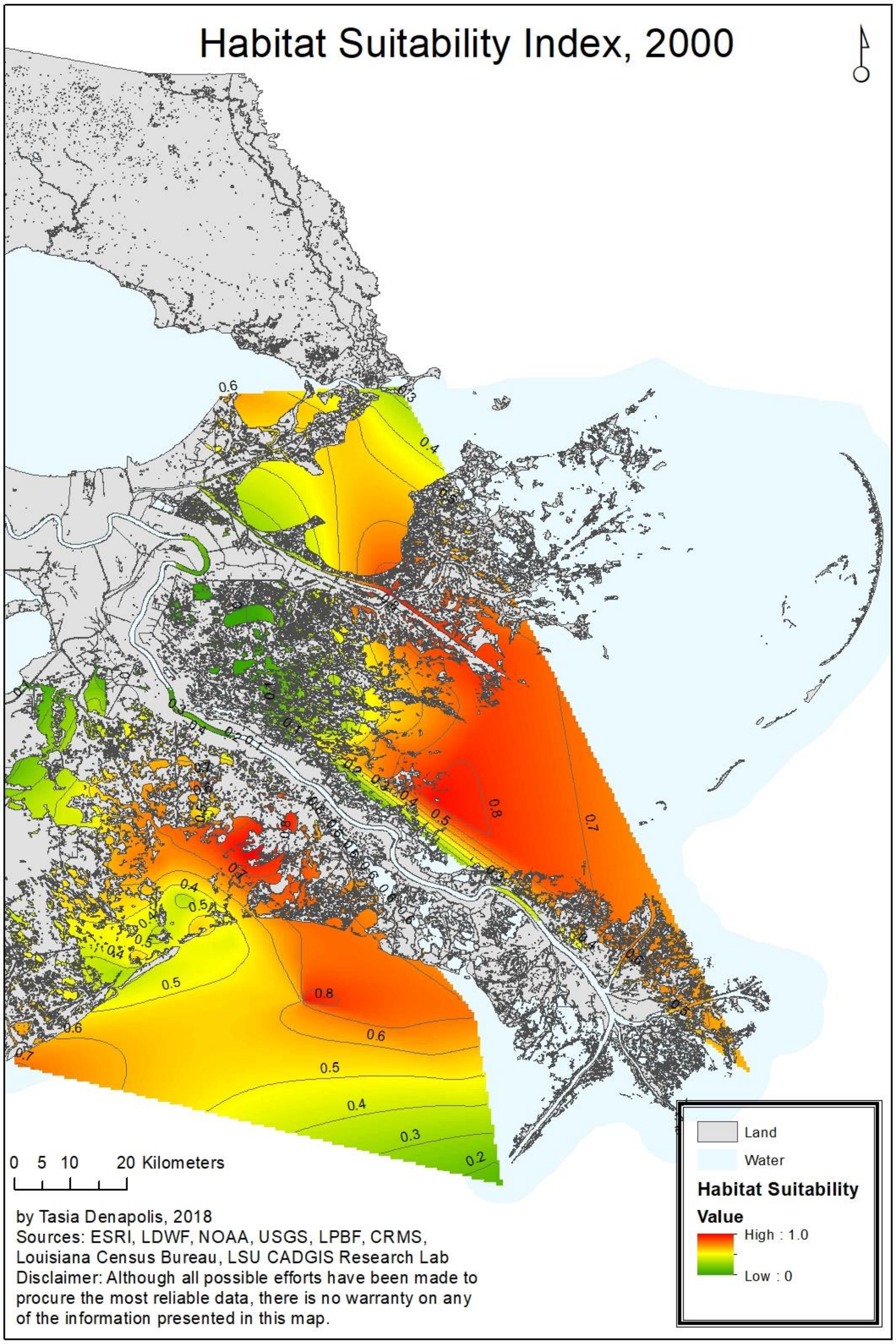

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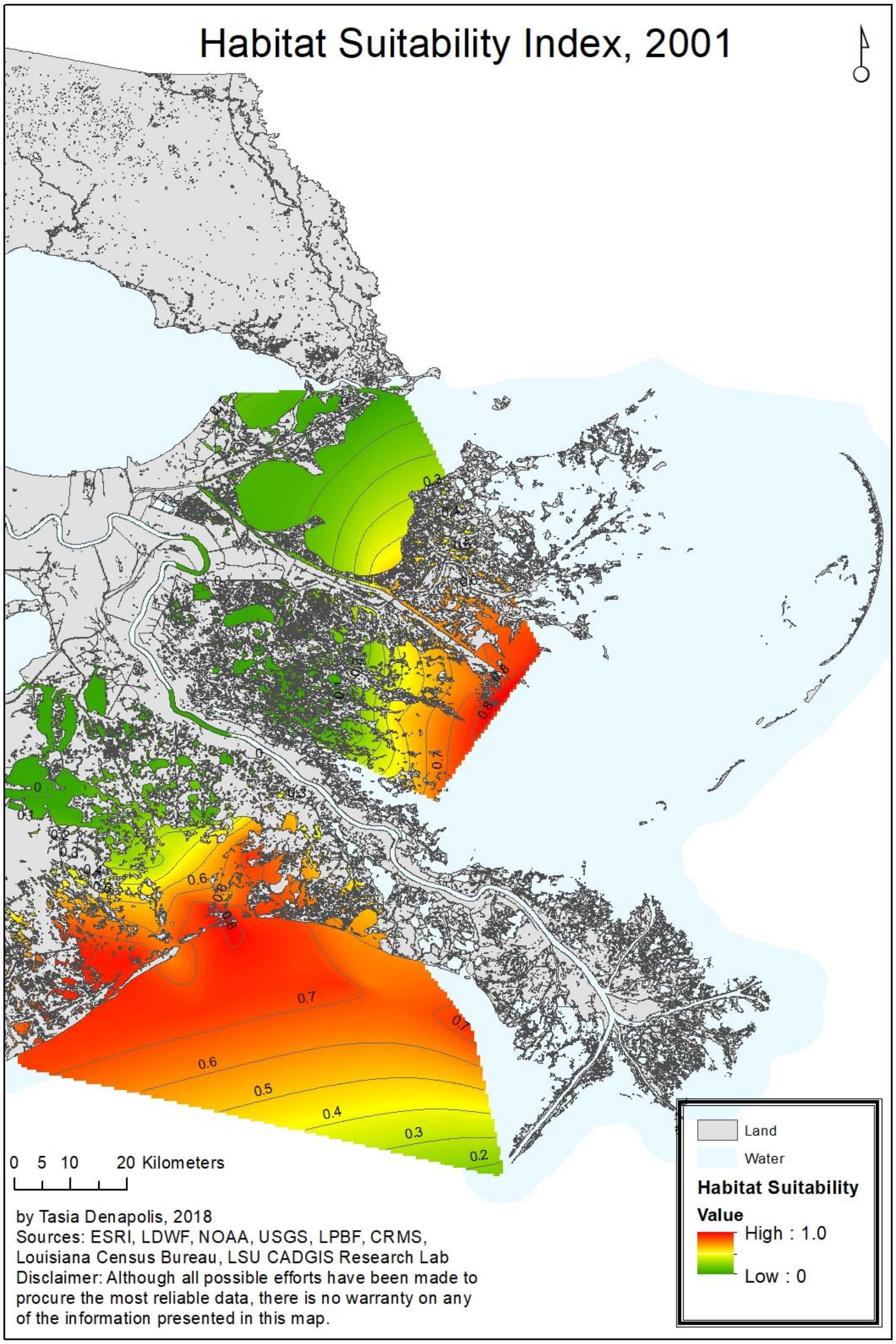

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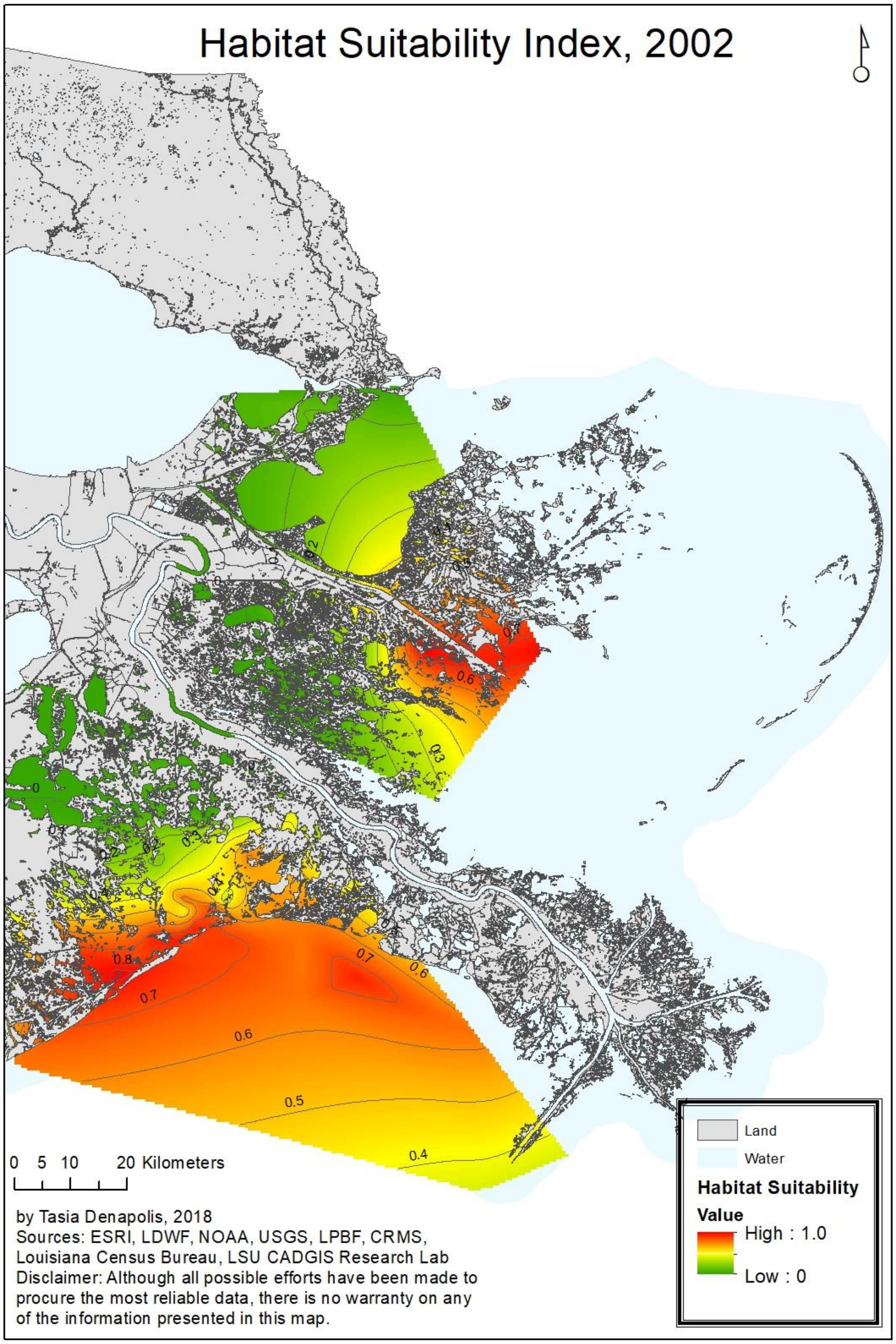

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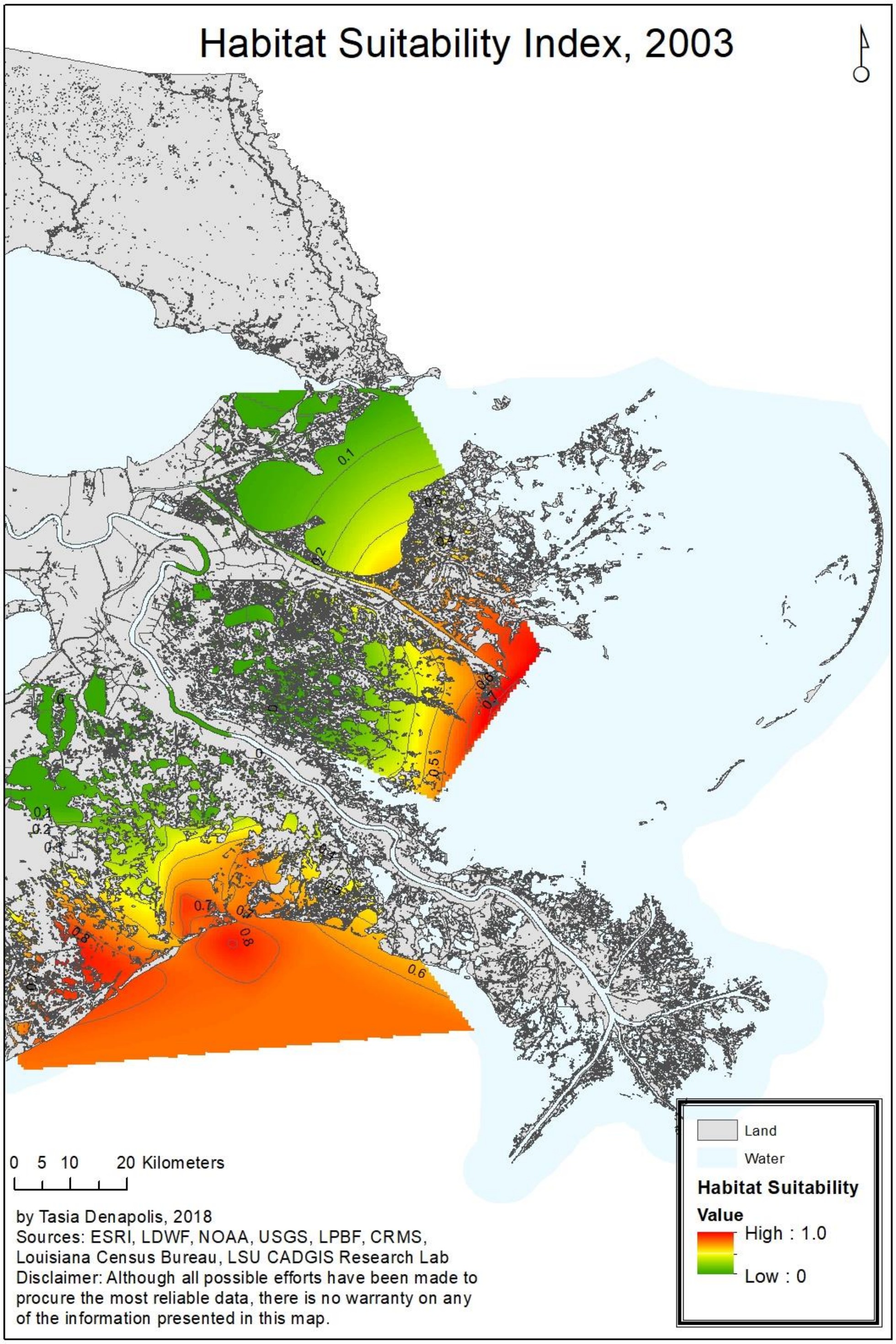

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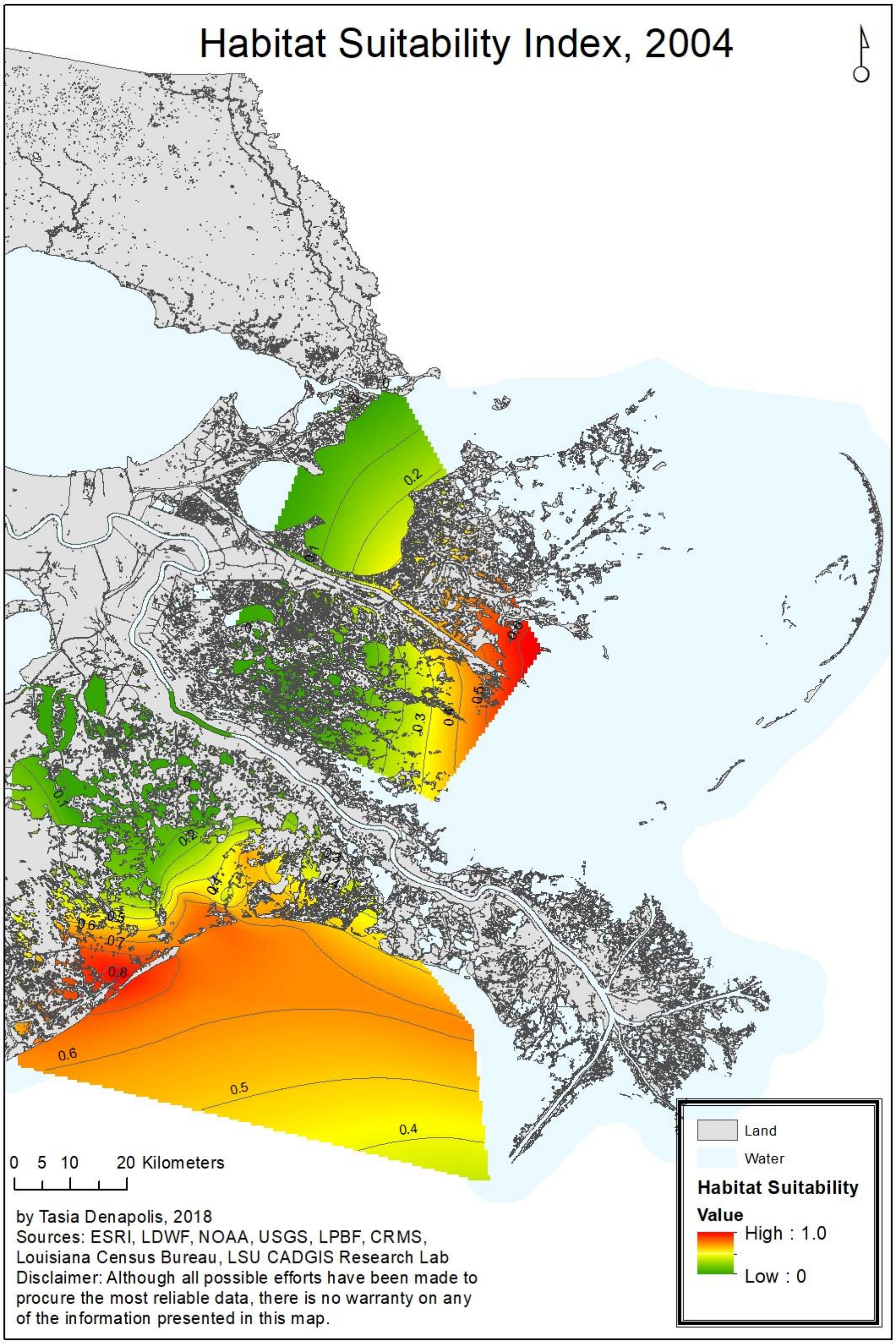

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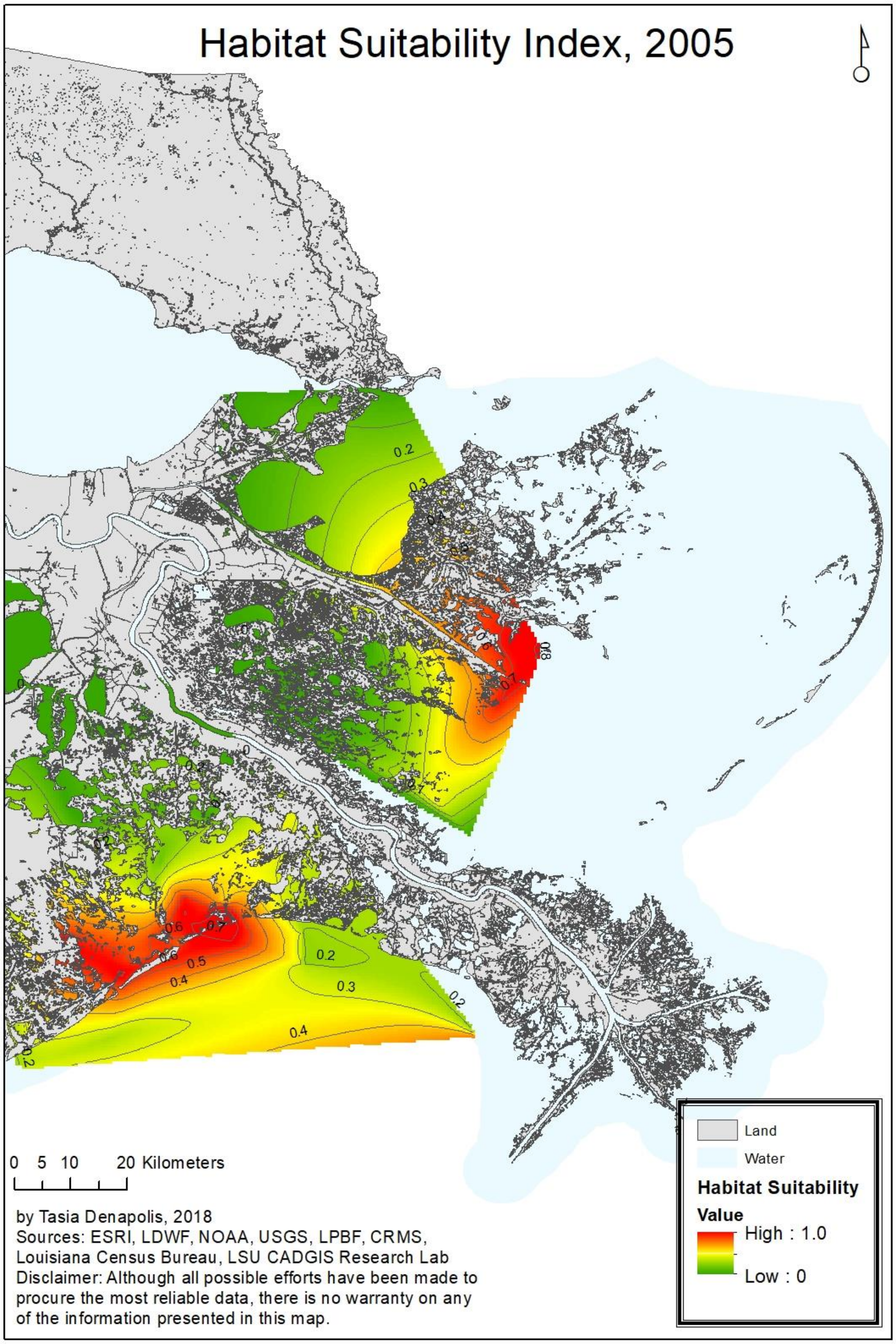

Figure 52: Habitat Suitability Index (HSI) 2005

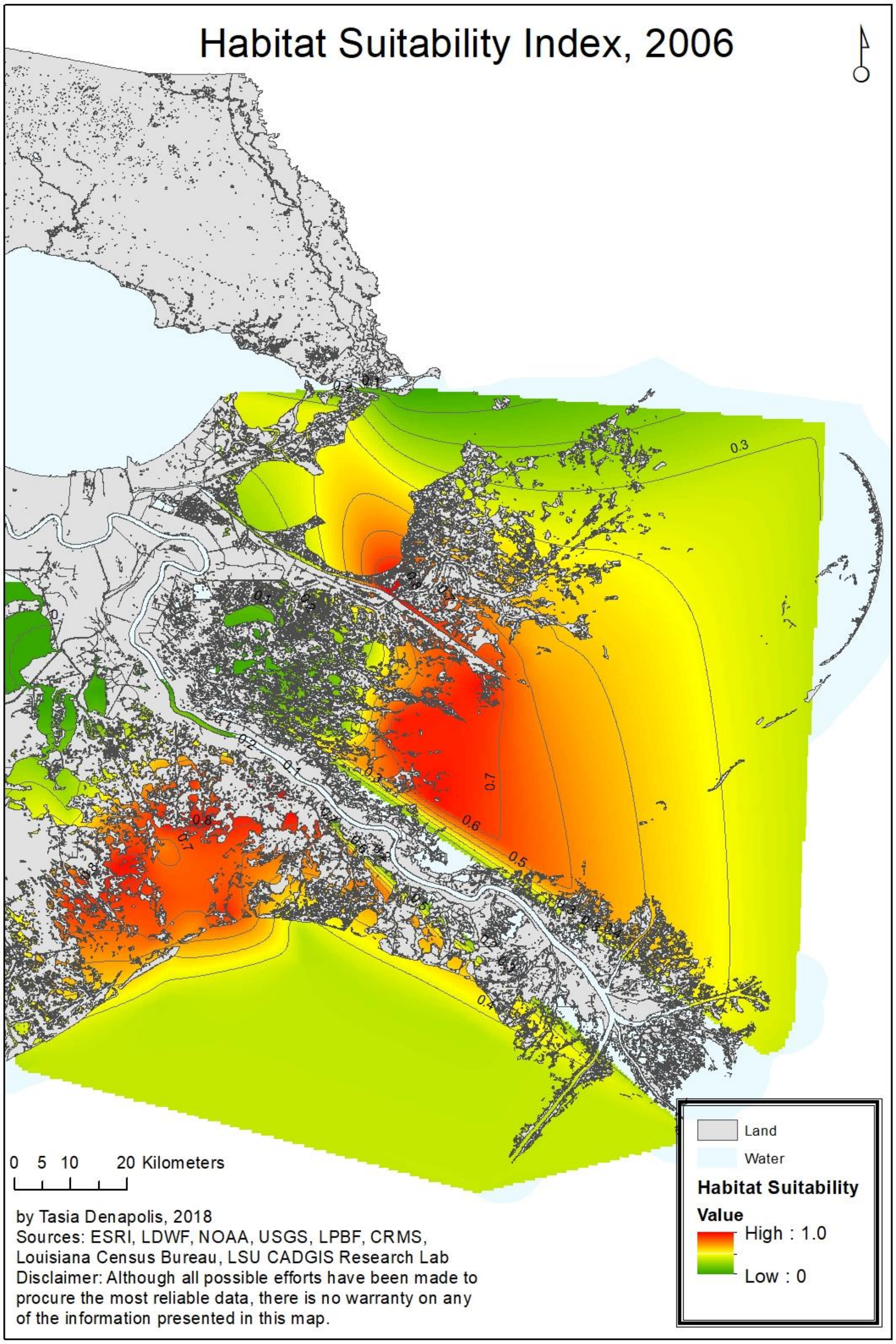

Figure 53: Habitat Suitability Index (HSI) 2006

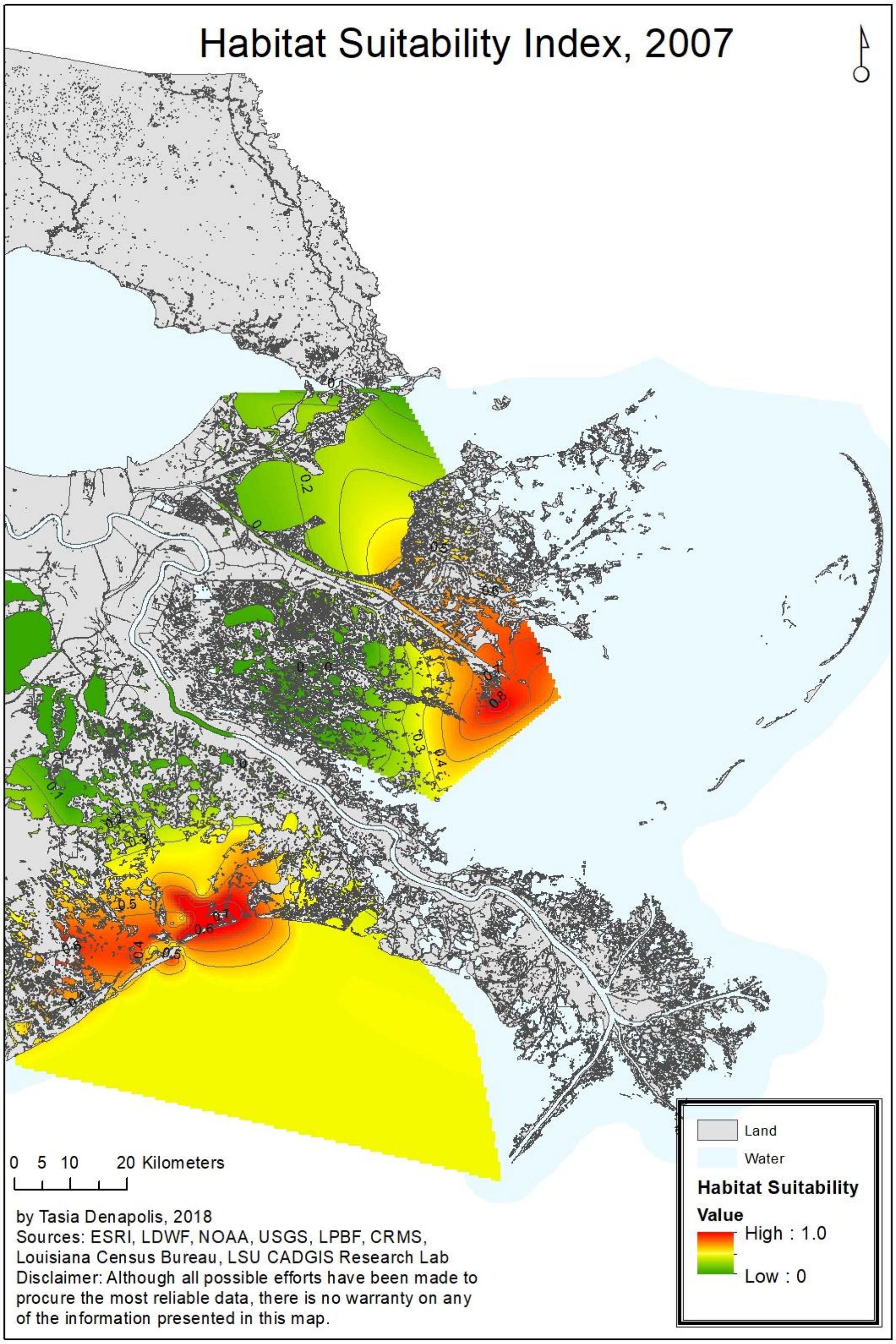

Figure 54: Habitat Suitability Index (HSI) 2007

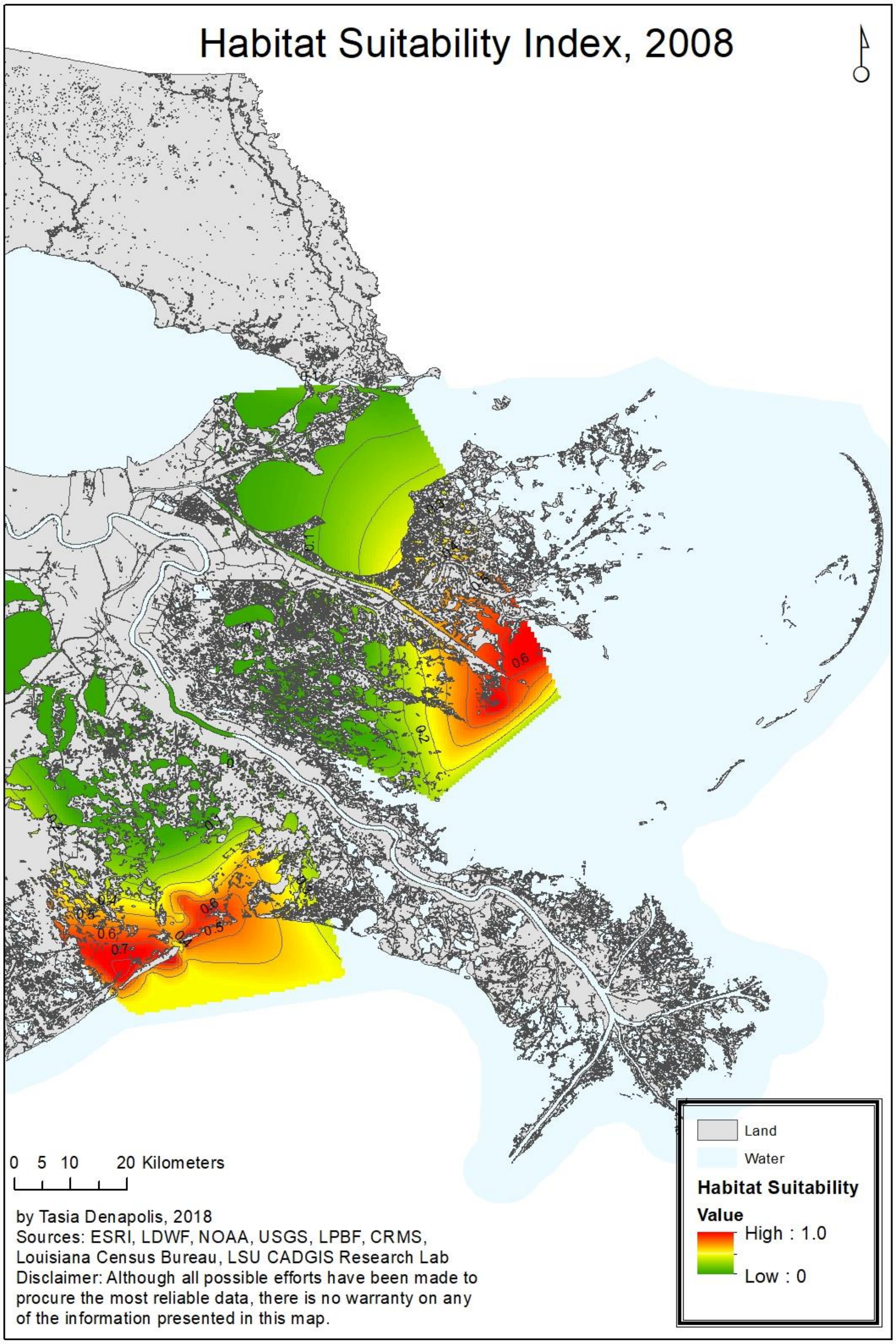

Figure 55: Habitat Suitability Index (HSI) 2008

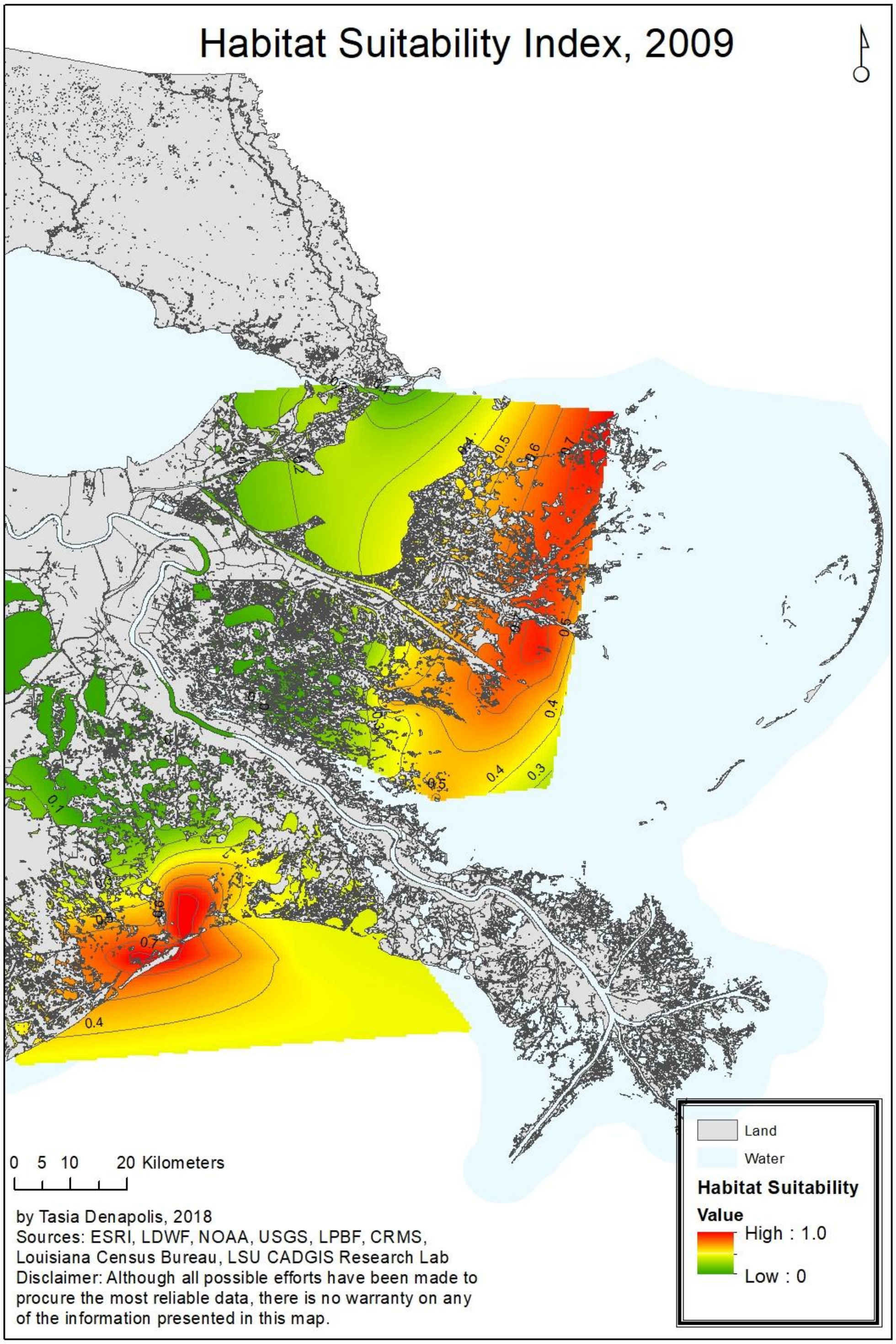

Figure 56: Habitat Suitability Index (HSI) 2009

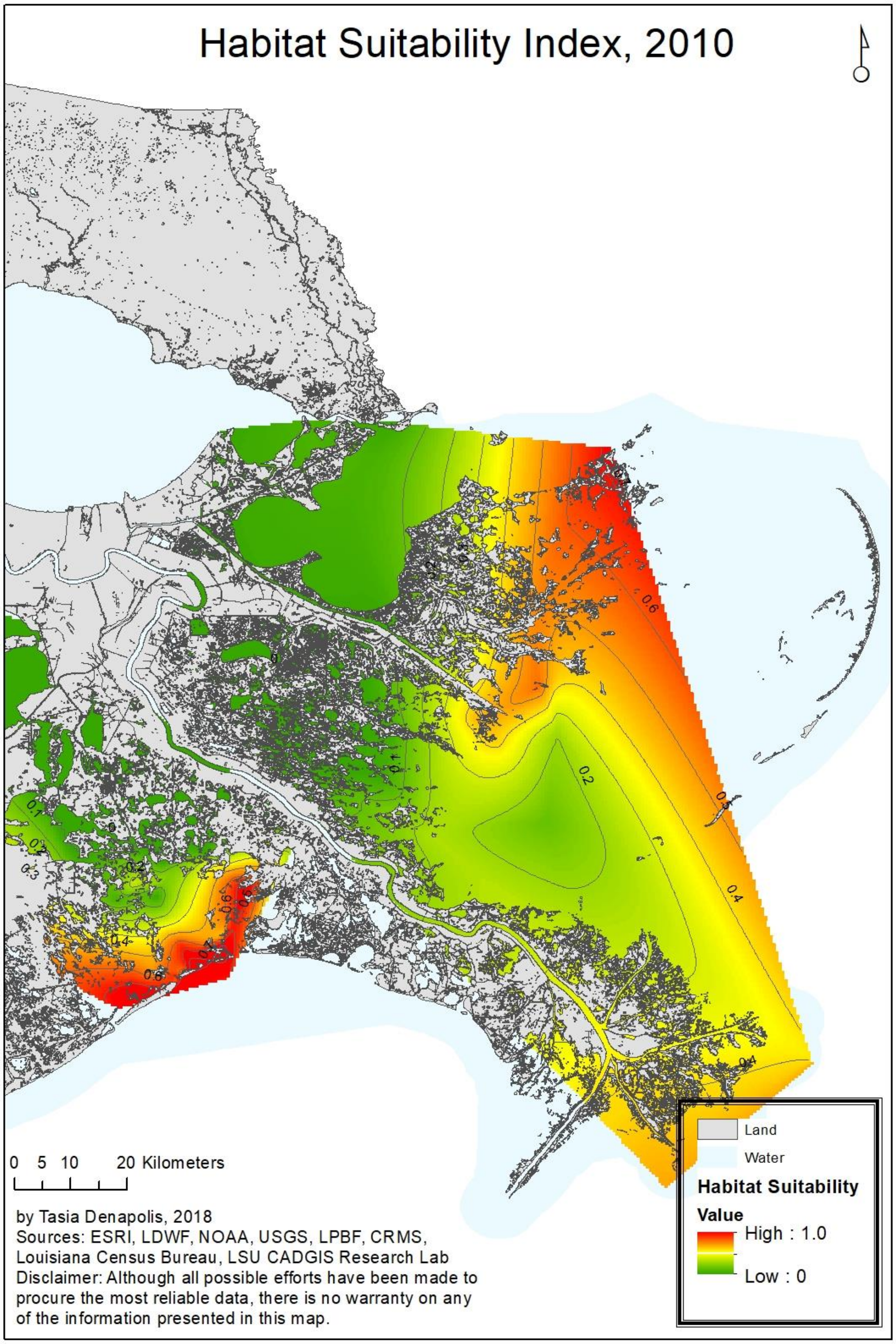

Figure 57: Habitat Suitability Index (HSI) 2010

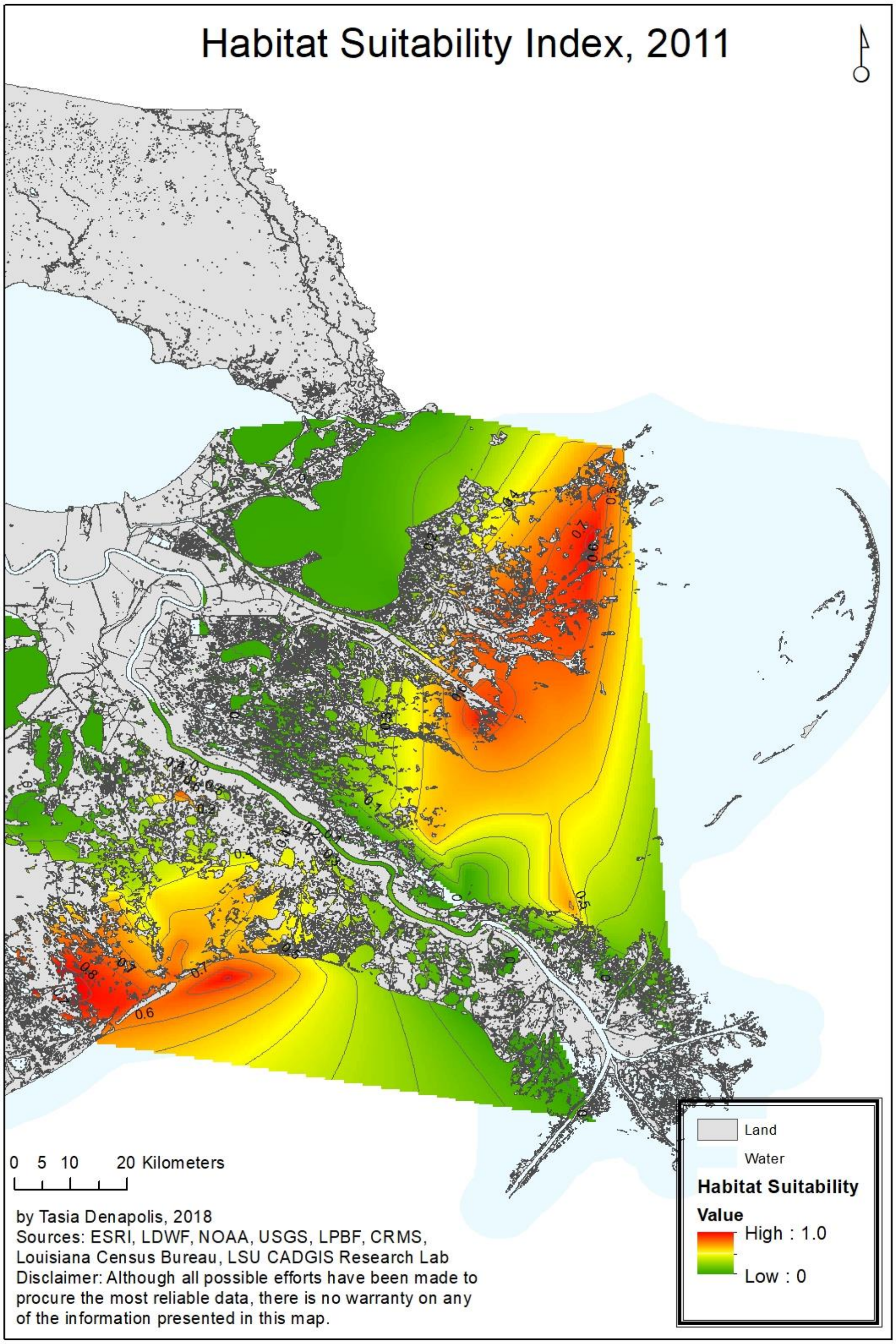

Figure 58: Habitat Suitability Index (HSI) 2011

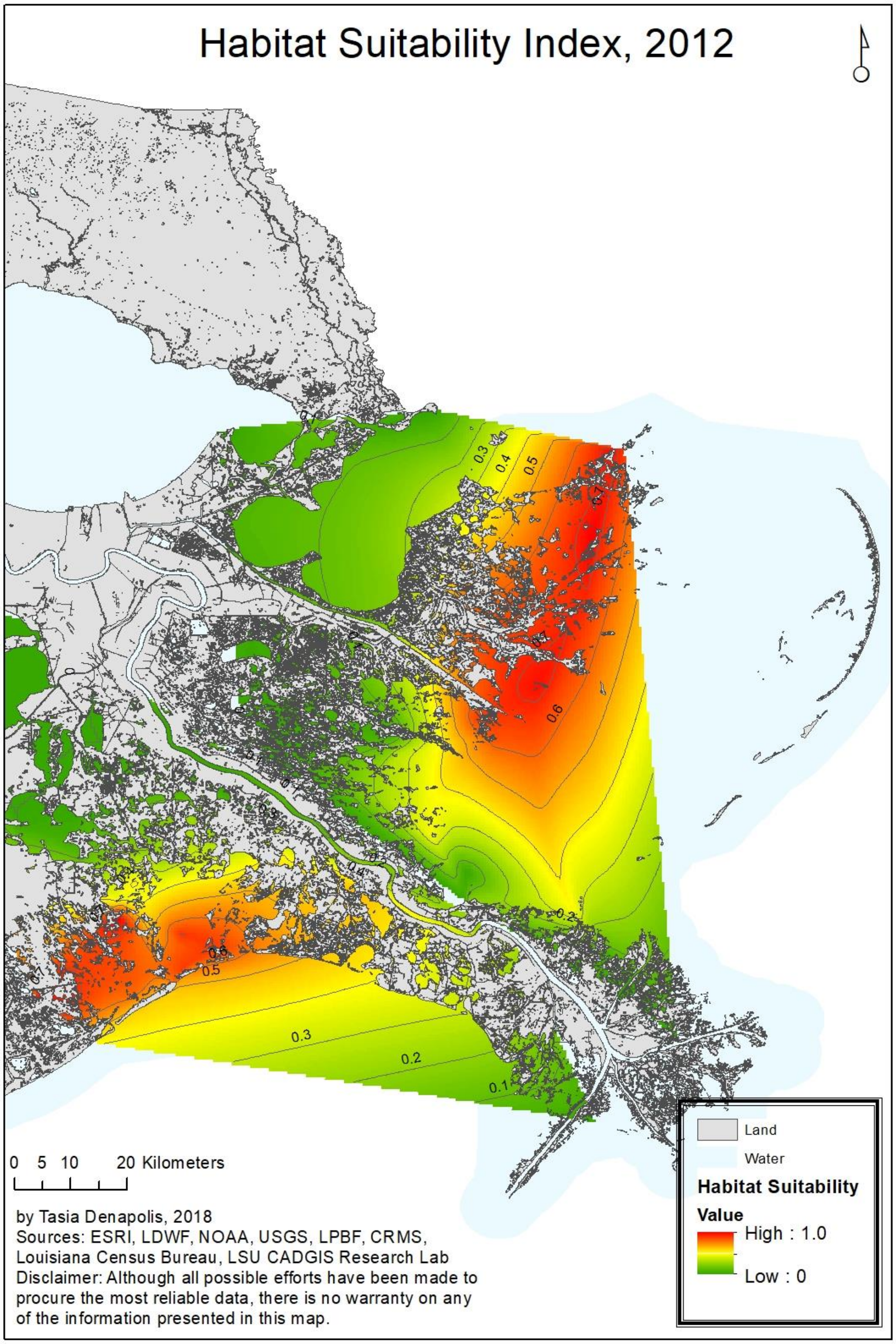

Figure 59: Habitat Suitability Index (HSI) 2012

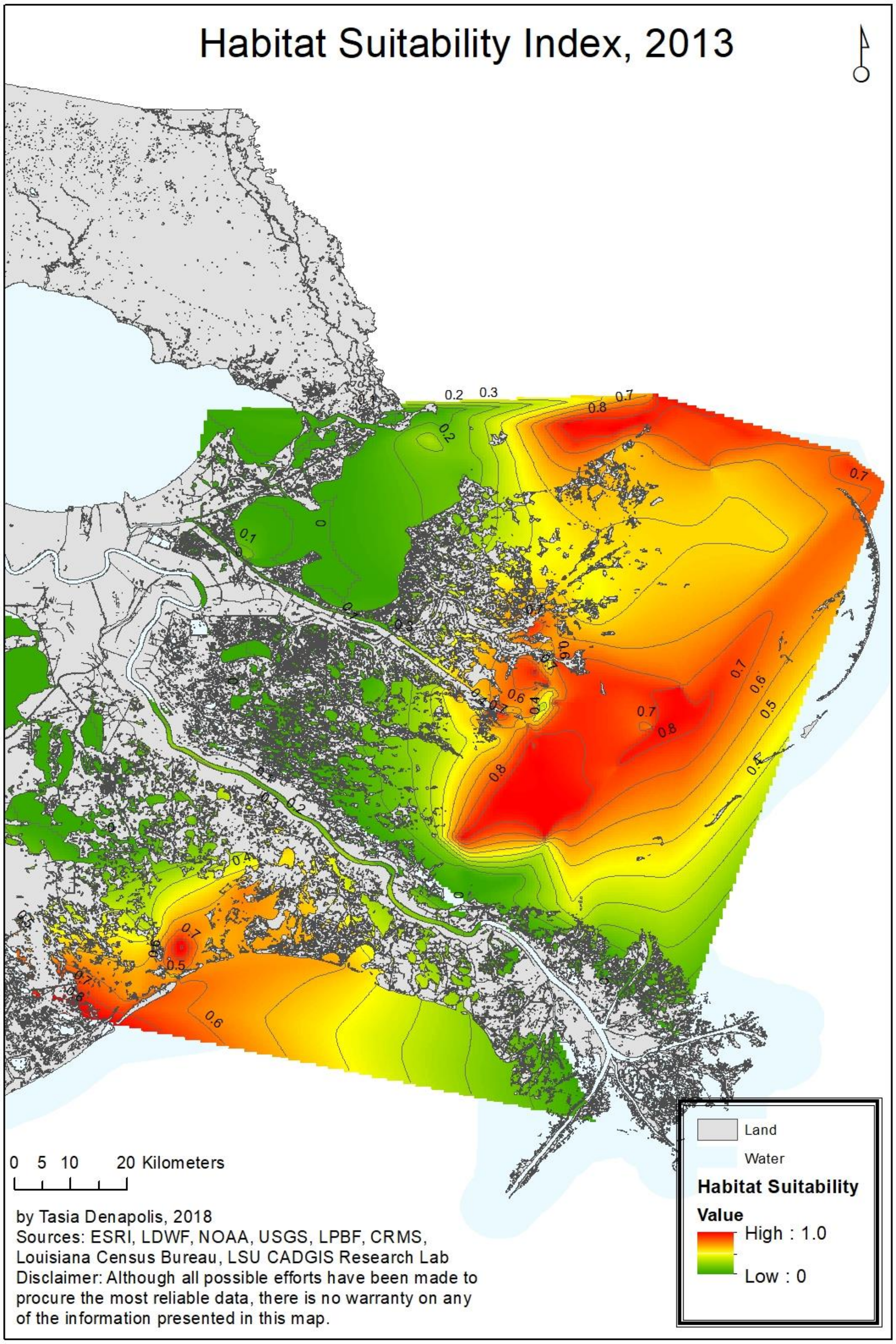

Figure 60: Habitat Suitability Index (HSI) 2013

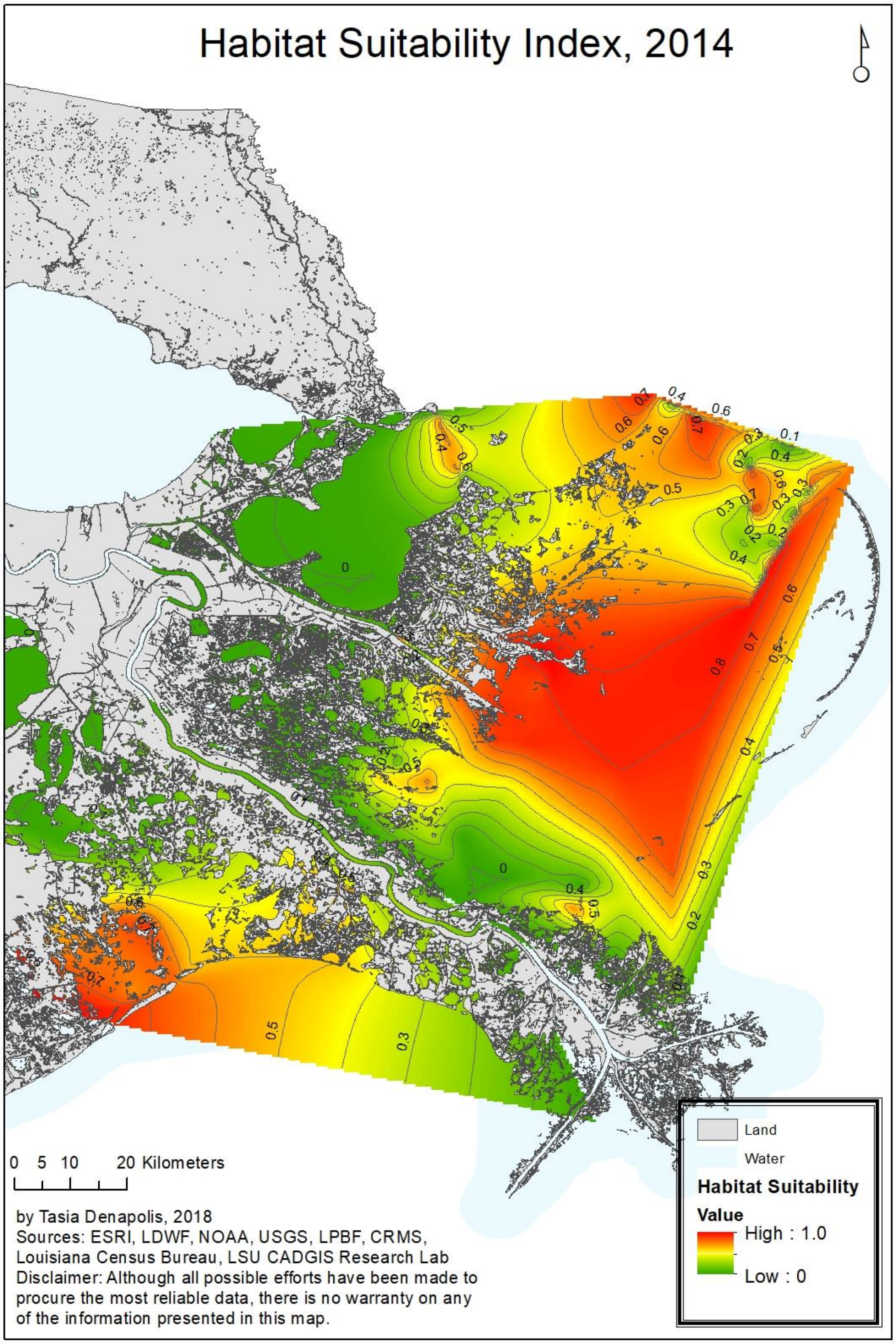

Figure 61: Habitat Suitability Index (HSI) 2014

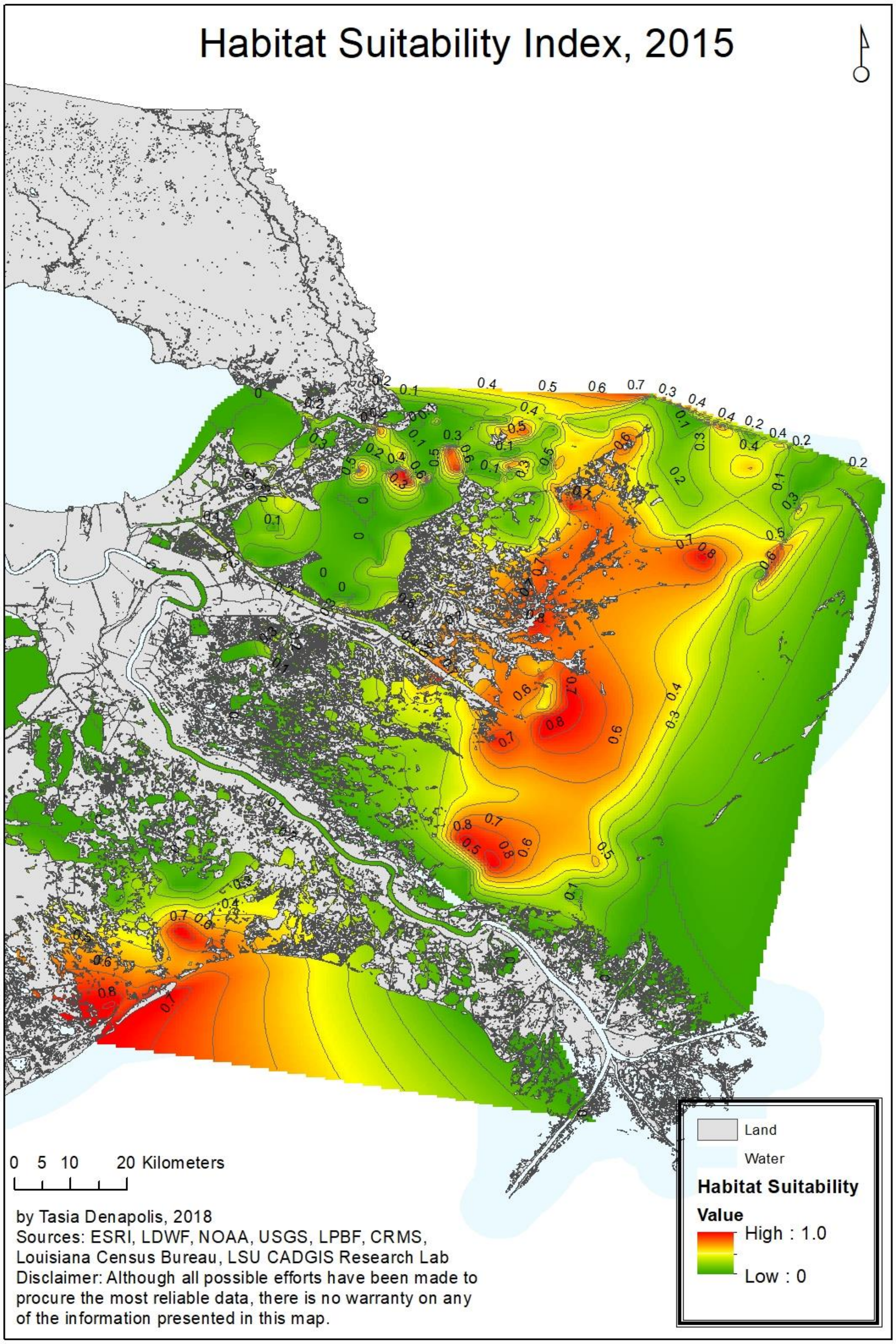

Figure 62: Habitat Suitability Index (HSI) 2015

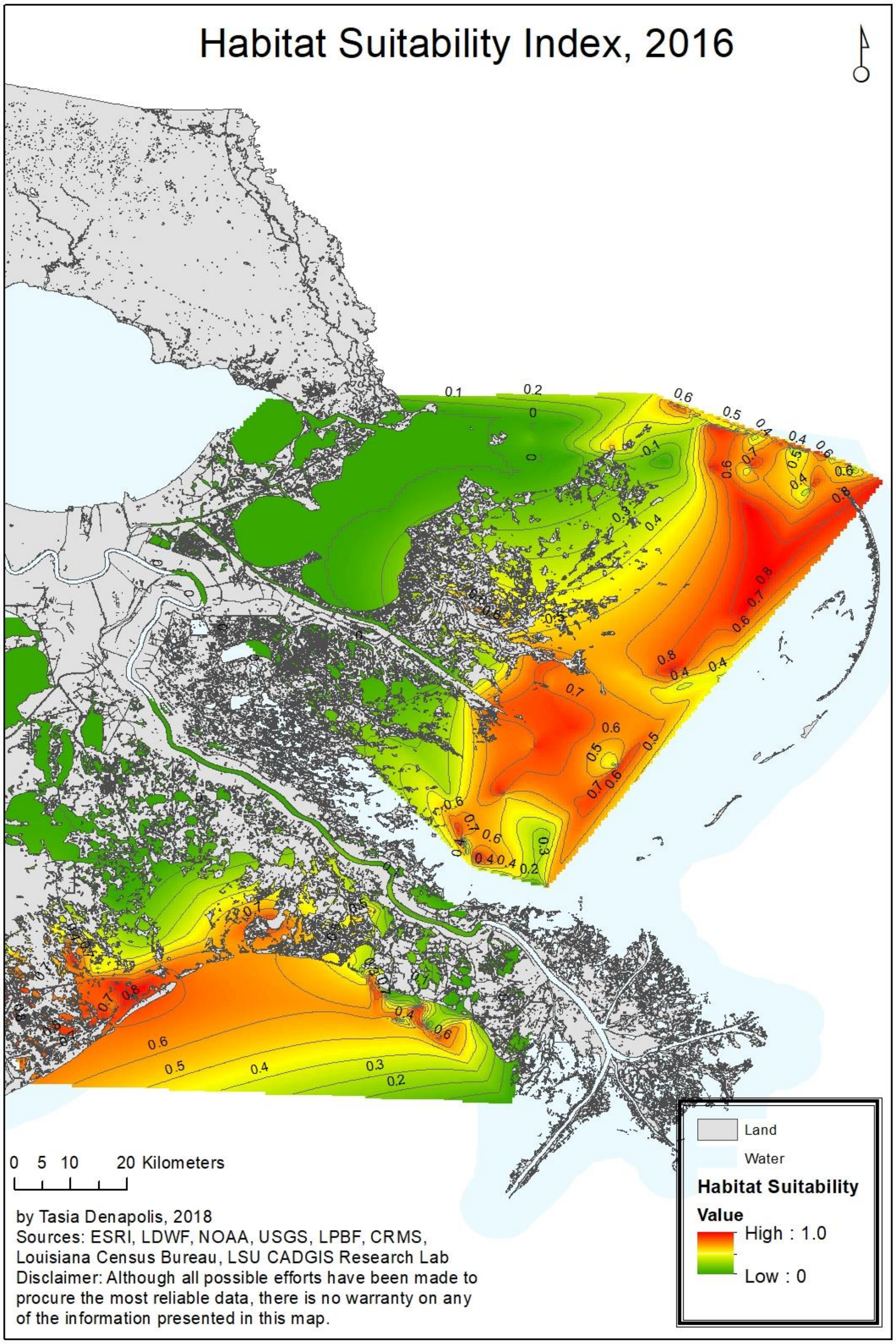

Figure 63: Habitat Suitability Index (HSI) 2016

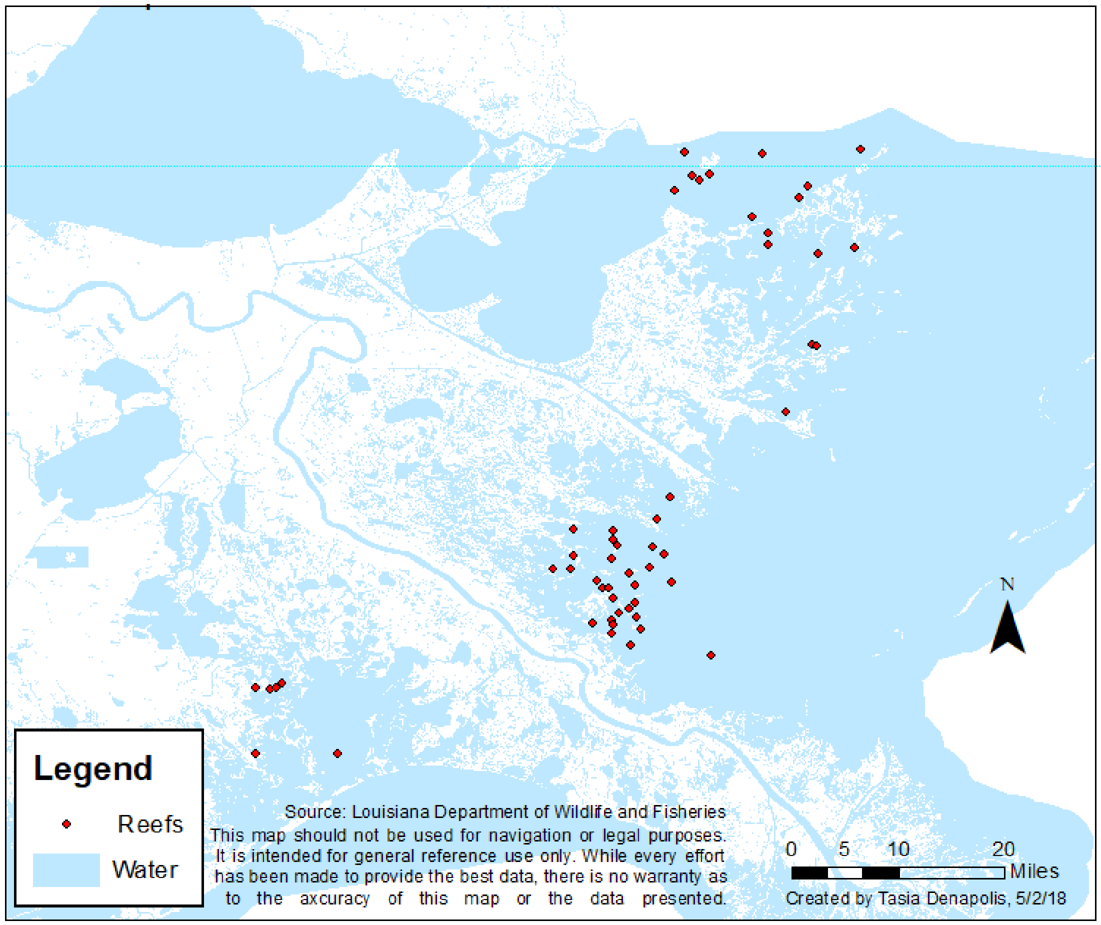

Figure 64: LDWF Reef Locations Oyster Abundance Stock Assessment Sampling

Table 9:

LDWF (2016): Stock Assessment Reef Locations.

STATION	Lat DD	Long DD	Spat Years	Seed Years	Sack Years
3-Mile	30.03917	-89.3528	2012, 2015-2016	2012-2016	2012-2016
3-Mile Pass 2013 Cultch Plant	30.0612	-89.373	2016	2016	2016
Cabbage Reef	30.15306	-89.2256	2012-2016	2013-2015	N/A
Drum Bay	29.88861	-89.2919	2012, 2015-2016	2012-2016	2012-2013, 2015-2016
Drum Bay 2013 Cultch Plant	29.88549	-89.2868	2016	2016	2016
E. Karako	30.02	-89.2339	2013, 2016	2013, 2015-2016	2013, 2016
Grand Banks	30.14778	-89.3603	2012, 2014, 2016	2013-2014, 2016	2014
Grand Pass *not included in map analysis	29.25861	-90.9333	2012, 2014, 2016	N/A	N/A
Grassy	30.15	-89.4667	2012-2013, 2015	2012-2016	2015-2016
Halfmoon	30.11944	-89.4319	2012	2012, 2014, 2016	2012, 2014, 2016
Johnson Bayou	30.0875	-89.3108	2012-2013, 2016	2012-2013, 2016	N/A
Millenium Reef	30.11278	-89.4461	2012, 2014, 2016	2012, 2014, 2016	2014-2016
Morgan Harbor	29.79583	-89.3286	2009, 2012, 2015	2012-2013, 2015	2012, 2014
Petit	30.09806	-89.4789	2013, 2015	2012-2016	2012-2016
Round Island 2011 Cultch Plant	30.1182	-89.455	2012, 2014-2016	2012, 2014-2016	2012, 2014-2016
Shell Point	30.02306	-89.3519	2012-2014, 2016	2012-2016	2012-2016
Turkey Bayou	30.10472	-89.2986	2012-2014	2012-2016	2012
W. Karako	30.01194	-89.2831	2012-2013, 2016	2012-2013, 2016	2012-2016
Battledore Reef	29.46412	-89.4288	2012, 2014	2014	N/A
Bay Crabe	29.55697	-89.5768	2013	2013	2012

Table 9:
LDWF (2016): Stock Assessment Reef Locations.

STATION	Lat DD	Long DD	Spat Years	Seed Years	Sack Years
Bay Gardene	29.58272	-89.6458	N/A	2012-2013	2012
Bay Long	29.50833	-89.5917	N/A	2014	2012, 2014
Bayou Lost	29.60088	-89.6173	N/A	2013	2012, 2014
Black Bay	29.59685	-89.5657	N/A	2013-2014	2012, 2014-2015
California Bay	29.51112	-89.5667	N/A	2013	2012-2013
California Bay 2011 Cultch Plant	29.50694	-89.5639	N/A	2014	N/A
Curfew	29.53685	-89.5335	N/A	2013	2012-2015
E. Bay Crabe	29.55665	-89.5698	N/A	N/A	2014
E. Bay Gardene	29.58167	-89.622	N/A	2014	2012-2013
E. Pelican	29.49952	-89.5265	2013	2013	N/A
E. Stone	29.58306	-89.5147	N/A	2013	2012
Elephant Pass	29.54125	-89.5641	N/A	2014	2012, 2015-2016
Horseshoe Reef	29.60261	-89.4939	2013-2014	2013	2012
Jessie	29.63502	-89.6182	2014	2012-2014	2012-2014
Lake Fortuna 2012 Cultch Plant	29.6794	-89.4849	N/A	2015-2016	2015
Lonesome	29.61355	-89.5568	2013	2013	2013-2014
Mangrove	29.479	-89.5403	N/A	N/A	2015
N. Black Bay	29.61278	-89.509	2012	N/A	N/A
N. California Bay	29.5279	-89.541	N/A	2013-2014	2012-2015
N. Lake Fortuna	29.6502	-89.5044	2012-2014	2012-2014, 2016	N/A
N. Lonesome	29.62153	-89.5643	2013	2013	2014-2015
S. Black Bay	29.56033	-89.5344	2013	2012-2013	2015
S. Lake Fortuna	29.6502	-89.5044	2012-2013	2012-2013	2014
Snake	29.63397	-89.5642	2013-2014	2013-2014	2012-2015

Table 9:

LDWF (2016): Stock Assessment Reef Locations.

STATION	Lat DD	Long DD	Spat Years	Seed Years	Sack Years
Stone	29.57612	-89.5415	N/A	2013	2012, 2015
Sunrise Point	29.49475	-89.5666	N/A	2013	N/A
Telegraph	29.516	-89.5323	N/A	2013	2012, 2014
W. Bay Crabe	29.56522	-89.5866	N/A	2013	2012-2014
W. Pelican	29.52278	-89.5564	N/A	2013-2014	2012, 2014
Wreck	29.56472	-89.4831	2013, 2016	2013, 2016	2016
Barataria Bay 2004 Cultch Plant	29.33028	-89.94	2013-2015	N/A	N/A
N. Hackberry 2004 Shell Plant	29.41722	-90.0325	2012-2016	2012-2016	2012-2014, 2016
S. Hackberry 2004 Shell Plant	29.33028	-90.0525	2012-2016	2012-2016	2012-2015
2008 Cultch Plant	29.42528	-90.0153	2012-2016	2012-2016	2012-2016
2012 Cultch Plant	29.42007	-90.052	2013, 2016	2013, 2015-2016	2013, 2015-2016
Hackberry 2014 Cultch Plant	29.42099	-90.0231	2015-2016	2016	2016
Lower Hackberry	29.38822	-90.0525	2012, 2014	2012-2014	2012-2014
Middle Hackberry	29.40169	-90.0292	2012, 2014	2012-2015	2012-2016
Upper Hackberry	29.42164	-90.0307	2012-2016	2012-2016	2012-2013, 2015-2016

“Station” refers to the common name of the general area where the data was collected. “Lat DD” and “Long DD” indicate global positioning decimal degrees of latitude and longitude respectively. ”Spat Years” indicates that spat abundance data was available for HSI calculation in the specified years. ”Seed Years” indicates that seed abundance data was available for HSI calculation in the specified years. ”Sack Years” indicates that sack abundance data was available for HSI calculation in the specified years – N/A indicates no available data.

Table 10.

USGS Streamflow information.

Year	Gage	CFS	Area	Up / Down
2011	USGS 07374525 Mississippi River at Belle Chasse, LA	19502454000	Barataria Basin and Breton Sound	Down
2011	USGS 295501090190400 Davis Pond Freshwater Diversion near Boutte, LA	75316794	Barataria Basin	Down
2011	USGS 07381235 GIWW West of Bayou Lafourche at Larose, LA	29338737.93	Barataria and Terrebonne Basins	Down
2011	USGS 07376500 Natalbany River at Baptist	895026.39	Lake Maurepas	Down
2011	USGS 07376000 Tickfaw River at Holden, LA	3284599.1	Lake Maurepas	Down
2011	USGS 07375500 Tangipahoa River at Robert, LA	11292849	Lake Pontchartrain	Down
2011	USGS 07375000 Tchefuncte River near Folsom, LA	1695150.6	Lake Pontchartrain	Down
2011	USGS 295124089542100 Caernarvon Outfall Channel at Caernarvon, LA	52591611	(Upper and into) Breton Sound	Down
2011	USGS 02492000 Bogue Chitto River near Bush, LA	23830871	Pearl River/ Rigolets	Down
2011	USGS 02489500 Pearl River near Bogalusa, LA	120782150	Rigolets	Down
2012	USGS 07374525 Mississippi River at Belle Chasse, LA	12718023310	Barataria Basin and Breton Sound	Down

Table 10.

USGS Streamflow information.

Year	Gage	CFS	Area	Up / Down
2012	USGS 295501090190400 Davis Pond Freshwater Diversion near Boutte, LA	36845314.1	Barataria Basin	Down
2012	USGS 07381235 GIWW West of Bayou Lafourche at Larose, LA	32211543.83	Barataria and Terrebonne Basins	Up
2012	USGS 07376500 Natalbany River at Baptist	3268771.24	Lake Maurepas	Up
2012	USGS 07376000 Tickfaw River at Holden, LA	5326592.6	Lake Maurepas	Up
2012	USGS 07375500 Tangipahoa River at Robert, LA	21721529	Lake Pontchartrain	Up
2012	USGS 295124089542100 Caernarvon Outfall Channel at Caernarvon, LA	38505237.13	(Upper and into) Breton Sound	Down
2012	USGS 02492000 Bogue Chitto River near Bush, LA	32439315	Pearl River/ Rigolets	Up
2012	USGS 02489500 Pearl River near Bogalusa, LA	169526530	Rigolets	Up
2013	USGS 07374525 Mississippi River at Belle Chasse, LA	17916993000	Barataria Basin and Breton Sound	Up
2013	USGS 295501090190400 Davis Pond Freshwater Diversion near Boutte, LA	71760174.1	Barataria Basin	Up
2013	USGS 07381235 GIWW West of Bayou Lafourche at Larose, LA	37341674.3	Barataria and Terrebonne Basins	Up

Table 10.

USGS Streamflow information.

Year	Gage	CFS	Area	Up / Down
2013	USGS 07376500 Natalbany River at Baptist	4105404.69	Lake Maurepas	Up
2013	USGS 07376000 Tickfaw River at Holden, LA	7735635.7	Lake Maurepas	Up
2013	USGS 07375500 Tangipahoa River at Robert, LA	22354838	Lake Pontchartrain	Up
2013	USGS 295124089542100 Caernarvon Outfall Channel at Caernarvon, LA	35031819.48	(Upper and into) Breton Sound	Down
2013	USGS 02492000 Bogue Chitto River near Bush, LA	41718235	Pearl River/ Rigolets	Up
2013	USGS 02489500 Pearl River near Bogalusa, LA	267324150	Rigolets	Up
2014	USGS 07374525 Mississippi River at Belle Chasse, LA	17224822000	Barataria Basin and Breton Sound	Down
2014	USGS 295501090190400 Davis Pond Freshwater Diversion near Boutte, LA	32211338.5	Barataria Basin	Down
2014	USGS 07381235 GIWW West of Bayou Lafourche at Larose, LA	44146095.75	Barataria and Terrebonne Basins	Up
2014	USGS 07376500 Natalbany River at Baptist	3771254.59	Lake Maurepas	Down
2014	USGS 07376000 Tickfaw River at Holden, LA	11005240.6	Lake Maurepas	Up

Table 10.

USGS Streamflow information.

Year	Gage	CFS	Area	Up / Down
2014	USGS 07375500 Tangipahoa River at Robert, LA	17302448	Lake Pontchartrain	Down
2014	USGS 295124089542100 Caernarvon Outfall Channel at Caernarvon, LA	17911305.68	(Upper and into) Breton Sound	Down
2014	USGS 02492000 Bogue Chitto River near Bush, LA	29958670	Pearl River/ Rigolets	Down
2014	USGS 02489500 Pearl River near Bogalusa, LA	170416350	Rigolets	Down
2015	USGS 07374525 Mississippi River at Belle Chasse, LA	21739573000	Barataria Basin and Breton Sound	Up
2015	USGS 295501090190400 Davis Pond Freshwater Diversion near Boutte, LA	51760462.13	Barataria Basin	Up
2015	USGS 07376500 Natalbany River at Baptist	5485228.9	Lake Maurepas	Up
2015	USGS 07376000 Tickfaw River at Holden, LA	17867620.6	Lake Maurepas	Up
2015	USGS 07375500 Tangipahoa River at Robert, LA	20358587	Lake Pontchartrain	Up
2015	USGS 07375000 Tchefuncte River near Folsom, LA	3458266.3	Lake Pontchartrain	Up *(2011)
2015	USGS 295124089542100 Caernarvon Outfall Channel at Caernarvon, LA	13910539.71	(Upper and into) Breton Sound	Down

Table 10.

USGS Streamflow information.

Year	Gage	CFS	Area	Up / Down
2015	USGS 02492000 Bogue Chitto River near Bush, LA	26312777	Pearl River/ Rigolets	Down
2015	USGS 02489500 Pearl River near Bogalusa, LA	141811000	Rigolets	Down
2016	USGS 07374525 Mississippi River at Belle Chasse, LA	21105005000	Barataria Basin and Breton Sound	Down
2016	USGS 295501090190400 Davis Pond Freshwater Diversion near Boutte, LA	32417045.22	Barataria Basin	Down
2016	USGS 07376500 Natalbany River at Baptist	9571490.9	Lake Maurepas	Up
2016	USGS 07376000 Tickfaw River at Holden, LA	23461178	Lake Maurepas	Up
2016	USGS 07375500 Tangipahoa River at Robert, LA	38007443	Lake Pontchartrain	Up
2016	USGS 07375000 Tchefuncte River near Folsom, LA	10767300.1	Lake Pontchartrain	Up
2016	USGS 295124089542100 Caernarvon Outfall Channel at Caernarvon, LA	4167202.09	(Upper and into) Breton Sound	Down
2016	USGS 02492000 Bogue Chitto River near Bush, LA	43126209	Pearl River/ Rigolets	Up
2016	USGS 02489500 Pearl River near Bogalusa, LA	188235550	Rigolets	Up

"Year" indicates the year that the data was taken. "Gage" is the title and location where data was collected. "CFS" stands for cubic feet per second of water flow. "Area" is the study location relevant to the gage. "Up / Down" indicates a raise or decline in CFS from the previous year. "*" indicates last year that data was available.

Vita

The author was raised in New Orleans, Louisiana. She obtained a Bachelor's degree in Biological Science with a concentration in chemistry, at the University of New Orleans in 2016. Inspired by her ancestor, Percy Viosca Jr., she continued into graduate school under the supervision of Dr. Tom Soniat to pursue her Master of Science in Biological Science.