QUANTIFYING ALLIGATOR GAR (*ATRACTOSTEUS SPATULA*) SPAWNING HABITAT SUITABILITY ON THE LOWER TRINITY RIVER, TEXAS

by

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
AFS	American Fisheries Society
AGTC	Alligator Gar Technical Committee
HSM	Habitat Suitability Model
LFMRC	Lepisosteid Fish Research and Management Committee
MINUR Regression	Multi-date Image Normalization Using
MLRC Consortium	Multi-Resolution Land Characteristics
NCEI	National Center for Environmental Information
NLCD	National Land Cover Dataset
PIF	Pseudo-Invariant Feature
RMSE	Root Mean Square Error
TPWD	Texas Parks and Wildlife Department
US	United States
USGS	United States Geologic Survey

1. INTRODUCTION

1.1 Background

Alligator Gar (*Atractosteus spatula*) is a long-lived predatory fish species found across the southeastern United States. Alligator Gar have few natural predators upon reaching adulthood and this, combined with their flexible diets and general hardiness, made them quite common in slow moving coastal rivers. Unfortunately, overfishing and anthropogenic environmental degradation has greatly reduced Alligator Gar populations across the U.S., even leading to threats of extirpation in several states (DiBenedetto 2009).

Pressures on Alligator Gar populations come from two main sources: exploitation and habitat degradation (Ferrara 2001; Garcia de Leon et al. 2001; Sakaris et al. 2003; Brinkman 2008; Buckmeier 2008; Buckmeier, Smith and Daugherty 2013). Alligator Gar have a long history as an undesirable fish because they are perceived to prey on valuable sport fishes. This, coupled with their somewhat intimidating appearance led to many gar being killed off with prejudice (Buckmeier 2008). More recently, Alligator Gar have been subjected to different pressures; their large sizes, up to 2.7 meters and 130 kilograms, makes them quite a catch for the burgeoning trophy angling industry. They are also prized as a food source in parts of Mexico and the U.S. (Garcia de Leon et al. 2001). These fishing practices target larger, older specimens and pose challenges to the reproductive success of the species (Ferrara 2001). Furthermore, evidence supports the idea that females, which tend to be larger (Ferrara 2001, Garcia de Leon et al. 2001, DiBenedetto 2009) and therefore more sought after by trophy anglers, are more valuable for reproduction as a result of Alligator Gar spawning behavior. Males tend to stage themselves near appropriate spawning locations until conditions become favorable. At that time, several males will accompany a female to an area for spawning (Garcia de Leon et al. 2001, Buckmeier 2008, and Layher et al. 2008). Males will also linger near spawn locations, possibly to fertilize multiple clutches of eggs during a spawning event (Garcia de Leon et al. 2001). This puts increased pressure on the females to reproduce, but the tendency of the males to linger in one location may leave them more vulnerable to exploitation (Buckmeier 2008). DiBenedetto (2009) suggests that overexploitation may be contributing to changing population dynamics such as Alligator Gar spawning at younger ages (e.g., in the Bayou DeLarge in Central Louisiana).

Habitat degradation prevents Alligator Gar populations from recovering from these exploitive practices (Ferrara 2001; Garcia de Leon et al. 2001; Sakaris et al. 2003; Brinkman 2008; Buckmeier 2008; Buckmeier, Smith and Daugherty 2013). Despite their hardiness, environmental quality is critical because individuals show fidelity to certain sites necessary for life history events like spawning and overwintering (Sakaris et al. 2003; Robertson, Zeug, and Winemiller 2008; Inebnit 2009; Buckmeier, Smith, and Daugherty 2013; and Militello 2013).

Spawning habitats are especially critical because Alligator Gar have stringent habitat needs and irregular spawning frequency. The species has a prolonged period of sexual immaturity: ten to fourteen years for females and six years for males (Ferrara 2001 and Buckmeier 2008). Reproduction is further hindered by the temporal inconsistency of primary Alligator Gar spawning habitat, which consists of lateral floodplain connectivity generated by seasonal flooding (Buckmeier 2008). Ideal spawning habitat is comprised of vegetated floodplains inundated by seasonal floods and includes shallow depths, warm water, and low flow rates (Brinkman 2008). A specific challenge associated with monitoring and managing Alligator Gar populations is that, while researchers are somewhat confident that ideal Alligator Gar spawning conditions are understood, the spatial distribution of spawning locations is not. Thus, field monitoring efforts to census gar populations are difficult.

Presently, Alligator Gar spawning habitat quantification has not occurred because the demand to study the fish has increased only recently. Many state fish and wildlife organizations began efforts to chart the decrease of Alligator Gar in earnest following the first meeting of the Lepisosteid Fish Research and Management Committee (LFRMC) in 2002 (Nicholls State University 2016). This included the American Fisheries Society (AFS) Alligator Gar Technical Committee (AGTC), which met in 2010 to discuss the decrease of Alligator Gar in the Mississippi River (Allen, Kimmel, and Constant 2014). The LFRMC itself was created in response to the increasing popularity of Alligator Gar among sporting anglers. This growing pressure on gar populations is increasing the need for an understanding of Alligator Gar distributions to aid conservation and management activities.

Despite the recent and current interest in the ecology of Alligator Gar, the research is still in its infancy. The Florida Fish and Wildlife Conservation Commission dubbed Alligator Gar as “one of the most mysterious fish in Florida” (Department of Management Services 2016). State agencies and universities studying Alligator Gar are still attempting to determine population sizes, life histories, and behaviors in various streams and bodies of water. Nearly all agree that Alligator Gar populations have declined drastically and that protecting spawning habitat is particularly important to keeping this species' populations at healthy levels.

To better understand the relationship between a species and its environment, researchers can employ habitat suitability models (HSMs). HSMs function primarily in one of two ways. The first type examines species distributions and delineates appropriate habitat conditions based on the relative abundances in which the species occurs (Yu-Pin, Wei-Chih, and Wei-Yao 2015). The second type uses expert knowledge of a species' needs and delineates areas that feature those conditions, similar to a habitat association study (Boone and Krohn 1999 and Leblond, Dussault, and St-Laurent 2014). With the completion of several exploratory studies aimed at determining Alligator Gar spawning habitat, general spawning habitat characteristics can be inferred. Using expert knowledge of the species' spawning habitat and delineating geographic areas that share those characteristics, this spatially-explicit information can be incorporated into a HSM to evaluate the distribution of Alligator Gar spawning habitat.

Habitat suitability studies have a long history as tools in biogeographic studies. Assessing habitat suitability is done in two main ways; from the animal perspective and from the habitat perspective (Leblond, Dussault, and St-Laurent 2014). Studies from the resource utilization perspective generally associate observed animal distributions, presences, or densities with the components of the landscape in order to determine a species' environmental requirements or desires. The Habitat Suitability Model (HSM) method uses expert knowledge to assess a landscape for traits or resources that a species requires for survival. These necessary traits and their resulting suitability models may vary by life history stage and require *in situ* validation before they can be applied (Leblond, Dussault, and St-Laurent 2014). Both methods inform researchers about the environmental needs of the species being studied. HSMs are valuable for conservation efforts because of the insights they provide for wildlife managers (Brooks 1997) regarding the effects of humans on the natural environment and the plants and animals living there.

1.2 Problem Statement

Our ability to validate our understanding of Alligator Gar ecology depends on the researcher's ability to find Alligator Gar populations. Unfortunately, Alligator Gar are difficult or sometimes impossible to find in many of their native ranges. Texas is a notable exception, as many Alligator Gar populations are well within healthy limits (Texas Parks and Wildlife Department; TPWD 2016). The health of the species in Texas has facilitated sufficient research into Alligator Gar habitats and life histories (Buckmeier 2008 and Buckmeier, Smith, and Daugherty 2013) to advance the scope of research in Texas. These studies, combined with environmental data collected from remote sensing platforms, provide enough information for the construction of an Alligator Gar HSM for the lower Trinity River. This research is aimed to quantify river stage specific suitable spawning habitat to facilitate continued research of the population.

1.3 Objectives

Objective 1: Generate HSM for Alligator Gar spawning habitat on the lower Trinity River, Texas

Objective 2: Examine historic trends in land cover change to determine amount of spawning habitat lost from the Lower Trinity River floodplain between 2001 and 2011.

1.4 Justification

Current research on Alligator Gar populations points to strong reductions in available spawning habitat and reduced populations throughout their historic native range. HSMs and research on Alligator Gar spawning habitat are critical tools that can be used by resource managers and wildlife conservation organizations to curb anthropogenic behavior that is detrimental to these sensitive populations and their critical habitats. This research is also important for the management of this species in light of its recent increase in popularity as a trophy fish.

2. LITERATURE REVIEW

2.1 Alligator Gar life history, ecology, and management

Alligator Gar are large, hardy fish which can survive in many environments including brackish waters (Sakaris et al. 2003, DiBenedetto 2009, Buckmeier, Smith, and Daugherty 2013). Nonetheless, the species is vulnerable. Alligator Gar best represent a periodic life-history strategy (Winemiller and Rose 1992) in that they require several years to reach sexual maturity and are only successful at recruiting during certain years. Furthermore, the species' reproductive success relies mostly on older individuals (Ferrara 2001). While effective for their natural environmental regimes, these specializations are not resilient in the context of anthropogenic landscape modification and overexploitation. Thus, Alligator Gar have been declared rare or extirpated in six of the fourteen states comprising their historic range in the United States (Buckmeier 2008). Human activity is thought to be largely responsible for the relative scarcity of Alligator Gar.

Several states have enacted catch limits to prevent overexploitation (Buckmeier, Smith, and Daugherty 2013). In areas not enforcing slot limits, these methods may still harm Alligator Gar populations because the large individuals taken are likely to be the most important for gar reproduction, namely older, more fecund females. This harm is incidental and nearly unavoidable as females are extremely difficult to identify without sacrificing the fish (Ferrara 2001, Sakaris et al. 2003, DiBenedetto 2009, Militello 2013). The tendency of large, sexually mature gar to stage in shallow waters in preparation for spawning also leaves them vulnerable to exploitation during their spawning period between late spring and late summer (Ferrara 2001; DiBenedetto 2009; Inebnit 2009;

Buckmeier, Smith, and Daugherty 2013). Unfortunately, managers and researchers in many areas do not know enough about Alligator Gar spawning habitats to study and protect Alligator Gar at their most vulnerable life stages. To enable that research, potential Alligator Gar spawning habitat sites must be identified and delineated according to suitability at a variety of conditions/river stages.

2.2 Alligator Gar habitat requirements

Suitable spawning locations are critical habitats due to their spatial and temporal irregularity in availability. Spawning habitat consists of vegetated areas inundated with warm (21-31 degrees Celsius), shallow water (0.3-0.6m). These locations are commonly comprised of grassy floodplains inundated by seasonal flooding. Such conditions are usually found adjacent to main river channels or in backwater tributaries, oxbow lakes, floodplain ponds, and flooded fields. (Ferrara 2001; Garcia de Leon et al. 2001; Sakaris et al. 2003; Brinkman 2008; Robertson, Zeug, and Winemiller 2008; DiBenedetto 2009; Inebnit 2009; Buckmeier, Smith, and Dougherty 2013). Additionally, estuaries influenced by tidal action may offer more reliable spawning conditions (Buckmeier, Smith, and Dougherty 2013), and lakes provide other possible spawning areas (Garcia de Leon et al. 2001).

On the other hand, not all inundation events make for good spawning conditions. Inebnit (2009) states that spawn success is determined by timing, duration, and frequency of lateral hydrologic connectivity and water temperature. Backflows of the Arkansas River into the Fourche LaFave River triggered Alligator Gar spawning while flooding from upstream (dam releases and watershed flow) did not. This could be a result of the

Alligator Gar's preference for slow-moving water for spawning, or a preference for warm water, as opposed to the colder, hypolimnion flow from dam releases (Layher et al. 2008). These habitats are limited in where they can occur spatially, but the fish require conditions that are temporally irregular as well. Layher et al. (2008) notes that Alligator Gar will stage near spawning habitats but will only engage in spawning behavior if the conditions are right. This means that many conditions must be present for spawning habitat to exist, even more time-sensitive conditions for spawning behavior to occur, and yet more conditions must be within tolerances for successful recruitment.

Even more challenging is that Alligator Gar larvae are vulnerable to predation and will often use their spawning habitat as a nursery (Robertson, Zeug, and Winemiller 2008). Unless sufficient flooding occurs to keep that habitat inundated with both water and food, the young Alligator Gar may not survive (Inebnit 2009). All in all, Alligator Gar spawning events are vital for maintaining a population but successful events can be quite irregular. Unfortunately, human modification of the landscape and flow regimes have made spawning events that conform to the Alligator Gar's needs even more rare. This, combined with human exploitation of gar populations, has pushed the Alligator Gar out of much of its historic range (Sakaris et al. 2003 and Buckmeier 2008).

2.3 Recent studies focused on Alligator Gar habitat suitability

In a study of Alligator Gar movement and life history, Sakaris et al. (2003) examined the Mobile-Tensaw delta in Alabama. The study area included Threemile Creek, a tributary thought to represent Alligator Gar spawning habitat. Researchers collected Alligator Gar using nets in two locations during daytime hours between March and May of 1999 and tagged the fish with sonic and radio transmitters. The fish were tracked one to three times per month for about a year and locations were marked in a GIS program. They found that larger Alligator Gar had a tendency to move more, while smaller, possibly juvenile Alligator Gar tended to exhibit site fidelity. This fidelity also made smaller fish easier to find. The researchers concluded that Alligator Gar home ranges vary significantly, with movements ranging between 1.55 km and 23.10 km between relocations and home ranges varying between 2.73 km and 12.25 km. No significant relationship was found between fish size and home range, however.

Buckmeier, Smith, and Dougherty (2013) performed a larger study on the lower Trinity River, Texas, which also evaluated Alligator Gar movement and habitat use. The 180 km of river below Livingston Dam represents a large, low gradient, sandy river surrounded by agriculture and forested lands, which frequently deposits woody debris into the river channel. The researchers divided the river into four segments and collected Alligator Gar from each segment, tagged them with ultrasonic transmitters, and released them near their capture site. The fish were then tracked using a combination of mobile and fixed telemetry devices to measure movement. They found that most Alligator Gar stayed within specific ranges and showed fidelity to spawning and overwintering sites. Their results suggest that spawning habitat consists of warm (> 18 degrees Celsius), shallow, vegetated areas and that tidally-influenced estuarine habitats may offer more reliable spawning conditions than tributaries relying on seasonal flooding.

Alligator Gar research on the lower Mississippi River (Allen, Kimmel, and Constant 2014b) sought to assess spawning habitat with remote sensing techniques. The lower Mississippi River is a large, low gradient river and St. Catherine Creek is a backwater tributary. The broad floodplain between the two is directly influenced by the Mississippi River, though several lakes and pools remain inundated at all times (Allen, Kimmel, and Constant 2014a). Using a previous analysis of movement and telemetry data similar to what was used by Buckmeier, Smith, and Dougherty (2013), they classified portions of the lower Mississippi River according to their suitability for Alligator Gar spawning habitat with respect to three variables: inundation frequency (determined by Landsat data where a pixel was classified as inundated for 90% of available imagery dates), water temperature (thermal difference from river channel), and physical structure (herbaceous cropland, herbaceous wetland, grassland, and shrub-scrub).

3. MATERIALS AND METHODS

Alligator Gar spawning habitat suitability was analyzed with surface inundation, water temperature, and land cover. These layers, representing increasing levels of suitability, were compiled using map algebra performed on remotely sensed datasets depicting the Lower Trinity River. Historic Alligator Gar spawning habitat was analyzed with reclassified land cover change products between 2001 and 2011.

3.1 Study area

The lower Trinity River basin runs through southeast Texas and is located in a humid subtropical climate that is heavily influenced by moist air from the Gulf of Mexico. Mean annual temperature is 20.2 degrees Celsius. Average annual rainfall for Liberty, Texas, is 1555.8 mm (NCIE 2015), with most precipitation falling during the spring and summer months. Periods of heavy rain in low lying areas can lead to frequent flooding, which can be exacerbated by El Nino Southern Oscillation patterns and tropical cyclone activity.

The lower Trinity River is a large, low gradient stretch of river flowing 131 m vertically over its 180 km course from Livingston Dam to Trinity Bay (Buckmeier, Smith, and Dougherty 2013). Blackwell, Murphy, and Pitman (2011) note that the lower Trinity River basin contains many backwater tributaries and low-lying floodplains downstream from the channelized reaches near Livingston Dam.

Compared to other river systems in the United States, the lower Trinity River carries a healthy population of Alligator Gar. The sandy river channel is surrounded by flat coastal prairie and marshlands. Land use and land cover in the area includes rice farming, cattle grazing, oil/gas extraction and transportation, and hardwood and pine forests (Land et al. 1998 and Buckmeier, Smith, and Dougherty 2013). Protected areas near the study area include Sam Houston National Forest, which does not connect directly to the lower Trinity River; the Big Sandy Creek Unit of Big Thicket National Preserve, which connects to the lower Trinity River through the Menard Creek Corridor Unit; and the Trinity River National Wildlife Refuge, which resides on the banks of the river near Liberty, Texas. At present, these protected areas are not expected to exert significant influence on Alligator Gar spawning habitat availability.

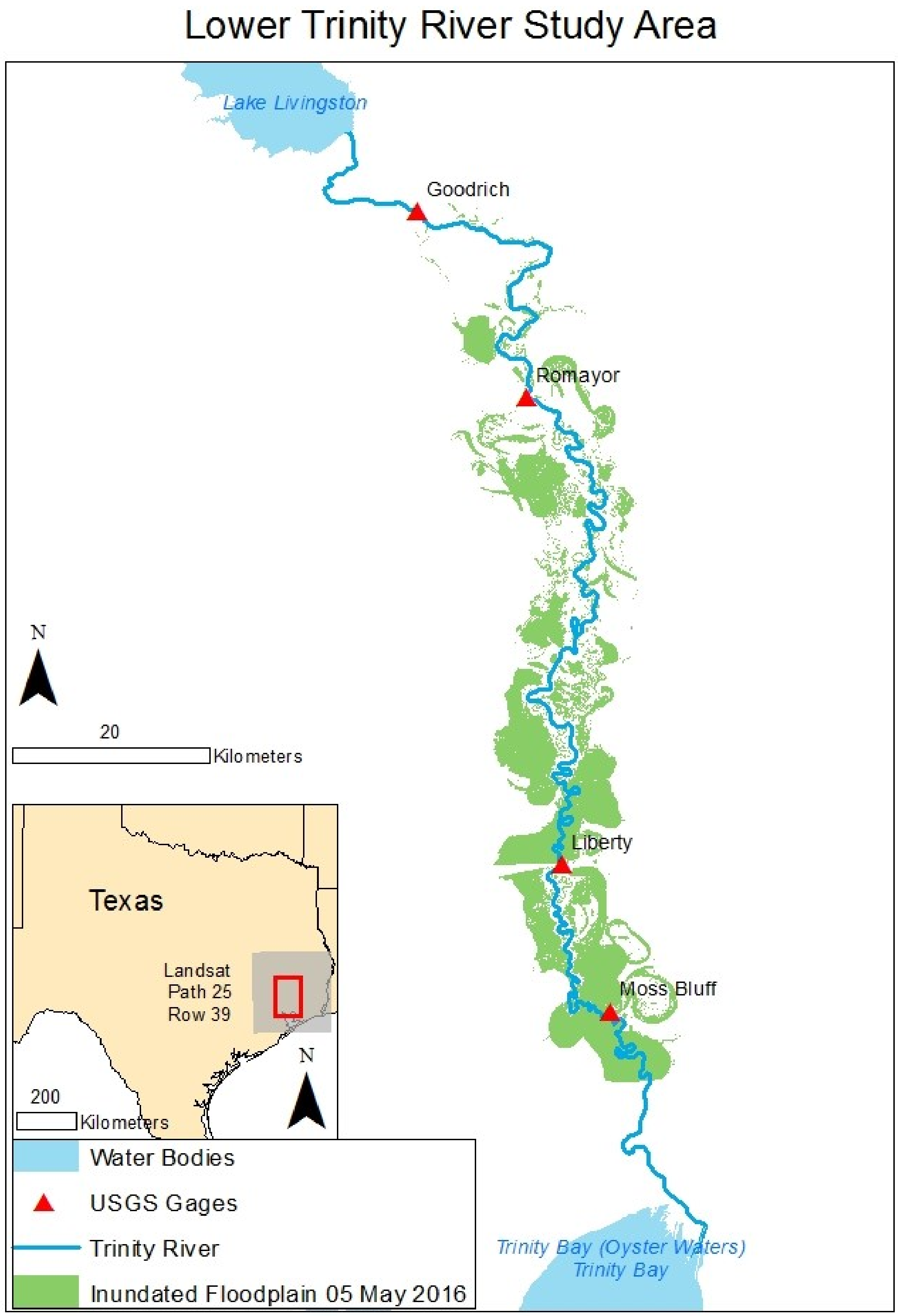

Figure 1: Map of Lower Trinity River study area.

3.2 Floodplain inundation models

Floodplain modeling started with DEM data from two sources: a lidar-derived 1 m DEM and a USGS 10 m DEM. Lidar data collected at one point per square meter in January of 2011 were processed into three dimensional shapefiles and converted into a 1 m DEM using the Topo to Raster interpolation algorithm in ArcGIS. This 1 m DEM covered about 136 km of river from Romayor, Texas, downriver to Moss Bluff, Texas. The remainder of the study area relied on a USGS 10 m DEM for modeling due to the unavailability of lidar coverage. This 10 m DEM extended from Romayor, Texas, upriver to Goodrich, Texas.

Integrating the lidar-derived DEM and the USGS 10 m DEM revealed a difference in channel elevations. Extracting a 60 m buffer along river channel centerline and comparing the overlapping extents of the DEMs resulted in an average difference of 1.2 m. The values of the USGS 10 m DEM were decreased by 1.2 m as a result to assure downslope flow within the channel. An elevation raster was generated for the entire study area by resampling the modified USGS 10 m DEM to 1m and mosaicking it with the lidar-derived 1 m DEM.

River geometry data were digitized using HEC-GeoRAS 10.1 in ArcGIS 10.1. Texas Ecological Mapping System (EMS) land cover products were reclassified to assign Manning's n values to the study area. Once these geometry data were imported into HEC-RAS 5.0.0, river geometry data were edited in the following ways: cross section filtered to 500 elevation points, Manning's n values simplified to reflect channel and laterally adjacent areas, and bank locations in cross sections were manually calibrated.

USGS rating curves for the gages at Goodrich, Liberty, and Moss Bluff were used to calibrate the discharges and corresponding stages for modeling. Inundation was then modeled for stage-specific flows corresponding to the Landsat 8 acquisition dates available during the spawning season (Table 1). Water surface elevation rasters and inundation boundaries were produced and exported for analysis in ArcGIS. Because HEC-RAS was designed to model flood inundation, low flow dates were modeled with low confidence. Higher flows, which presumably correspond to better Alligator Gar spawning habitat, are modeled with high confidence.

Using the Union tool in ArcGIS, the two shapefiles representing the length of the lower Trinity River inundated area were combined into a single shapefile containing all inundated areas for the study area for each Landsat date.

3.3 Water temperature

Water temperature was derived from Landsat 8 Thermal/Infrared data for path 25 row 39, which covers the entire study area. Landsat imagery were downloaded from United States Geologic Survey (USGS) Earth Explorer website for dates corresponding to the 2016 Alligator Gar spawning season.

Table 1: Landsat 8 OLI imagery dates, corresponding Julian dates, and discharge values according to USGS gages used to model floodplain inundation using HECRAS. Historic Landsat dates express the Landsat data used for replacing cloud-obscured pixels in the 2016 thermal data.

Date	Julian Date	Discharge at Goodrich, TX (m^3)	Discharge at Liberty, TX (m^3)	Historic Landsat Date
05 May 2016	JD 126	1566	1603	None
21 May 2016	JD 142	484	603	13 May 2013
06 June 2016	JD 158	1218	1472	02 June 1997
22 June 2016	JD 174	1130	1036	27 June 2006
08 July 2016	JD 190	396	524	04 July 1997
24 July 2016	JD 206	210	207	20 July 2000
09 August 2016	JD 222	48	90	13 August 2000
25 August 2016	JD 238	252	303	17 August 2013

Thermal data from Landsat 8 are collected at a spatial resolution of 100 m and resampled to 30 m resolution (landsat.usgs.gov 2016). Only Band 10 (10.60 – 11.19 µm) data were used for calculating temperature data as Band 11 data carry a warning from the USGS about inaccuracies related to stray light (landsat.usgs.gov 2016). Processing brightness value into degrees Celsius was performed in ERDAS Imagine with the model presented in Figure 2.

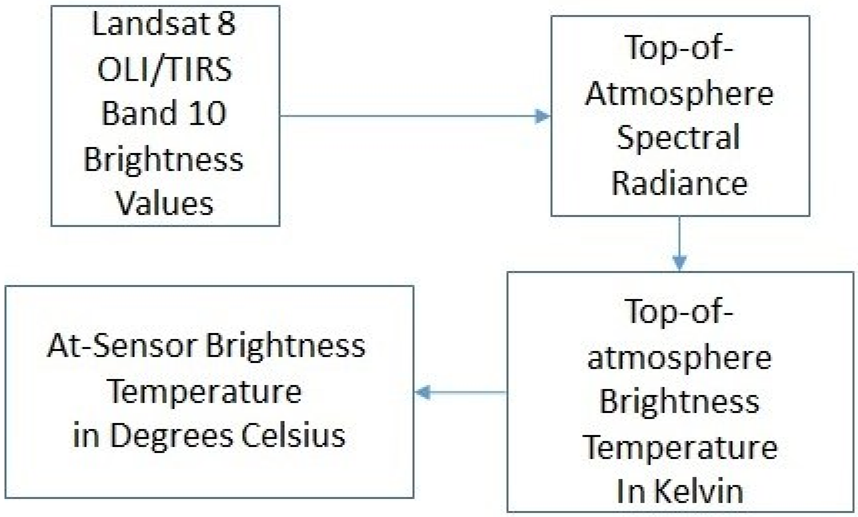

Figure 2: A visualization of the model used to convert Level 1T Data from Landsat to at-sensor brightness temperatures in degrees Celsius.

Due to cloud contamination in all 2016 spawning season images besides 05 May, historic Landsat data were normalized and substituted into cloud-masked pixels (Figure 4). Cloud-free Landsat data from previous years with Julian dates as close as possible to the 2016 Landsat data were downloaded. These data were normalized with using linear regressions, a process referred to here as the Multi-date Image Normalization Using Regression (MINUR) process. This process compensates for atmospheric differences between scenes by assessing the linear relationship between pseudo-invariant features (PIFs) between scenes and modifying the comparison raster using a linear regression model. In this case the linear relationship between the historic data and the 2016 spawning season data was assessed and that regression was applied to all pixels in the historic Landsat raster, resulting in a simulated historic Landsat scene with data values more representative of each coincident 2016 scene (Table 2).

Table 2: 2016 Spawning season Landsat data dates, their associated historic Landsat data dates, the number of PIFs used in the MINUR process, the R^2 of the resulting regression, and the root mean square errors (RMSE) of the data generated by the MINUR process compared to the 2016 data.

2016 Data	Historic Landsat Data	Number of PIFs	R^2	RMSE
2016 JD 142	2013 JD 133	6	0.98	0.61
2016 JD 158	1997 JD 153	5	0.99	0.42
2016 JD 174	2006 JD 178	5	0.99	0.29
2016 JD 190	1997 JD 185	7	0.99	0.38
2016 JD 206	2002 JD 202	4	0.99	0.02
2016 JD 222	2002 JD 215	5	0.99	0.35
2016 JD 238	2013 JD 229	6	0.99	0.16

The values from the MINUR rasters were substituted into the cloud-masked pixels of the respective 2016 scenes to generate a full thermal dataset for each 2016 spawning season date (Figure 5).

Thermal data were masked according to modeled inundation area in order to include only areas that are accessible to Alligator Gar. These masked thermal rasters were then classified per the ranges presented in Table 3.

Table 3: Temperature ranges for the classification of thermal data corresponding to suitable Alligator Gar spawning temperature Buckmeier (in press).

0-21.5 degrees Celsius	0	Unsuitable temperature-too cold
21.5-31 degrees Celsius	1	Suitable spawning temperature
31-100 degree Celsius	0	Unsuitable temperature-too warm

3.4 Land cover

In order to provide statewide land cover data at a spatial and thematic scale suitable for management and conservation efforts, TPWD created the Texas Ecological Mapping System (EMS) (TPWD EMS Final Summary 2014). This dataset represents the state of Texas at a spatial resolution of 10 m with 398 ecological classes corroborated by 12,000 *in situ* measurements in raster and vector file formats. These classes are based on remotely sensed land cover classifications and field-based measurements accounting for both biotic and abiotic factors relevant for local ecology (Texas Parks and Wildlife Department 2014). For this study, these land cover classes were used to assess the physical structure of the study area. The primary data of interest in the Texas EMS classification system attribute table are contained in the “Veg_ID” and “CommonName” fields. These fields organize the EMS description document from TPWD which contains information about the dominant tree, shrub, and herbaceous species in each assemblage. These data were used to classify the land cover classes, and by proxy, the physical structure as suitable or unsuitable for Alligator Gar spawning habitat.

The statewide raster product was clipped to depict the entire lower Trinity River and areas surrounding its floodplain to ensure that all inundation models fit within the area. Clipping the raster was necessary to expedite the manual reclassification process. A 4000 m buffer polygon delineating the FEMA 100 year floodplain was used to clip the statewide EMS raster. Using the FEMA 100 year floodplain map, which covers a larger spatial area than the inundation modeling data, ensured that all floodplain environment connected to the lower Trinity River in the study area was included in the analysis. The resulting EMS raster reduced the number of relevant EMS classes from 398 to 90, drastically reducing the time needed to manually assess the suitability of each vegetation class.

Using the information on dominant species in the TPWD EMS descriptions document, EMS Veg_ID and Common Name land cover classifications were cross referenced with existing studies on Alligator Gar spawning habitat. Classes dominantly covered by cordgrass or cypress swamp (DiBenedetto 2009), spike rush (Inebnit 2006), woody debris (Inebnit 2009 and Militello 2013), willow species (Layher et al. 2008), as well as vegetation similar to these plant species were classified as suitable Alligator Gar spawning habitat (Table 4).

Table 4: EMS reclassification for Alligator Gar spawning suitability.

Common_Name	Veg_ID	Binary Suitability
Blackland Prairie: Disturbance or Tame Grassland	207	1
Post Oak Savanna: Live Oak Motte and Woodland	602	1
Post Oak Savanna: Post Oak - Redcedar Motte and Woodland	603	0
Post Oak Savanna: Post Oak Motte and Woodland	604	0
Gulf Coast: Salty Prairie Shrubland	2206	1
Gulf Coast: Salty Prairie	2207	1
Pineywoods: Herbaceous Seepage Bog	2307	1
Pineywoods: Pine Forest or Plantation	3001	0
Pineywoods: Pine - Hardwood Forest or Plantation	3003	0
Pineywoods: Upland Hardwood Forest	3004	0
Pineywoods: Dry Pine Forest or Plantation	3011	0
Pineywoods: Dry Pine - Hardwood Forest or Plantation	3013	0
Pineywoods: Dry Upland Hardwood Forest	3014	0
Pineywoods: Sandhill Pine Woodland	3201	0
Pineywoods: Sandhill Oak - Pine Woodland	3203	0
Pineywoods: Sandhill Oak Woodland	3204	0
Pineywoods: Sandhill Grassland or Shrubland	3207	1
Pineywoods: Northern Mesic Pine - Hardwood Forest	3303	0
Pineywoods: Southern Mesic Pine - Hardwood Forest	3403	1
Pineywoods: Southern Mesic Hardwood Forest	3404	1

Table 4 Continued: EMS reclassification for Alligator Gar spawning suitability.

Pineywoods: Herbaceous Flatwoods Pond	3507	1
Pineywoods: Seepage Swamp and Baygall	3604	0
Pineywoods: Wet Hardwood Flatwoods	3704	0
Pineywoods: Longleaf or Loblolly Pine Flatwoods or Plantation	4001	0
Pineywoods: Longleaf or Loblolly Pine - Hardwood Flatwoods or Plantation	4003	0
Pineywoods: Hardwood Flatwoods	4004	0
Pineywoods: Southern Calcareous Mixedgrass Prairie	4407	1
Pineywoods: Small Stream and Riparian Temporarily Flooded Mixed Forest	4803	0
Pineywoods: Small Stream and Riparian Temporarily Flooded Hardwood Forest	4804	0
Pineywoods: Small Stream and Riparian Deciduous Successional Shrubland	4806	1
Pineywoods: Small Stream and Riparian Herbaceous Wetland	4807	1
Pineywoods: Small Stream and Riparian Seasonally Flooded Hardwood Forest	4814	0
Pineywoods: Small Stream and Riparian Wet Prairie	4817	1
Pineywoods: Small Stream and Riparian Baldcypress Swamp	4824	0
Pineywoods: Bottomland Temporarily Flooded Live Oak Forest	4902	0
Pineywoods: Bottomland Temporarily Flooded Mixed Pine - Hardwood Forest	4903	0

Table 4 Continued: EMS reclassification for Alligator Gar spawning suitability.

Pineywoods: Bottomland Temporarily Flooded Hardwood Forest	4904	0
Pineywoods: Bottomland Deciduous Successional Shrubland	4906	0
Pineywoods: Bottomland Herbaceous Wetland	4907	1
Pineywoods: Bottomland Seasonally Flooded Hardwood Forest	4914	0
Pineywoods: Bottomland Wet Prairie	4917	1
Pineywoods: Bottomland Baldcypress Swamp	4924	0
Gulf Coast: Near-Coast Baldcypress Swamp	5004	0
Gulf Coast: Coastal Prairie	5207	1
Gulf Coast: Coastal Prairie Pondshore	5307	1
Chenier Plain: Live Oak Fringe Forest	5502	0
Chenier Plain: Mixed Live Oak - Deciduous Hardwood Fringe Forest	5503	0
Chenier Plain: Hardwood Fringe Forest	5504	0
Coastal: Tidal Flat	5600	0
Coastal: Sea Ox-eye Daisy Flats	5605	1
Coastal: Salt and Brackish Low Tidal Marsh	5607	1
Coastal: Salt and Brackish High Tidal Shrub Wetland	5616	1
Coastal: Salt and Brackish High Tidal Marsh	5617	1
Chenier Plain: Salt and Brackish Low Tidal Shrub Wetland	5706	1
Chenier Plain: Salt and Brackish Low Tidal Marsh	5707	1
Chenier Plain: Salt and Brackish High Tidal Shrub Wetland	5716	1
Chenier Plain: Salt and Brackish High Tidal Marsh	5717	1
Chenier Plain: Fresh and Intermediate Tidal Shrub Wetland	5806	1

Table 4 Continued: EMS reclassification for Alligator Gar spawning suitability.

Chenier Plain: Fresh and Intermediate Tidal Marsh	5807	1
Coastal: Fresh and Intermediate Tidal Marsh	5907	0
Upper Gulf Coast: Beach	6000	0
Central and Lower Coastal: Beach	6100	0
Coastal and Sandsheet: Deep Sand Shrubland	6306	1
Coastal and Sandsheet: Deep Sand Grassland	6307	1
Coastal and Sandsheet: Deep Sand Live Oak Forest and Woodland	6402	1
Barren	9000	0
Mud Flat	9002	0
Swamp	9004	0
Marsh	9007	1
Native Invasive: Juniper Woodland	9101	0
Native Invasive: Deciduous Woodland	9104	0
Native Invasive: Juniper Shrubland	9105	0
Native Invasive: Mesquite Shrubland	9106	0
Native Invasive: Common Reed	9107	1
Native Invasive: Baccharis Shrubland	9116	1
Native Invasive: Huisache Woodland or Shrubland	9124	0
Native Invasive: Deciduous Shrubland	9126	1
Pineywoods: Disturbance or Tame Grassland	9197	1
Non-native Invasive: Saltcedar Shrubland	9204	0
Non-native Invasive: Rose Shrubland	9205	1

Table 4 Continued: EMS reclassification for Alligator Gar spawning suitability.

Non-Native Invasive: Chinese Tallow Fores	9214	1
Pine Plantation >3 meters tall	9301	0
Pine Plantation 1 to 3 meters tall	9305	0
Row Crops	9307	1
Grass Farm	9317	0
Urban High Intensity	9410	0
Urban Low Intensity	9411	0
Invasive: Evergreen Shrubland	9505	0
Open Water	9600	0

Because inundation is a necessary component of the HSM, EMS classes with light shrub cover and heavy herbaceous cover were listed as suitable habitat even if they are not described as floodplain environments. Allen, Kimmel, and Constant (2014b), implementing guidance from the AGTC, describes open canopy as being an important feature for habitat, so EMS classes with strictly closed canopy cover were marked as unsuitable spawning habitat, even if they contained suitable vegetation species. EMS classes described as containing some open canopy, even if they were predominantly canopied, were classified as suitable in order to include those open areas. Due to the large amounts of forest in the study area, this determination is expected to reduce the amount of suitable habitat significantly. Pixels containing suitable habitat were classified as “10” and unsuitable habitat pixels were classified as “0.” This binary method will enable users to determine which characteristic (i.e., temperature or vegetation cover) is unsuitable for a given pixel in the HSM.

3.5 Habitat suitability modeling

Habitat suitability modeling was accomplished by combining the EMS, modeled inundation, and thermal data to evaluate the Lower Trinity River study area for Alligator Gar spawning suitability according to land cover, inundation, and temperature, respectively. Stage-specific inundated area shapefiles for each date were used as masks to extract the Landsat thermal data for the same date. The resulting raster files represent inundated areas with cloud-free thermal data classified to represent suitable and unsuitable spawning habitat. The Map Algebra function in ArcGIS was used to add the land cover raster to the combined inundation/thermal raster for each Landsat date (Figure 3). Note that non-inundated pixels were eliminated from the habitat suitability model during the inundation masking process.

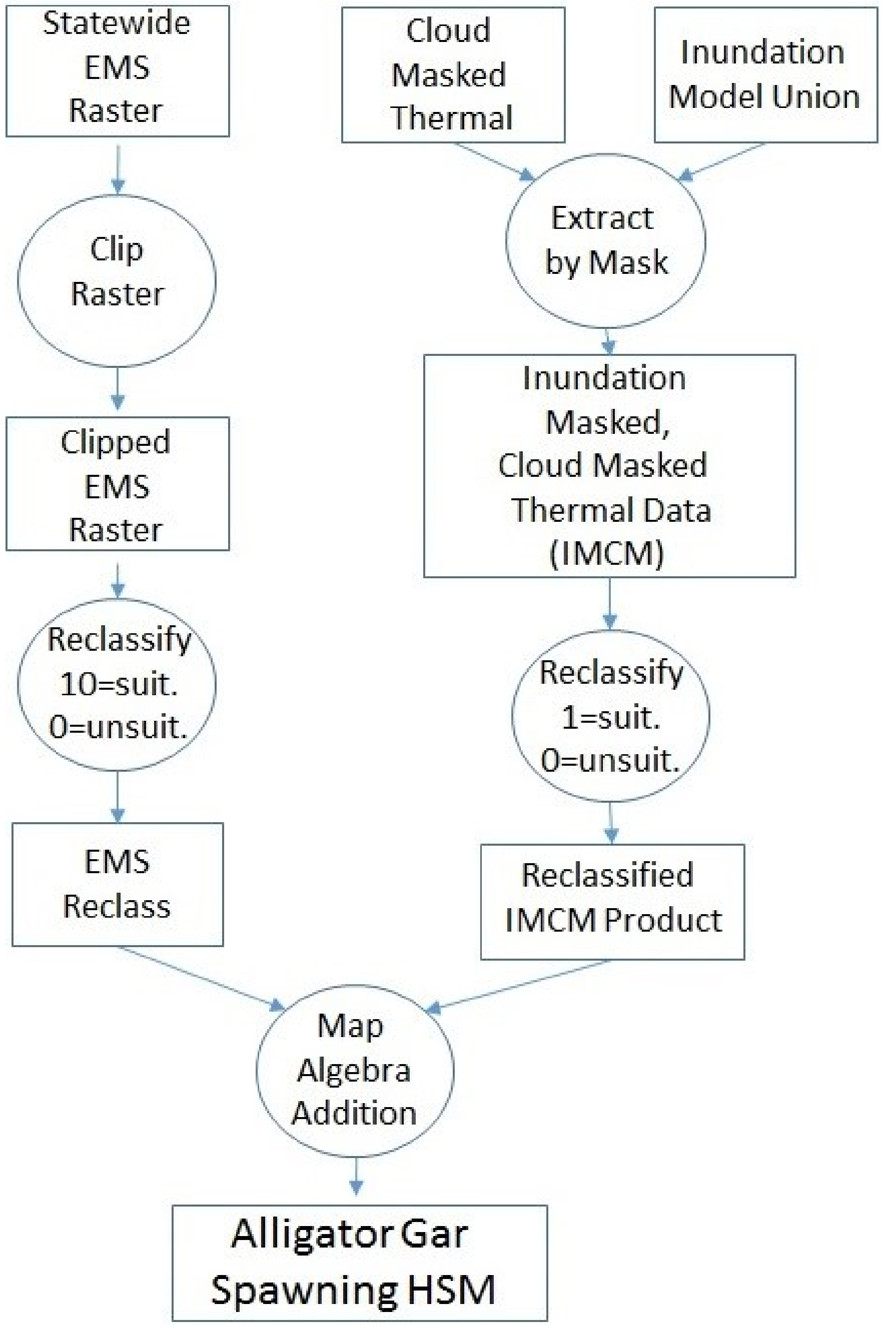

Figure 3: Graphical depiction of HSM workflow. "EMS" stands for Ecological Mapping System and denotes land cover. "IMCM" stands for Inundation-Masked Cloud-Masked product combining thermal and inundation suitability layers. Note that non-inundated

areas are not given a score as they are excluded from the suitable area analysis by the masking process.

The result is a habitat suitability model with the following categories for each inundated cloud-free pixel:

Table 5: Pixel classifications for Alligator Gar spawning habitat suitability model.

0	Unsuitable temperature and physical structure
1	Unsuitable physical structure
10	Unsuitable temperature
11	Suitable physical structure and temperature

One HSM raster was created for each Landsat date, corresponding to different river stages. These rasters were combined to determine where suitable Alligator Gar spawning habitat exists throughout the spawning season. Pixels in this layer were classified according to the frequency of Landsat dates that contain suitable habitat during a given spawning season.

3.6 Historic land cover change

Historical analysis of Alligator Gar habitat suitability with the National Land Cover Dataset (NLCD) offers insight into the state of suitable spawning habitat from 2001 to 2011 and can inform managers and policymakers for future decisions regarding the lower Trinity River floodplain.

The National Land Cover Dataset depicts land cover/land use across the contiguous United States and is generated by the Multi-Resolution Land Characteristics Consortium (MRLC). NLCDs were published for 1992, 2001, 2006, and 2011, though the 1992 dataset was excluded from this study because it cannot be compared with the subsequent datasets (MRLC 2016). The NLCDs were clipped to Landsat path 25 row 39, which corresponds to the Lower Trinity River, and were used to map historic suitable Alligator Gar spawning habitat in the Lower Trinity River. NLCD gridcodes were recoded into values between 1 and 4, with 1 representing completely unsuitable habitat and 4 representing ideal spawning habitat, by comparing published literature with land cover types featured in the NLCD. Table 6 shows the recode results for NLCD classes. In order to facilitate analysis using Map Algebra, these recode values were multiplied by 10 and 100 for the 2006 and 2001 NLCDs, respectively. All three NLCDs were added together using the Map Algebra function in ArcGIS 10.1, resulting in a three digit integer describing the habitat status of that pixel during all three years. For example, a pixel with a value of 421 changed from ideal suitability (4) in 2001 to low suitability (2) in 2006, and finally to unsuitability (1) in 2011.

Table 6: Recode values for NLCDs from 2001, 2006, and 2011.

NLCD Gridcode	NLCD Class	2001 Suitability Recode	2006 Suitability Recode	2011 Suitability Recode
11	Open Water	200	20	2
12	Perennial Ice/Snow	100	10	1
21	Developed Open Space	200	20	2

Table 6 Continued: Recode values for NLCDs from 2001, 2006, and 2011.

22	Developed Low Intensity	100	10	1
23	Developed Medium Intensity	100	10	1
24	Developed High Intensity	100	10	1
31	Barren Land	200	20	2
41	Deciduous Forest	200	20	2
42	Evergreen Forest	200	20	2
43	Mixed Forest	200	20	2
52	Shrub Scrub	300	30	3
71	Grassland Herbaceous	400	40	4
81	Pasture Hay	400	40	4
82	Cultivated Crops	400	40	4
90	Woody Wetlands	300	30	3
95	Emergent Herbaceous Wetlands	400	40	4

4. RESULTS

4.1 Thermal suitability

Heavy cloud contamination affected all Landsat scenes besides 05 May. MINUR substitution helped to mitigate the effects of clouds. The same area is shown in Figure 4, which depicts the pure Band 10 Landsat data, and Figure 5, which depicts the results of the MINUR substitution process which were used in the suitability analysis. With the exceptions of 21 May, 06 June, and 25 August, the study area is within a suitable temperature range (21.5 degrees C and 31 degrees C). Thermal suitability of inundated portions of the Lower Trinity River on 05 May 2016 is presented in Figure 6 as an example of the thermal suitability product. All thermal suitability rasters are available in the appendix.

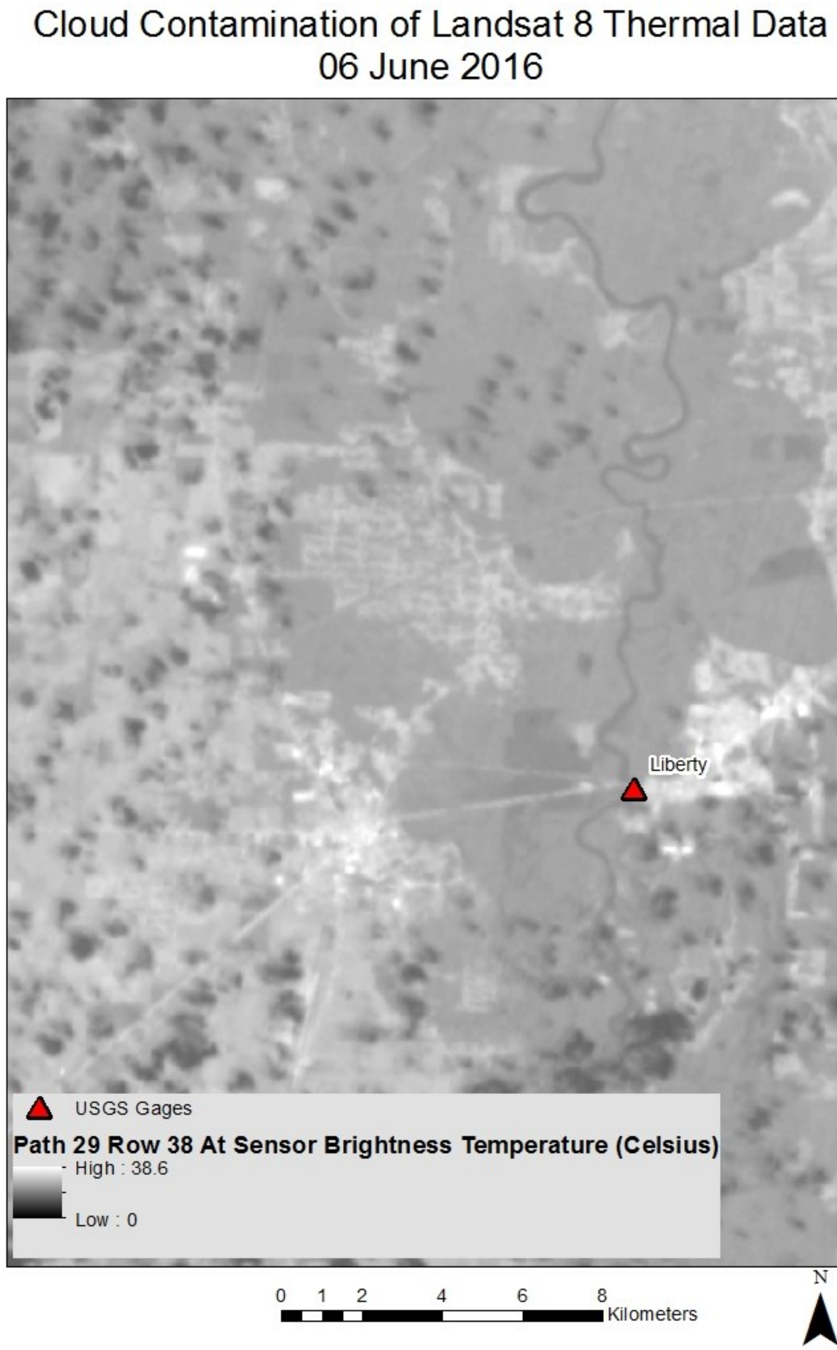

Figure 4: Cloud contamination of the thermal raster for 06 June, 2016.

Figure 5: The interim thermal data product before being clipped. The red circles highlight patches of different land surfaces temperatures which represent artifacts of the MINUR process.

Figure 6: Thermal suitability of the Lower Trinity River on 05 May 2016.

4.2 Land cover

The suitability of physical structure is depicted in Figure 7. EMS is a single dataset, so the physical structure classifications do not change throughout the spawning season. The majority of the floodplain is covered in dense forests, which are unsuitable for gar spawning, but most grassy areas near the river channel provide suitable habitat. There are also many examples of human development breaking up patches of suitable habitat, as seen west of the gaging station at Liberty, Texas.

Figure 7: Alligator Gar spawning land cover suitability according to reclassified EMS data. Inundation data and USGS gaging stations are present as references.

4.3 Habitat suitability modeling

Habitat Suitability Model results for all eight 2016 dates are presented below. The channelization just downstream of Livingston Dam is evident in the models, but suitable habitat exists sporadically throughout the study area.

Table 7: HSM summary table for 2016 inundation dates.

Inundation Date	Inundated Pixels	Percent Suitable	Percent Out of Temperature Range	Percent Poor Physical Structure	Percent Inundated Only
05 May	390242	7.14	0.11	90.66	2.08
21 May	180257	5.19	1.10	41.09	52.62
06 June	345402	3.11	3.88	23.20	69.81
22 June	318237	6.76	0.05	92.25	0.94
08 July	156646	6.39	0.00	93.43	0.17
24 July	85082	5.41	0.09	92.73	1.77
09 August	60195	4.97	0.01	94.89	0.13
25 August	97947	3.80	1.78	34.71	59.72

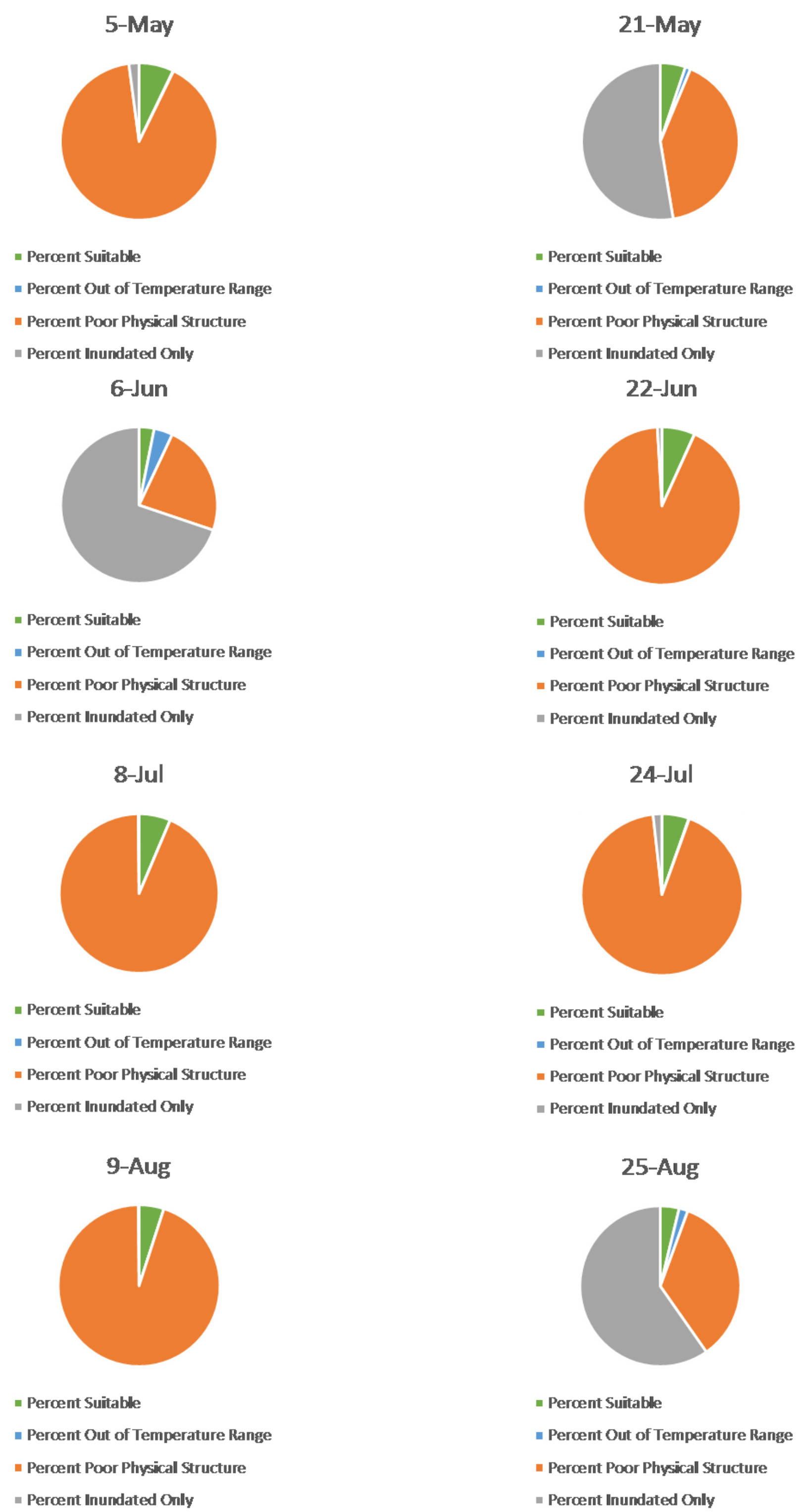

Figure 8: Pie charts summarizing HSM results for 2016 study dates.

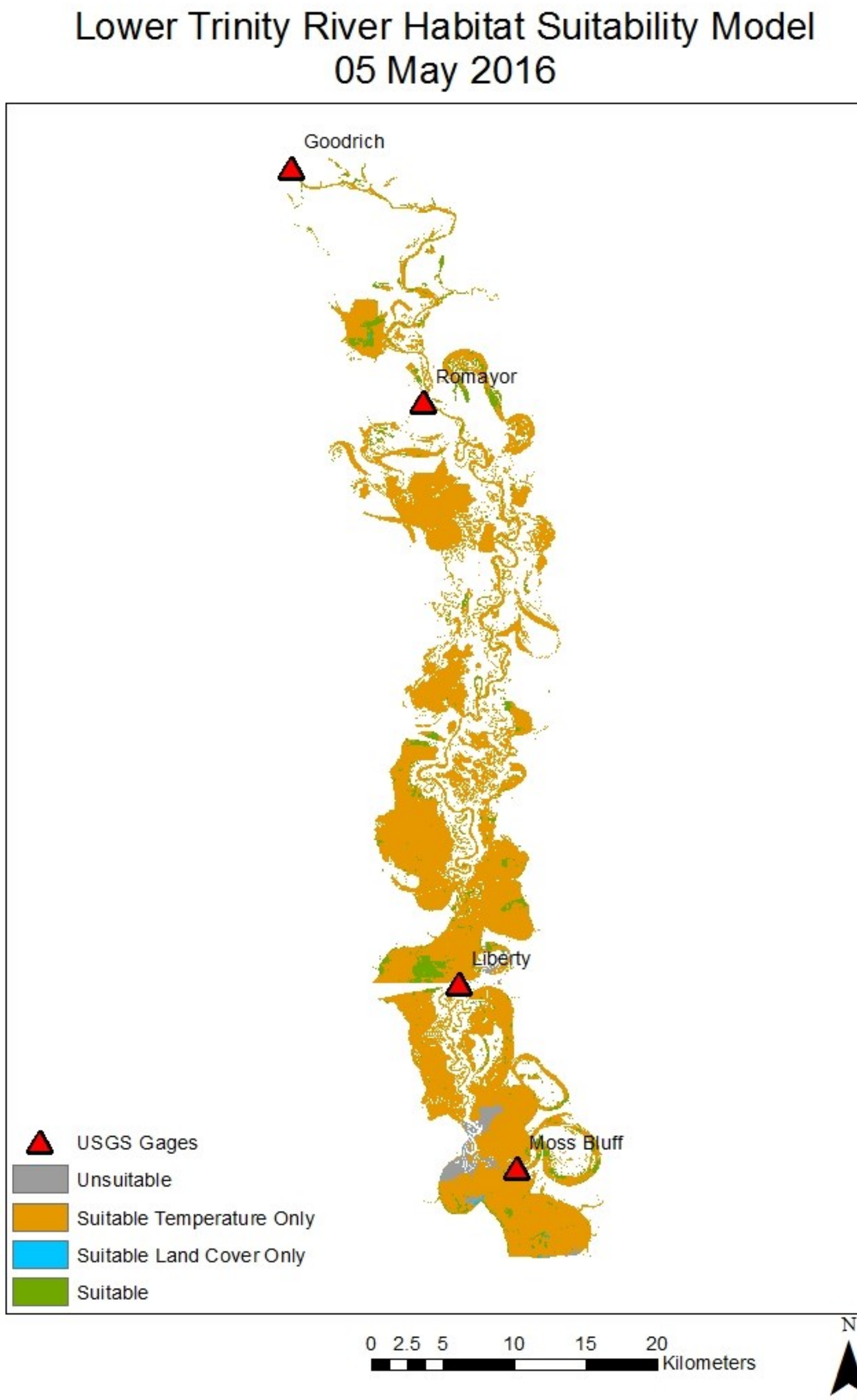

Figure 9: HSM for 05 May 2016 with USGS gaging stations at Goodrich, Romayor, Liberty, and Moss Bluff provided as reference points.

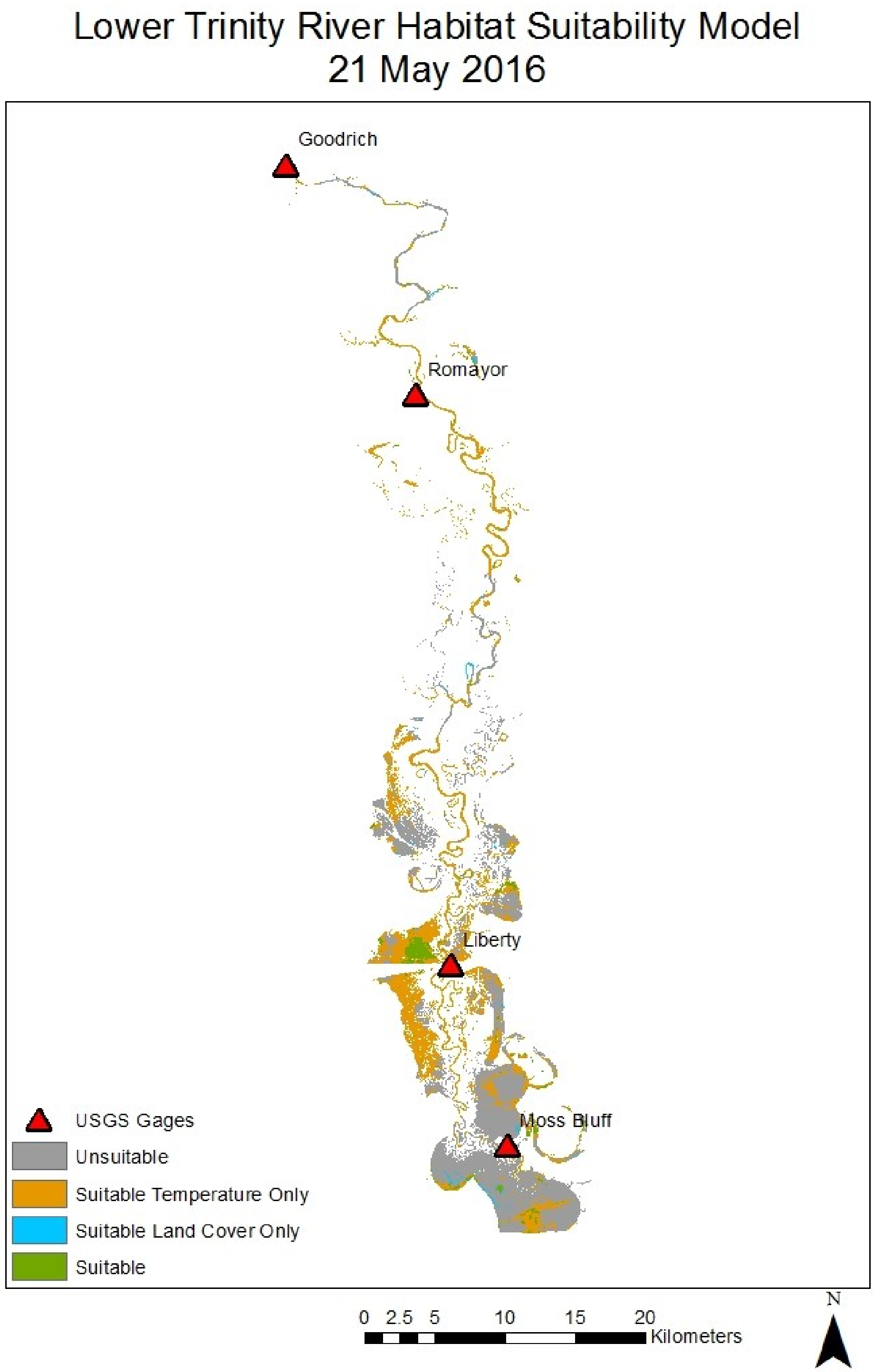

Figure 10: HSM for 21 May 2016 with USGS gaging stations at Goodrich, Romayor, Liberty, and Moss Bluff provided as reference points.

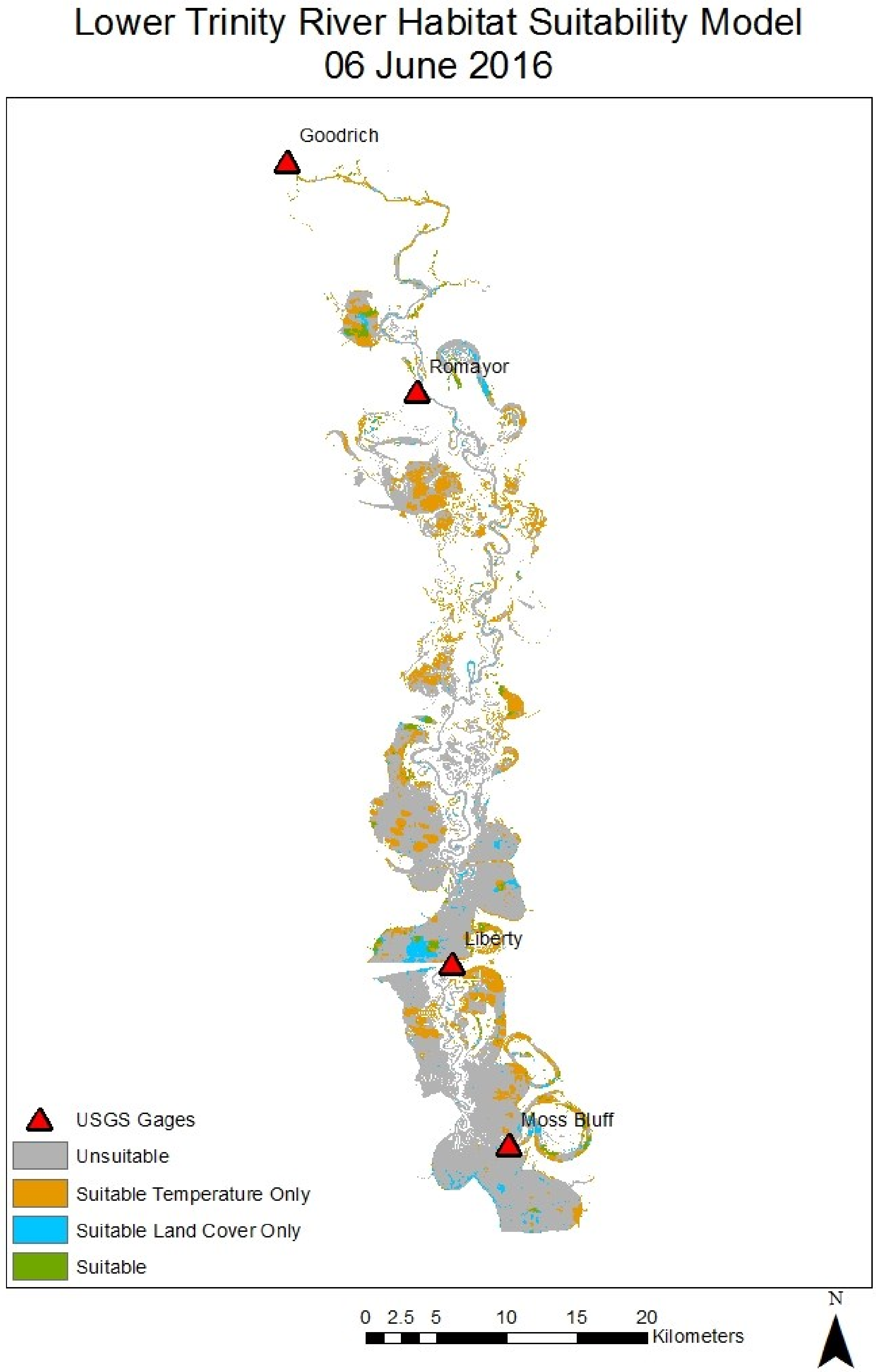

Figure 11: HSM for 06 June 2016 with USGS gaging stations at Goodrich, Romayor, Liberty, and Moss Bluff provided as reference points.

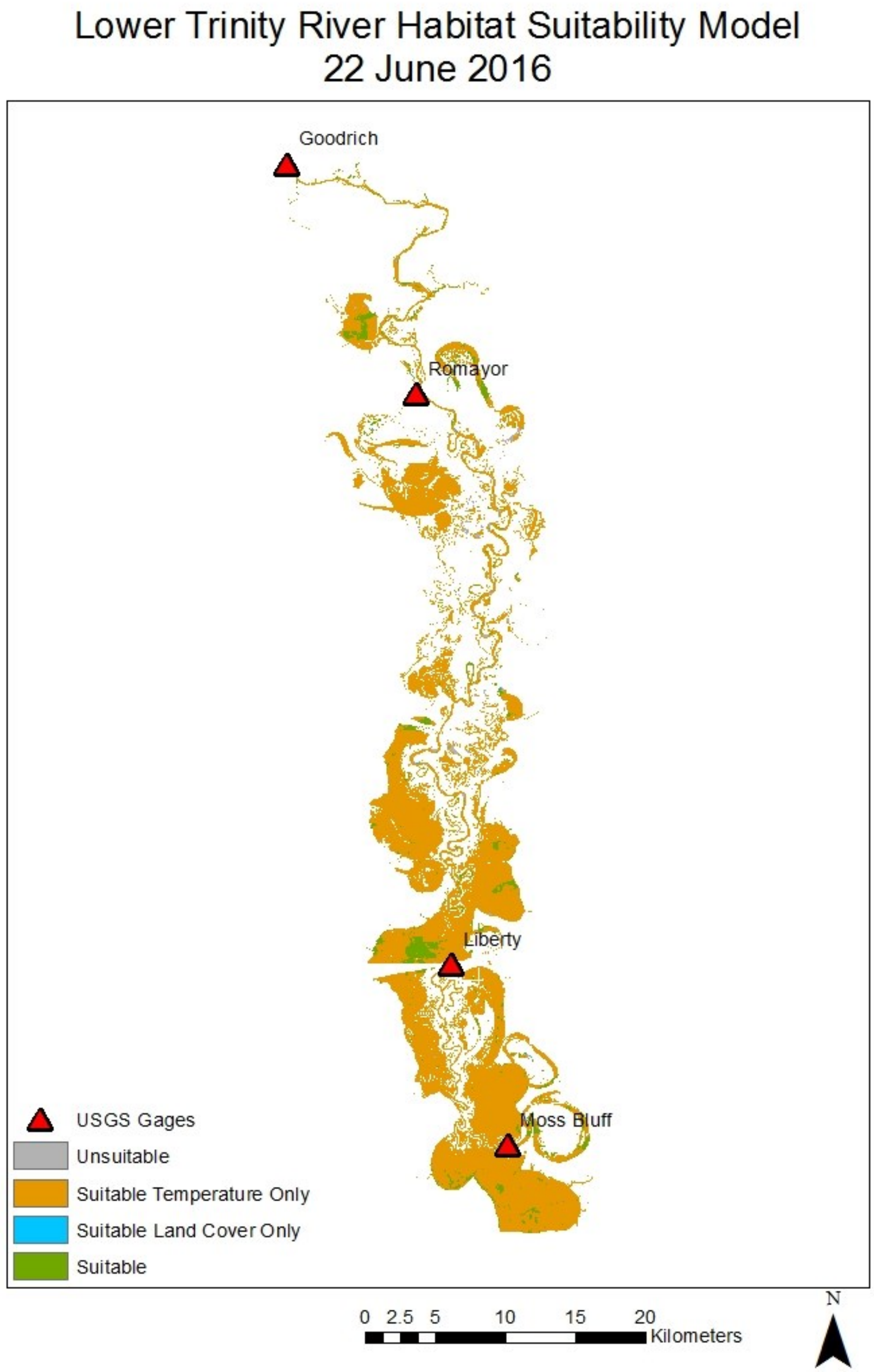

Figure 12: HSM for 22 June 2016 with USGS gaging stations at Goodrich, Romayor, Liberty, and Moss Bluff provided as reference points.

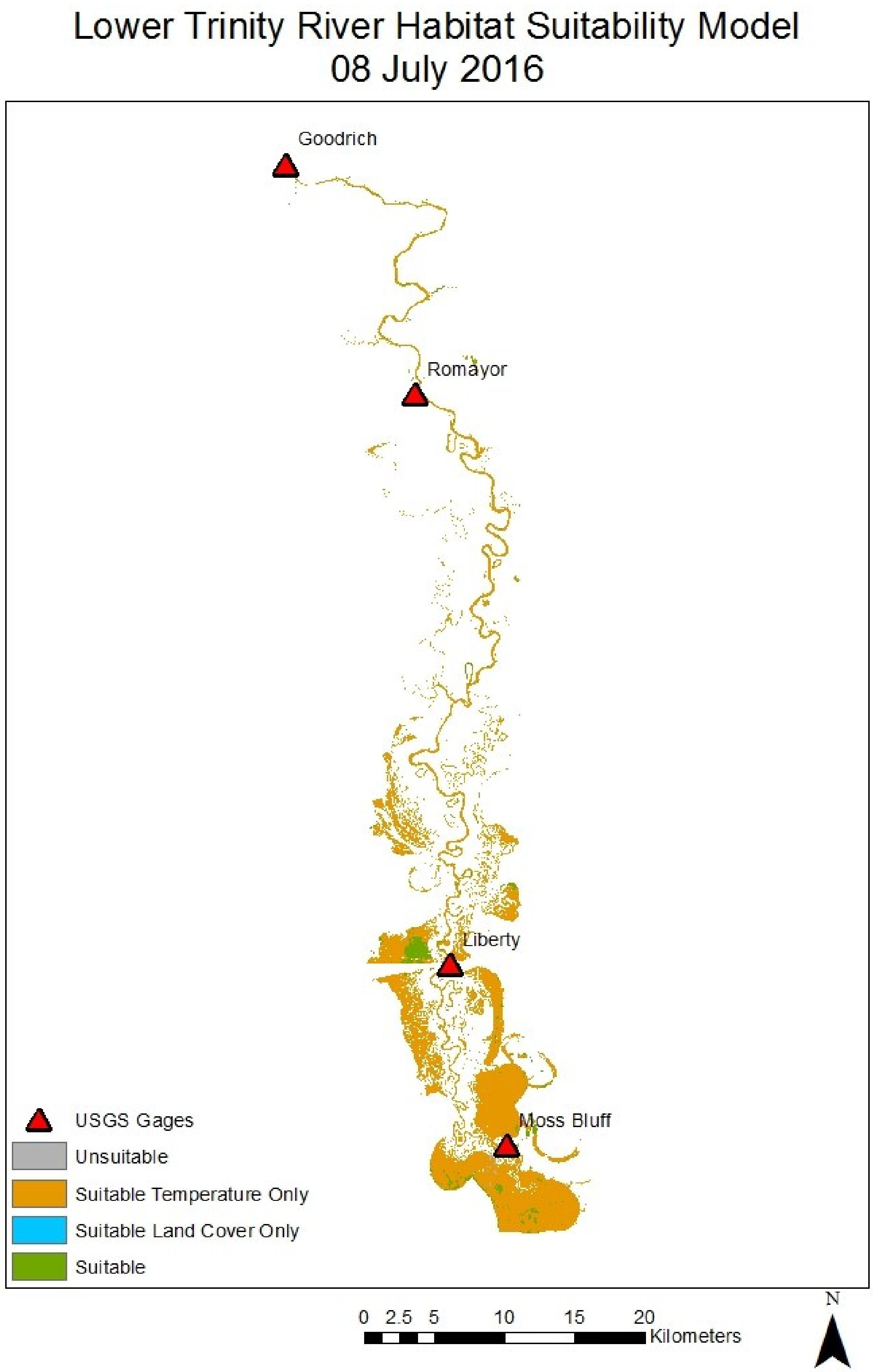

Figure 13: HSM for 08 July 2016 with USGS gaging stations at Goodrich, Romayor, Liberty, and Moss Bluff provided as reference points.

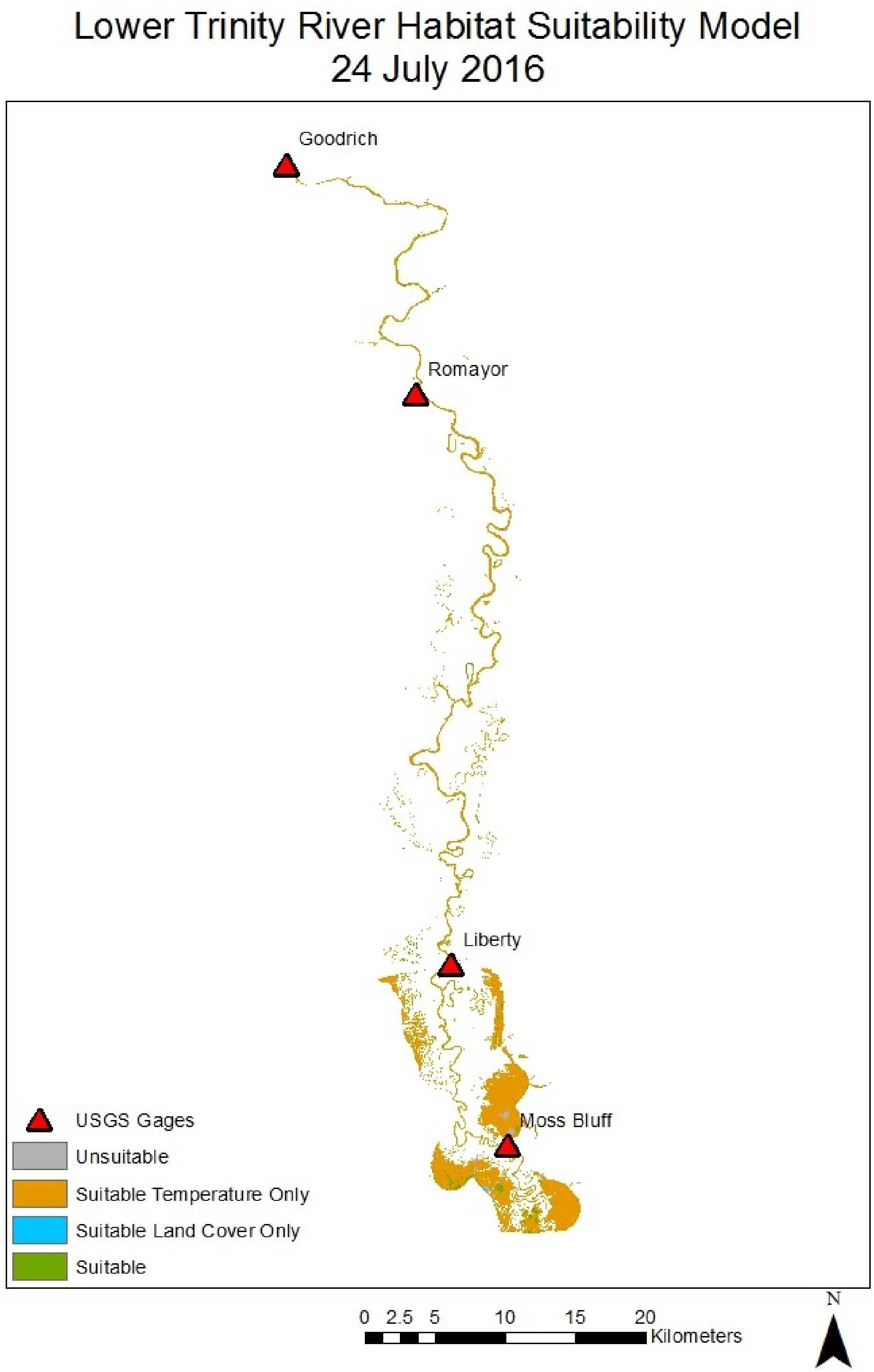

Figure 14: HSM for 24 July 2016 with USGS gaging stations at Goodrich, Romayor, Liberty, and Moss Bluff provided as reference points.

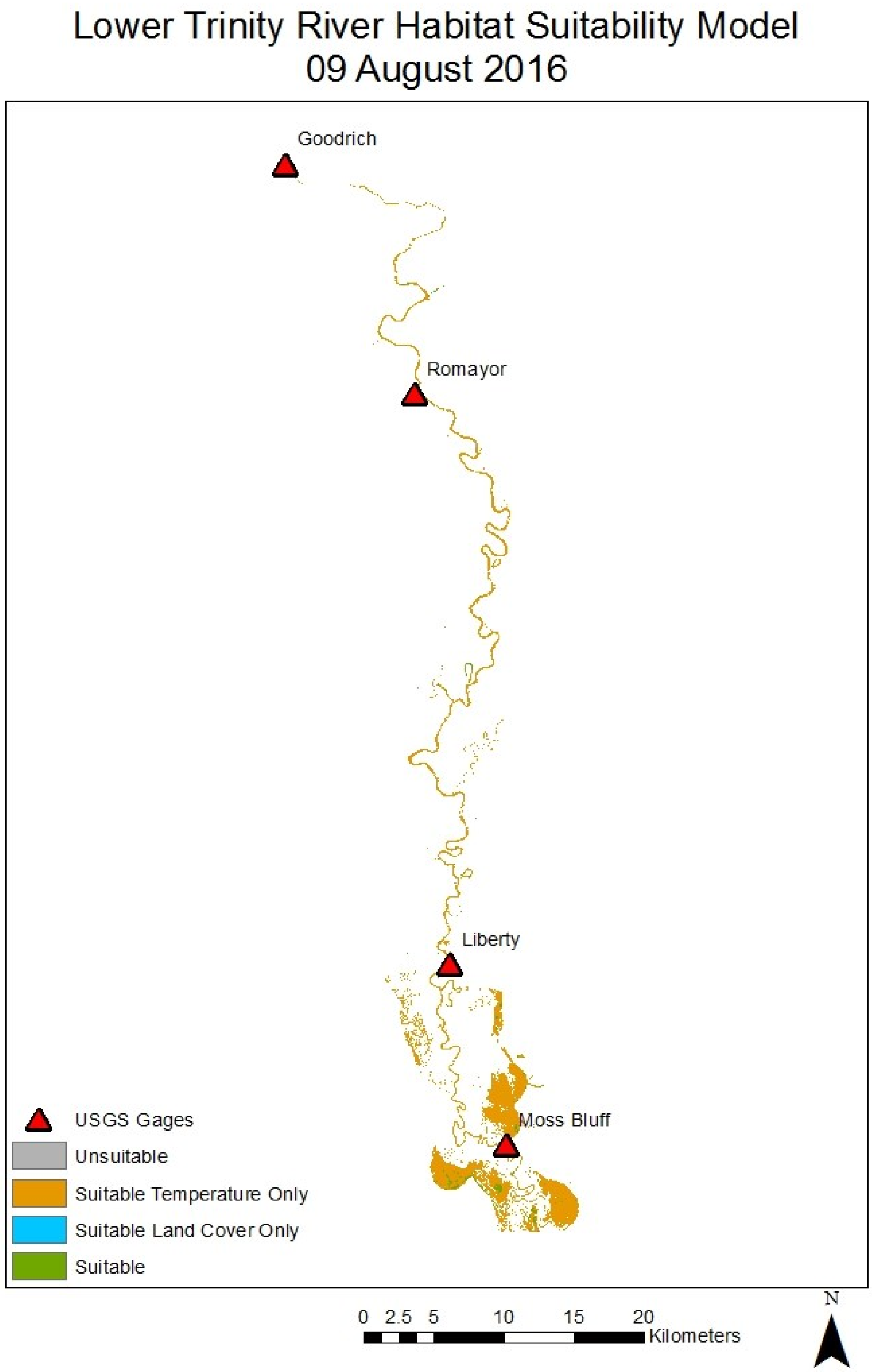

Figure 15: HSM for 09 August 2016 with USGS gaging stations at Goodrich, Romayor, Liberty, and Moss Bluff provided as reference points.

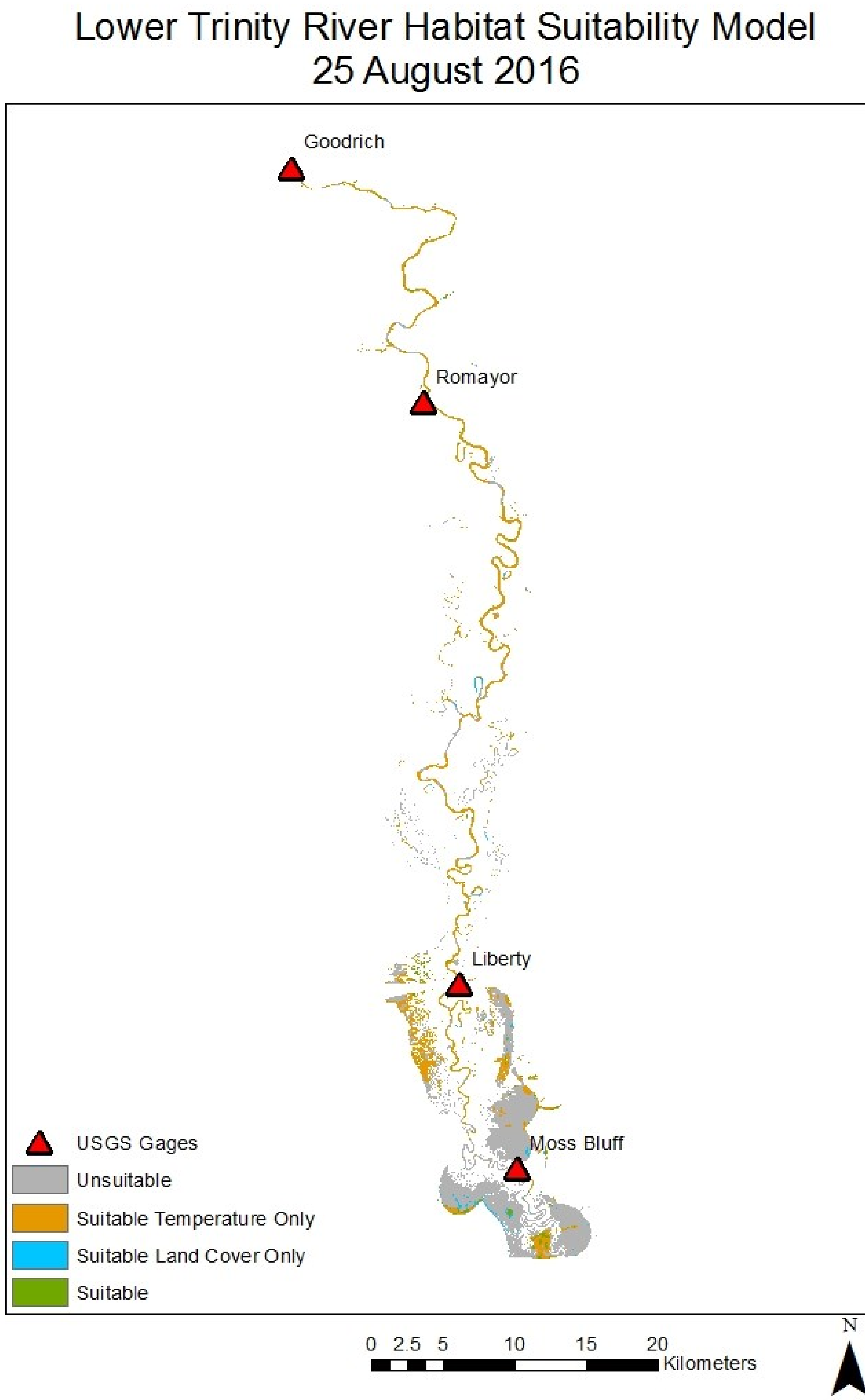

Figure 16: HSM for 25 August 2016 with USGS gaging stations at Goodrich, Romayor, Liberty, and Moss Bluff provided as reference points.

4.4 Historic land cover changes

Reclassifying the NLCD into four classes resulted in a spatially-explicit product representing historic suitable land cover (Figure 16). An interim suitability product was generated for each NLCD year between 2001 and 2011.

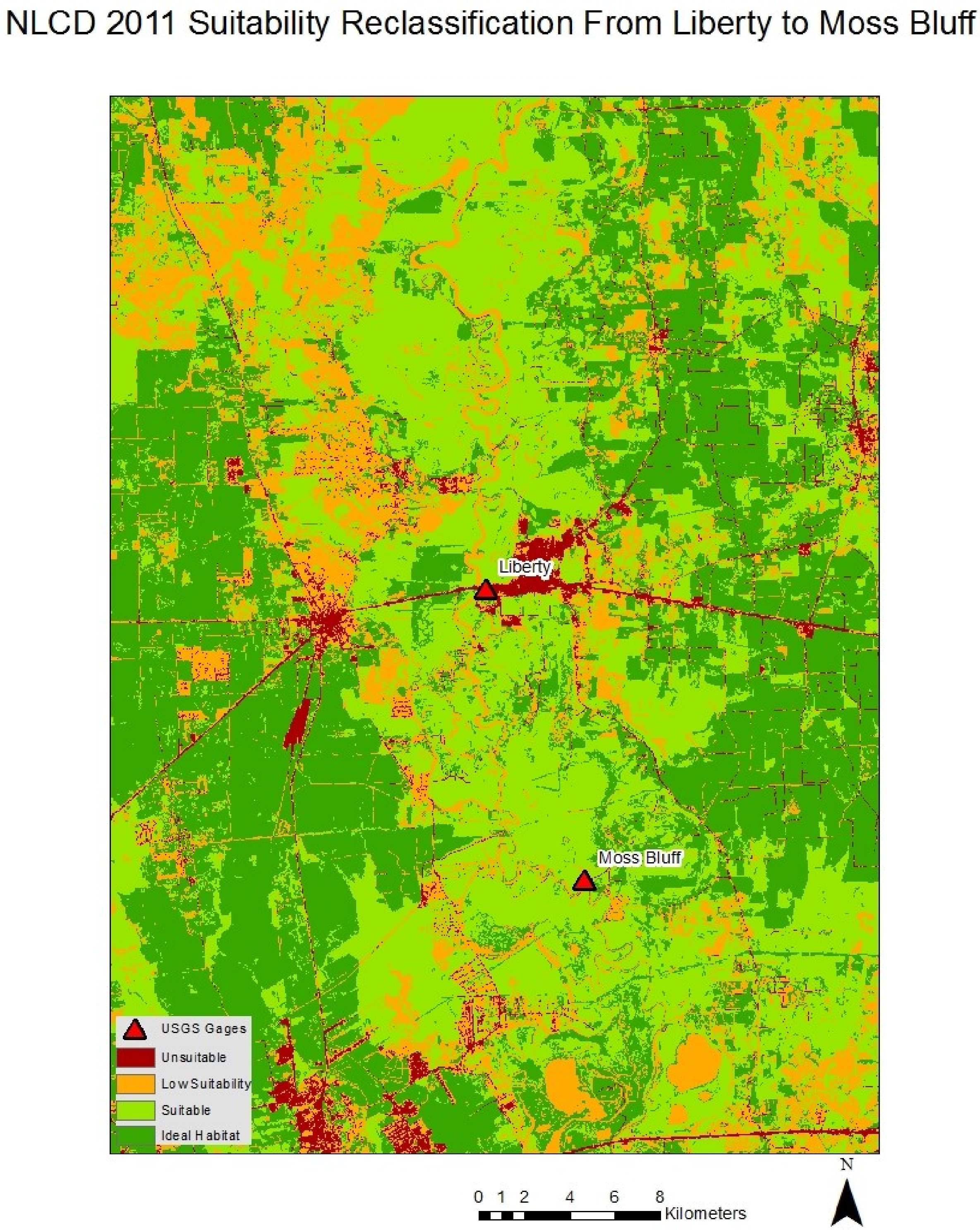

Figure 17: NLCD 2011 reclassification as an example of interim results for the historic landscape change analysis.

The addition of these rasters using Map Algebra resulted in the following change product, which depicts change from 2001, 2006, and 2011. The raster contains three digits for each pixel. The first digit is the suitability rating in 2001, the second digit is the rating for 2006, and the third digit describes the suitability value of the area in 2011. Pixel values for this change product in areas inundated on 05 May 2016 and in Landsat path 25 row 39 can be found in Table 8 and Table 9, respectively.

Historic Habitat Change: 2001, 2006, and 2011 in Areas Inundated on 05 May 2016

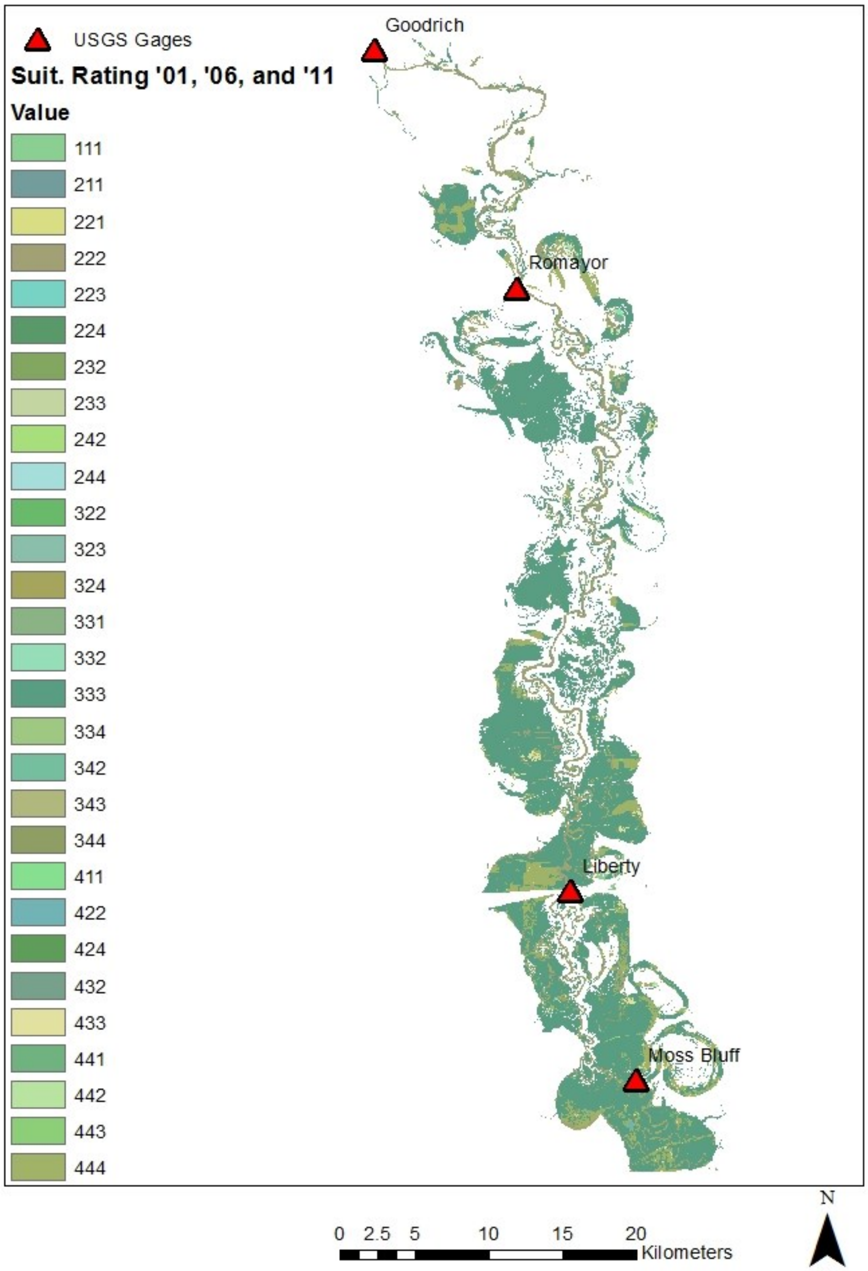

Figure 18: Changes in land cover suitability between 2001, 2006, and 2011 for portions of the Lower Trinity River floodplain inundated on 05 May 2016. Each pixel is described by three digits: the first digit describes the pixel's suitability in 2001, the second in 2006, and the third in 2011.

Table 8: Pixel percentages for NLCD suitability change classes for areas inundated on 05 May 2016.

Inundated Areas 05 May 2016	
Suitability Change Class	Percent
111	0.86
211	<0.01
221	<0.01
222	11.28
223	0.01
224	0.01
232	<0.01
233	0.01
242	<0.01
244	<0.01
322	0.12
323	<0.01
324	<0.01
331	<0.01
332	0.13
333	73.08
334	0.13
342	0.01
343	0.01
344	0.50
411	<0.01
422	0.25
424	<0.01
432	0.01
433	0.99
441	<0.01
442	0.07
443	0.20
444	12.31

Table 9: Pixel percentages for NLCD suitability change classes for path 25 row 39.

Landsat Path 25 Row 39	
Suitability Change Class	Percent
111	14.26
211	0.33
221	0.27
222	33.21
223	1.46
224	1.00
231	<0.01
232	0.16
233	0.38
234	0.01
241	<0.01
242	0.02
243	0.75
244	0.33
311	0.08
321	0.02
322	0.68
323	0.02
324	0.01
331	0.06
332	0.61
333	16.61
334	0.22
341	<0.01
342	0.01
343	0.14
344	0.23
411	0.22
421	0.04
422	0.19
423	<0.01
424	<0.01
431	<0.01
432	0.52
433	1.14
434	0.01

Table 9 Continued: Pixel percentages for NLCD suitability change classes for path 25 row 39.

441	0.15
442	0.30
443	0.63
444	25.95

5. DISCUSSION

5.1 Analysis

During the Landsat flyover dates analyzed in this study, peak inundation occurred on 05 May, with other large pulses occurring on 06 June and 22 June. Other dates exhibited lower inundation. Lowest inundation came toward the end of the season on 09 August. Increases in river stage increase the inundated areal extent of the floodplain, especially along the low-lying regions downstream from Lake Livingston. Thermal suitability also largely coincides with the expected Alligator Gar spawning season (Buckmeier, Smith, and Dougherty 2013) with thermal suitability present across the study area except on 21 May, 06 June, and 25 August. Landsat-derived thermal data was compared to in-stream data from the Surface Water Quality Web Reporting Tool published by Texas Commission on Environmental Quality (TCEQ). Only 8 temperature data taken at a depth of 0.3m were available for the Lower Trinity River during the 2016 spawning season, and calculations returned an absolute error of 4.2 degrees C for the Landsat data. This is a significant difference, likely resulting from the cloudiness of the 2016 Landsat data.

Hypolimnion flows, described by Layher et al. (2008) as being detrimental to Alligator Gar spawning suitability, were not observed in either dataset for areas immediately below Livingston Dam and are not expected to influence suitability on the Lower Trinity River.

Cloud contamination also affects the HSM for 05 May 2016 (Figure 8). The gray patches west and northwest of the USGS gage at Liberty, Texas, are a result of a single patch of clouds obscuring the inundated portion of the study area. This wispy cloud was not masked by the Landsat cloud-mask product because it was too thin to be detected. Investigating this feature resulted in an interesting find; the water surface temperatures downstream of the clouds-but not under direct influence of the clouded pixels-were low enough to be classified as unsuitable for gar spawning. It should be noted that this phenomenon was not observed in other scenes. Nevertheless, this data suggests that clouds, or perhaps rainfall from clouds may have a significant cooling effect on Alligator Gar spawning habitats, especially given their preference for shallow areas more susceptible to temperature fluctuations. While satellite-remotely sensed data may not show the effect at all because the surface would be blocked by cloud cover, the MINUR approach to cloud-masking may also negate the important effects of these clouds on water surface temperature as it pertains to spawning suitability. The MINUR process involves searching for cloud-free data from historic Landsat dates, which introduces a bias for sunny, warmer days, which could explain why suitable temperatures are largely constant across the study area during the spawning season. This further emphasizes the importance of *in-situ* data for validating these HSMs. Allen, Kimmel, and Constant (2014b) assessed temperature differences of tributaries to the main stem of the Mississippi river in order to characterize thermal refuges. This method involved sampling numerous thermal data from different dates and finding the average temperatures of the study area. This method would effectively negate any one cloudy day's effects on the data (if it had included cloudy or snowy dates), but it does not provide the spatially continuous snapshot found in my study.

Physical structure of the study area is dominated by dense forests, which are not classified as suitable for Alligator Gar spawning. Grassy areas are common farther away from the main channel, but many exist as agricultural areas, right-of-ways, or patches otherwise broken up by human development. Several large patches of suitable habitat exist near Liberty, Texas, and many oxbows provide suitable structure as well. Frequently, meanders in the main channel are designated as suitable, but many of these patches represent vegetated sandbars, which may not provide ideal structure during all types of flooding.

Physical structure does not change across the spawning season, so the main variability in the habitat suitability model results from differences in temperatures and inundation as a result of river stages. After June, river stages drop and the amount of suitable habitat available decreases as well. Immediately downstream of Goodrich, the river is still channelized as a result of outflows from Livingston Dam, but a number of tributaries display suitable habitat for Alligator Gar spawning. On closer analysis, many of these suitable areas are in fact vegetated sandbars. Most of the suitable habitat can be found downriver of Menard Creek. Several open grassy fields provide suitable habitat, and are inundated on Landsat flyover dates between May and July. Menard Creek itself is inundated throughout the spawning season and provides suitable habitat as well. South of Romayor, inundated grasslands again provide suitable spawning habitat, but heavy development inhibit the sizes of these suitable swaths. Most of the inundated areas are covered in thick forests, which also reduce the suitability of these areas for Alligator Gar spawning. South of this point, the floodplain consists of dense forests with patches of suitable grassy areas.

Natural levees, oxbow lakes, and meander scars are prominent in the suitability models and have strong implications for Alligator Gar spawning habitat. Militello (2013) found that areas adjacent to gradual bank slopes tend to attract juvenile Alligator Gar, possibly because these areas flood more readily than areas with steeper banks. This higher density could be related to floodplain accessibility or fidelity to spawning and nursery habitats. Natural levees disconnect important floodplain habitats from Alligator Gar in the main channel, and their effects may decrease the likelihood of spawning events in habitats classified as suitable in these models. Allen, Kimmel, and Constant (2014a) notes that Alligator Gar on St. Catherine Creek use deep pools not heavily influenced by changes in river temperature as thermal refuges. While thermal refuges may not be as important on the warmer Lower Trinity, Buckmeier, Smith, and Dougherty (2013) found that Alligator Gar movements on the Lower Trinity increased as temperature increased, suggesting that the fish were still seeking thermal refuge in pool habitats. Aside from thermal refuges, pool habitats offer benefits for gar such as energy conservation and plentiful food sources (Militello 2013). Buckmeier, Smith, and Dougherty (2013) also concludes that Alligator Gar are likely to show fidelity to pools that enable access to habitats for spawning and feeding. Thermal data for 05 May shows higher temperatures in oxbow lakes and inundated meander scars when compared to the main channel. The high suitability of these floodplain features is supported by anecdotal evidence and some published reports of juvenile Alligator Gar in oxbows, as was the case on the Middle Brazos River in Texas (Robertson, Zeug, and Winemiller 2008). Suitable spawning habitats near oxbow lakes and meander scars with sufficient depths and food supplies to support Alligator Gar may therefore provide better than average habitat, even compared to other areas classified as ideal.

While telemetry and macrohabitat use studies have been conducted (Buckmeier, Smith, and Dougherty 2013), these models are the first to provide spatially continuous data for the Lower Trinity River for a given date or river stage as it pertains to Alligator Gar spawning habitat. Allen, Kimmel, and Constant (2014a) performed a similar suitability analysis for parts of the Lower Mississippi River, but that study utilized inundation frequency and thermal averages across a time period rather than stage-dependent modeled inundation extents and temporally explicit thermal data. As a result, their study characterizes the landscape across the pre-spawning season while this study focused on temporal snapshots within the spawning season. The habitat suitability models are relatively simple products, but they rely on the assumptions presented above. All issues in the input data manifest themselves in the final outputs. As a result, these HSMs are capable of guiding researchers or conservation efforts, but additional research is needed to refine them.

The NLCD change product clipped to the inundated models for 05 May-which had the greatest inundated extent of the Landsat scenes studied-shows that 98% of the study area’s land cover did not change. Pixels with values of 111 are underrepresented (.86%) because they largely depict human developments which are rarely inundated. Outliers of this class include trails, smaller roads connecting low-lying oil and gas structure pads, and some sandbars in the main river channel. Class 222 (11.2% of pixels) predominantly represents bodies of water including the main channel, some lakes and ponds, and small creeks. Other classes are included, but are rarely found in the floodplain. Class 333 (73% of pixels) comprises the woody wetlands and shrub scrub NLCD classes. These areas make up the majority of the inundated study area. While they have the potential to support Alligator Gar spawning because the NLCD classifications do not specify a canopy cover, it is not expected that all pixels provide suitable habitat. Class 444 (12% of pixels) comprise ideal habitats including emergent herbaceous wetlands and a number of agricultural areas.

By applying my 2011 NLCD reclassification to the nationwide dataset, comparisons were made to telemetry studies. The highest density of Alligator Gar were located in the following cover types: woody wetlands (Sakaris et al. 2003; Militello 2013; and Allen, Kimmel, and Constant 2014a), deciduous forest, cultivated crops (Militello 2013), and emergent wetland herbaceous (Sakaris et al. 2003). During the 2013 spawning season, Militello (2013) found an increase in Alligator Gar relocations near areas on the Clark River which would have been classified as suitable and ideal in my study. Similarly, Allen, Kimmel, and Constant (2014a) also describes significant Alligator Gar observations near areas that I would have classified as suitable and ideal. This lends some credibility to the reclassification of NLCD with regards to spawning suitability, and suggests that NLCD cover type reclassifications may be suitable products for future studies. But NLCD is not an ideal dataset because of its coarse spatial and temporal resolution.

NLCD is intended to monitor land cover changes for the entire contiguous United States. As a result, it is less effective for monitoring the fine-scale changes relevant to Alligator Gar spawning habitat than fine-scale datasets like EMS. NLCD does, however, depict coarse land cover changes resulting from management policies enacted by the various land owners with holdings on the Lower Trinity River floodplain. Unfortunately, three rasters over a ten year period do not offer the temporal resolution needed to accurately assess management practices from one spawning season to the next. Given that few land cover changes occurred during the study period, NLCD may be adequate for broad-scale evaluation. But if researchers intend to establish up-to-date baselines before enacting policy changes in order to monitor the direct effects of those new policies, a dataset with a higher temporal resolution would be ideal.

5.2 Looking Forward

Because Landsat flyover dates and their corresponding river stages determined the dates of study, the river stages assessed in this study do not represent the magnitude or durations of flood events occurring during the spawn season. These variables are important for Alligator Gar spawning habitat suitability and will be included in subsequent models. Depth is another critical variable and HEC-RAS modeled depths will also be assessed as part of the HSM. No validation of the floodplain inundation models were performed for this project, but at least one area exists which would benefit from data validation. The wedge-shaped cutout in the model where Highway 90 intersects the Lower Trinity River just west of Liberty, Texas, is an artifact of the cross-section geometry used during the inundation modeling process. In reality, there is a wedge-shaped landform caused by the raised roadway on the south and the raised railroad to the north, but the inundation modeling does not display the drainage ways built into these raised structures. While that cutout area is not marked as being inundated in this model, water would be able to flow into it at any stage which inundates culverts under Highway 90, including 2016 Landsat dates between 05 May and 08 July. As grasslands cover this area (Figure 16), it is likely that suitable habitat exists here as well. Because the highway to the south and the raised railroad on the northern border are broken by occasional bridges and culverts, the impact of hydrology on the spawning suitability is difficult to assess through this project's remotely sensed data alone.

Landsat-derived thermal data for the spawning season of 2016 were heavily contaminated by clouds, and this contamination persisted despite the application of the MINUR process for some dates, i.e. 06 June. The pixels replaced in the MINUR process are within suitable ranges, but the 2016 data are classified as being too cold due to thin clouds that could not be masked out, so the actual suitability of the water temperature is difficult to determine. Estimates could be improved with an intensive historic analysis cross-referenced by data on the ground, low-altitude aerial imagery, or a classification of the types of cloud cover present in the Landsat scene and performing a unique MINUR adjustment to each cloud cover type. Figure 18 shows examples of these anomalies as they exist in the thermal layer used in the HSMs.

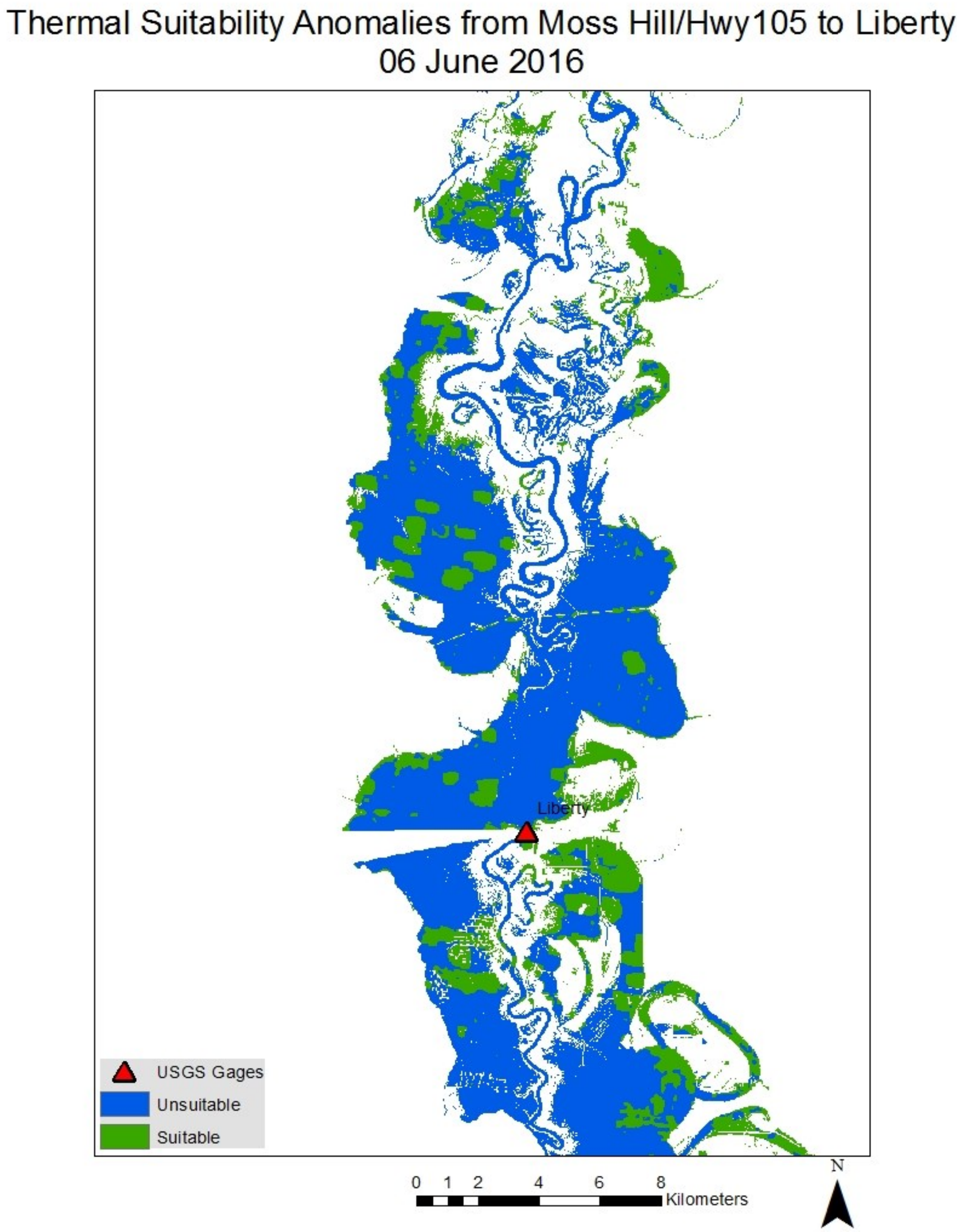

Figure 19: Thermal suitability anomalies for 06 June 2016. Green patches are examples of cloud-generated anomalies in thermal data after replacement of cloud-masked pixels using the MINUR approach.

Given the high thermal suitability across the study area despite the cloudy conditions, absolute temperature suitability should not be a primary focus for future studies. The importance of relative temperature characteristics are supported in the literature and methods for assessing relative temperature are less problematic than determining absolute temperature from satellite platforms (Allen, Kimmel, and Constant 2014b and Buckmeier, Smith, and Dougherty 2013).

Implementing a gradient approach for reclassifying EMS would go a long way toward improving the functionality of the HSMs. Unfortunately, more research needs to be done to accurately assess the suitability of specific physical structure types. There are few published reports of spawning events and detailed data of the structure of those locations are rarely recorded. Allen, Kimmel, and Constant (2014a) mentions that, while most of these anecdotal accounts and telemetry readings occur in open areas, there is also a strong bias toward open areas for these types of observations. Few efforts have been made to seek Alligator Gar spawning events in physically complex areas, and telemetry transmitters often suffer reduced effective ranges in dense habitats. Without *in-situ* data and a large sample size, subcategorizing physical structure types can quickly become spurious. Cover types can also change frequently, which would reduce the usability of highly focused datasets or models. The EMS was published in 2014 and this analysis was done under the assumption that no cover types changed significantly between then and 2016. In reality, low-intensity, high-frequency events can alter the habitat suitability of an area, i.e. a flood removing grassy vegetation from a sandbar. Without extensive ground work, there is no way to quantify changes on that scale across the entire study area, however. Given the lack of significant land cover change in the NLCD suitability product and the unreasonable cost of quantifying such minute changes across the study area, remotely sensed data provide the most valuable information for this study.

NLCD is intended to monitor land cover changes for the entire contiguous United States. As a result, it is less effective for monitoring the fine-scale changes relevant to Alligator Gar spawning habitat than fine-scale datasets like EMS. NLCD does, however, depict coarse land cover changes resulting from management policies enacted by the various land owners with holdings on the Lower Trinity River floodplain. Unfortunately, three rasters over a ten year period do not offer the temporal resolution needed to accurately assess management practices from one spawning season to the next. Given that few land cover changes occurred during the study period, NLCD may be adequate for broad-scale evaluation. But if researchers intend to establish up-to-date baselines before enacting policy changes in order to monitor the direct effects of those new policies, a dataset with a higher temporal resolution would be ideal.

The HSM as it is presented here excludes habitats with closed canopies and only includes parts of the floodplain inundated on the Landsat flyover dates, both of which could decrease the amount of habitat classified as suitable. Accommodating more variables for Alligator Gar spawning, such as depth and data about hydrologic regimes during the study period will also add to the accuracy of the model.

6. CONCLUSION

Alligator Gar are vulnerable to anthropogenic exploitation and degradation of their natural habitats. Quantifying suitable spawning habitat on the Lower Trinity River using remotely sensed data for floodplain inundation, water surface temperature, and physical structure can offer insights into how to protect this species during its most important life history stages and what can be done by land managers to minimize the human impact on this important fish. While the Lower Trinity River features a healthy population of alligator gar, it does not seem to feature an abundance of suitable spawning habitat according to stage-specific HSMs created for dates corresponding to Landsat flyover dates during the spring and summer of 2016. On the date of greatest modeled inundation for the studied time period, 05 May 2016, total suitable habitat comprises only 7.14% (2,507,695m^2) of the inundated portion of the Lower Trinity River floodplain (35,121,780m^2). Historically, the land cover component of suitable Alligator Gar spawning habitat did not changed significantly between 2001, 2006, and 2011. To be most effective, these remotely sensed data should be validated with *in-situ* data because conditions which are conducive to spawning events often hinder satellite remote sensing capabilities. Furthermore, specific spawning habitat requirements are still somewhat unknown. HSMs can supplement research and conservation efforts, but HSMs are not yet adequate for providing actionable information on their own. Incorporating other variables, such as depth and hydrologic regimes can vastly improve the utility of HSMs.

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