THE FLORIDA STATE UNIVERSITY

COLLEGE OF SOCIAL SCIENCES

QUANTIFICATION, ANALYSIS, AND MANAGEMENT OF INTRACOASTAL WATERWAY CHANNEL MARGIN EROSION IN THE GUANA TOLOMATO MATANZAS NATIONAL ESTUARINE RESEARCH RESERVE, FLORIDA

By

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ABSTRACT

The Guana Tolomato Matanzas National Estuarine Research Reserve is one of twenty-six such reserves in the United States established with the intent of protecting coastal estuaries. GIS-based analysis of aerial photographs of the southern half of the reserve reveals high rates of erosion along the margin of the Atlantic Intracoastal Waterway which runs through the reserve. From 1970/1971 to 2002 nearly 70 hectares (approximately 170 acres) of shoreline habitat were degraded by erosion along the 64.8 kilometers of channel margin analyzed. Wakes generated by vessels in the Intracoastal are hypothesized to be the primary cause of this erosion. An examination of the relationships between lateral movement of the channel margin and factors with the potential to affect erosion and accretion supports this hypothesis. Exposure to boat wakes was found to be the causal factor most strongly correlated with rate of lateral margin movement. Margin movement rates were also found to vary significantly with exposure to wind waves and with the type of channel margin eroded. A reduction in nearshore wave energy appears to be necessary to allow the recovery of impacted ecosystems. Approaches to erosion management based on nearshore stabilization and regulation of navigation are discussed, and the intricacies of the implementation of such plans are described.

INTRODUCTION

Coastal wetlands worldwide are increasingly valued for buffering the capacity of coastal storms to flood or erode uplands, filtering urban runoff, providing wildlife habitat, and supporting coastal fisheries (Beatley, Brower, & Schwab, 2002). Rapid development of coastal regions has led to the establishment of an array of local, state, and national regulatory efforts to protect these values. Among the national programs in the United States which support conservation of coastal wetlands is the National Estuarine Research Reserve (NERR) system.

The NERR program was created by the Coastal Zone Management Act of 1972 (National Estuarine Research Reserve System, 2004) to encourage “long-term research, water-quality monitoring, education, and coastal stewardship” (Guana Tolomato Matanzas Reserve, 2004, February 18). The reserves, which constitute the system, are selected from areas nominated by states to represent distinct biogeographic regions. If chosen for incorporation into the national program, the reserves enter into a federal-state partnership in which the National Oceanic and Atmospheric Administration (NOAA) provides 50% of funding for reserve operation and a cohesive, system-wide management structure. State partners are responsible for providing the remaining 50% of funding and for management of resources and administration of programs at the local level.

The federal government does not purchase or assert direct management authority over the reserve lands, but instead relies on the states to provide resource protection to “ensure a stable environment for research" (National Estuarine Research Reserve System, 2005(a)). Still, conservation is a significant focus of the NERR system. This is well-reflected in one of the stated objectives of the reserve program— to “maintain and enhance the integrity of reserve habitats through stewardship and restoration” (National Estuarine Research Reserve System, 2004). The emphasis on resource protection is further emphasized in the fact that NOAA is authorized to withdraw the designation of a reserve if a stable research environment is not maintained (National Estuarine Research Reserve System, 2005(b)). With this in mind, it is clear that any degradation of habitat within a reserve would be an issue of concern. This study addresses one such issue of concern in the Guana Tolomato Matanzas National Estuarine Research Reserve (GTMNERR)— the issue of habitat degradation due to erosion along the margin of the Atlantic Intracoastal Waterway (AICW). Not only is such habitat degradation an issue of concern given the reserve management objectives, but it also contradicts the desired trend of "no net loss of wetlands" supported by local regulations (Flagler County, 2004) and federal commitments (U.S. Environmental Protection Agency, 2004).

The GTMNERR is divided into two sections, together comprising approximately 24,000 hectares (60,000 acres) in St. Johns and Flagler counties in northeastern Florida. The Guana, Tolomato, and Matanzas Rivers are the major estuarine bodies of the reserve; together they form a string of relatively narrow "bar bounded" estuaries behind the barrier islands which line the Atlantic coast. This study focuses on the AICW in the southern portion of the GTMNERR (Figure 1). The AICW in the study area consists of a marked channel in the Matanzas River, portions of which have been deepened and straightened to provide for navigation, and several reaches of completely man-made channel.

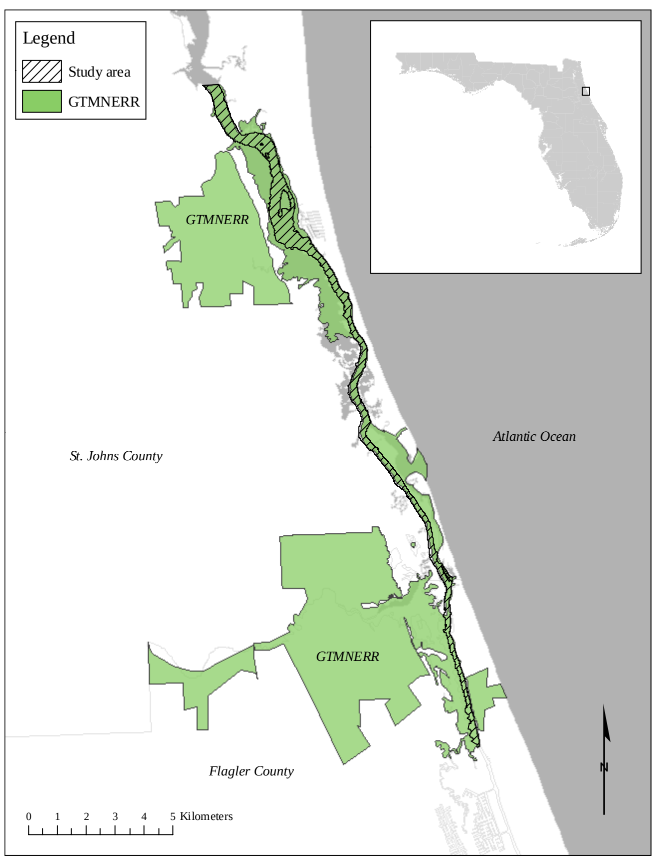


Figure 1: Study area – Southern portion of Guana Tolomato Matanzas National Estuarine Research Reserve (GTMNERR)

Habitats found in the reserve include salt marsh and mangrove tidal wetlands, oyster bars, estuarine lagoons, creeks and rivers, dredge spoil disposal areas, upland, and a section of the adjoining Atlantic Ocean. It is of interest that the mangrove wetlands in the reserve constitute “the northern-most extent of mangrove habitat on the east coast of the United States” (Guana Tolomato Matanzas Reserve, February 18, 2004). Although the reserve is described as relatively undeveloped, the hydrology of the estuaries has been significantly altered by human activities, including the construction of the AICW (Guana Tolomato Matanzas Reserve, 2004, February 18) which was first dredged as early as 1883 (Florida Inland Navigation District, 1967).

Years of personal observations and a brief pilot study conducted in the fall of 2003 made apparent the process of erosion and subsequent habitat degradation in the GTMNERR. Although erosion is a natural process, the high rate of erosion observed in the GTMNERR appeared to be degrading natural habitats at a rate far faster than they could rebuild. Studies have shown that lateral erosion of salt marsh channels, such as that of the AICW and its tidal tributaries, is naturally offset by deposition in other areas (Letzsch & Frey, 1980). Thus, any observation of widespread erosion, not offset by accretion elsewhere, warrants careful examination.

The margin of the AICW channel which runs through the reserve has eroded considerably over the past thirty years. As a result, productive habitats, including salt marsh, mangroves, and oyster bars, are being eroded and replaced by intertidal sand flats which are considerably less productive (Montague & Wiegert, 1990) and thus, also considerably less valuable from an anthropocentric perspective. The channel of the AICW in the GTMNERR is lined with tidal creeks, oyster bars, salt and mangrove marshes, dredge spoil islands, and developed uplands. The intent of this study is to quantify the extent of habitat loss due to channel margin erosion from 1970 to 2002, examine correlations between erosion rates and possible causal factors, investigate management alternatives which could be used to limit habitat degradation, and examine the regulatory framework surrounding the implementation of such alternatives.

CHAPTER 1

QUANTIFICATION AND ANALYSIS OF EROSIVE TRENDS

Background

The process of habitat loss to erosion in the GTMNERR can be described as erosion along the margin of a major estuarine channel which has been modified to provide for navigation. Sediment transport in estuaries has been widely studied, and the basic mechanics of it are well understood. While the majority of studies concerned with erosion and accretion within estuaries have focused specifically on salt marsh channels, the findings have applications to channels of other margin types. Along estuarine channel margins, erosion and accretion are regulated by the interaction of forces that add energy to the nearshore environment with variables which regulate the input of new sediment and which govern sediment mobility (Figure 2).

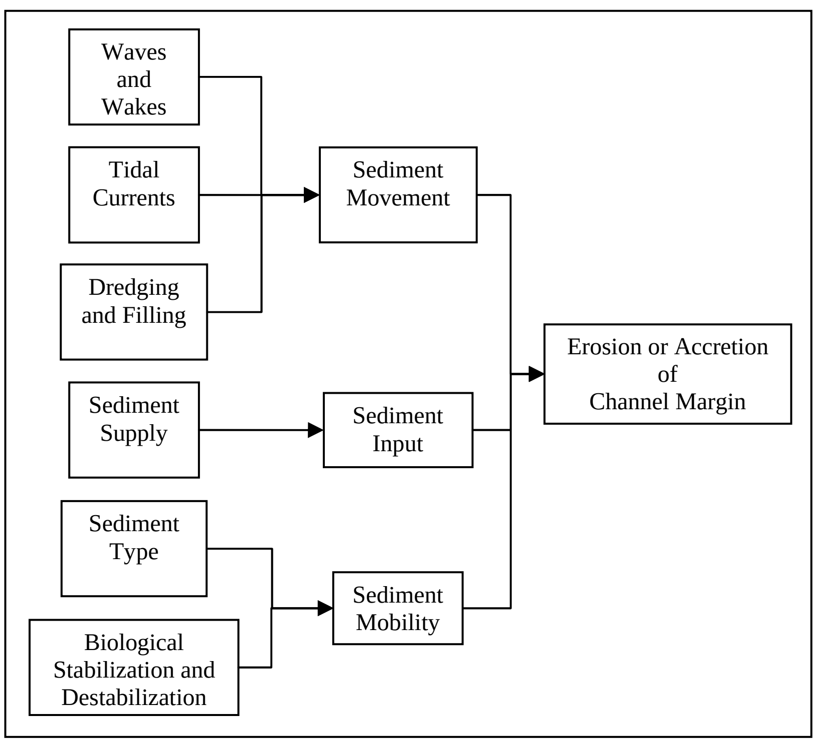


Figure 2: Factors affecting erosion and accretion along an estuarine channel margin

As displayed in Figure 2, the primary forces responsible for the movement of sediment are waves, currents, and human dredging and filling. Waves and currents affect shoreline sedimentary processes by adding energy to the nearshore environment. Dredging and filling physically add or remove sediment. Sediment supply regulates the amount of sediment available for accretion, and the sediment type and level of biological stabilization or destabilization govern the mobility of channel margin sediments. Of these factors, several can be disregarded as potential causes of the erosion in the GTMNERR and several are likely contributing causes. The role of sea level is also addressed below due to its connection to the global climate change debate and frequent association with coastal erosion.

Waves and Wakes

In modern estuarine systems, the two major sources of wave energy are wind waves and boat wakes. Both are recognized as capable of causing significant sediment transport in a variety of aquatic environments.

The shoreline impact of waves generated in estuaries is influenced by a number of factors, but two of the most significant of these are nearshore bathymetry and bottom friction. Because waves break and lose energy when they enter sufficiently shallow water, the wave energy at impact, and thus the erosive capacity of a wave, is significantly affected by the bathymetric profile of nearshore areas. A gently sloping profile allows wave energy to dissipate gradually because waves break farther from the shore, while a steep profile focuses a larger portion of the wave energy directly on the shoreline. In a similar manner, submerged bars off a shoreline can significantly reduce the impact of waves approaching from open water. Increased bottom friction also leads to a decrease in wave energy.

Quantification of the effects of bathymetry and bottom friction in the GTMNERR is difficult; however, these factors are certainly of importance. Even a cursory observation of shorelines in the study area reveals a great deal of variation in nearshore depths and substrate types. The level of variation makes measurement and analysis of the role of this variation difficult.

Wind waves are cited as a cause of marsh erosion in a number of studies (Day, Scarton, Rismondo, & Are, 1998; Doane, Wells, & Merman, 1998; Downs, Nicholls, Leatherman, & Hautzenroder, 1994; Phillips, 1986b; Schwimmer, 2001). Waves cause marsh erosion directly by undermining the stabilizing root mat of smooth cordgrass, *Spartina alterniflora*, the dominant marsh vegetation in the GTMNERR. Non-marsh channel margins are eroded more gradually. The prediction of the extent of wind wave erosion is difficult due to the number of factors which influence wave energy at bank impact. These factors include wind speed, duration and fetch (distance that winds blows over water), as well as water depth and angle of wave impact. Previous studies (Hershberger & Ting, 1996) have shown that even complex models of inshore wave propagation can encounter considerable error. Hershberger and Ting's research in the Gulf Intracoastal Waterway compared field measurements of wave height and period with those predicted by the U.S. Army Corps of Engineers (USCOE) Automated Coastal Engineering System model and found the model to over-predict waves when wind was blowing along the channel and under-predict waves when wind was blowing across the channel. Considerable expertise is necessary to accurately predict wind wave-caused erosion through the prediction of wave energy in a channel such as the AICW. A simpler predictor of channel margin erosion may be the presence or absence of exposure to causal factors such as wind waves.

Wind wave erosion has been found to be most severe downwind of the prevailing wind and largest local fetch (Day et al., 1998; Doane et al., 1998; Downs et al., 1994; Schwimmer, 2001). National Oceanographic and Atmospheric Administration data from a coastal automated weather station approximately 2 km east of the study area show the predominant direction of winds over 10 knots to be from 345^{o} to 45^{o} (National Oceanographic and Atmospheric Administration, 2003). The Beaufort wind scale defines 10 knots as the wind velocity at which small waves generally start to form and thus wind wave erosion can be expected to begin to occur. Given the results of previous studies, wind wave erosion can be expected to be most severe along the Matanzas River downwind of this wind direction, or along river channel margins facing from 90 to 300 degrees.

Boat wakes are also widely recognized as a cause of bank erosion in inland bodies of water (Grossfeld, 1997; Kennish, 2002; Maynord et al., 2001; Raines, 2003; Wilcox, n.d.; Williams, 1993; Zabawa, Ostrom & Byrne, 1980). Factors influencing the erosive impact of boat wakes include the size of the wake, the water depth, the current direction and velocity, the morphology of the impacted bank, the presence of wind waves, and the distance of the vessel from the shore (Macfarlane & Renilson, 1999). The size of the wake is governed by vessel speed, hull form, draft, loading, and trim. Generally, fast moving vessels displacing large volumes of water produce the largest wakes while vessels displacing less water and moving slowly or at planing speed produce the smallest wakes.

Although boat wakes and wind waves affect the channel margin in a similar manner, wake-caused erosion can be distinguished from wind wave-caused erosion in that it occurs in areas sheltered from wind waves and may be most severe where the AICW channel is closest to the channel margin. Wakes can be expected to be a much more significant problem in the GTMNERR than in wider bodies of water such as the nearby St. Johns River. The relatively narrow channel of the AICW does not allow significant distance for wake energy to subside before wakes impact the margin. The narrow channel also does not provide as large a fetch for the development of wind waves as wider channels do; thus, ecosystems along the margins of the AICW are adapted to significantly lower energy levels than those along channels where larger wind wave propagation is possible. Personal observations supported by consultation with knowledgeable locals and experts in the field of coastal geomorphology (Sergio Fagherazzi, personal communication, 2004) have led to the hypothesis that boat wakes in the AICW are the primary case of erosion in the GTMNERR.

Tidal Currents

Tidal currents are capable of causing erosion along estuarine channels in the same manner that riverine currents erode river banks. Generally, channels erode on the outside of bends, where current velocity and resultant shear stress is highest, and accrete on the point bars on the inside of bends. Tighter bends, with smaller radii of curvature, erode on the outside and accrete on the inside faster than wider bends with larger radii of curvature (Leopold, Wolman, & Miller, 1992). In stable systems lateral, current-induced erosion in one area is offset by accretion in another (Letzsch & Frey, 1980).

Dredging and filling

Dredging and filling for navigational or other purposes can cause erosion or accretion in several ways. Most obviously, channels can be dredged directly through an area or existing channels can be filled. This results in apparent erosion or accretion in a map or aerial photograph. According to Brian Brodehl of the USCOE Jacksonville district (personal communication, September 10, 2004), dredging can also cause channel widening when a channel is dredged to such a depth that when channel bed sediments reach their natural angle of repose, the bank is under cut. If the dimensions of a channel and the angle of repose of constituent sediments are known, it is possible to calculate the potential for erosion due to this mechanism. Considering that the planned dimensions for the AICW navigation channel are 125 feet wide by 12 feet deep and that the approximate angle of repose of bed sediments is 1:2.5 (according to B. Brodehl.), the current mean width of the entire tidal channel, over 1000 feet, is more than sufficient to accommodate the construction of the channel without under cutting banks. Mr. Brodehl acknowledged that although the USCOE considers this calculation in the dredging of the AICW channel, it is likely that historically dredging efforts were not as carefully engineered.

It is also possible for dredging to alter depth or fetch available for wave propagation, or to alter current direction or velocity and thus indirectly influence local erosion rates. One mechanism through which channel dredging may increase current velocities and increase erosion rates is through alteration of the tidal prism (the difference in the volume of water in a water body between low and high tides) (Cox, Wadsworth, & Thomson, 2003). It is likely that dredging associated with the creation of the AICW altered the local tidal prism, but it is difficult to determine the magnitude of the change or to relate this change to sedimentary processes.

A second manner in which navigation related dredging and filling may have affected tidal currents, and thus affected sedimentation, is through the alteration of natural channels in the vicinity of Matanzas Inlet, both during the initial construction of the AICW and again in the 1970’s. Figure 3 allows the comparison of the modern channel configuration with the unmodified channel, as depicted in United States Coast Survey maps created in 1867 and 1872. The channel to the north of the inlet was realigned during construction of the AICW channel as was the smaller channel running south from the inlet. The thin strip of land dividing the inlet and the navigation channel was also fortified to prevent tidal currents from depositing sediment in the channel. Together these modifications dramatically altered the natural tidal channels in the vicinity of the inlet and are likely to have caused substantial changes in sediment transport processes.

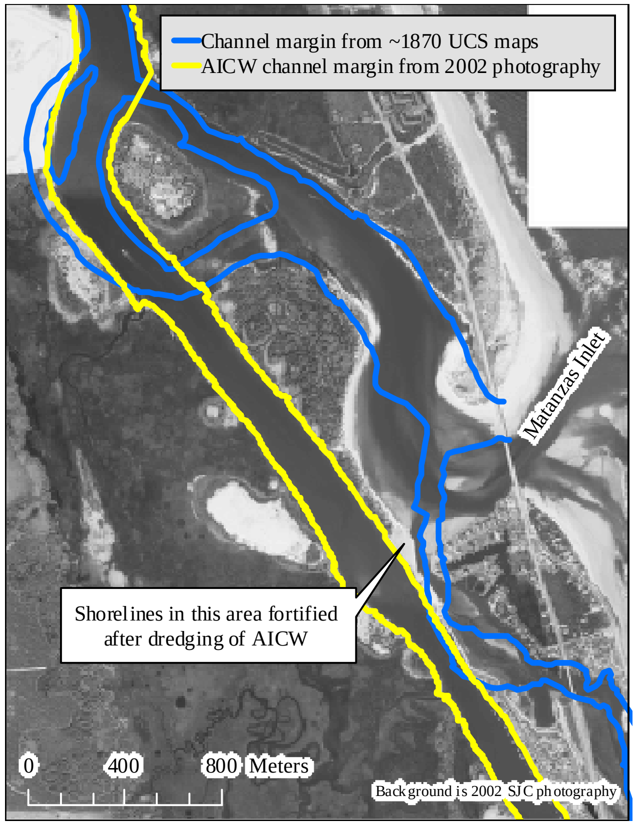


Figure 3: Alterations in the vicinity of Matanzas Inlet

The precise effect of such alterations is again difficult to discern. However, a portion of the study area, from the State Road 206 Bridge to the north end of the study area, has apparently never been dredged (judging from the absence of dredge spoil islands) and can be viewed as a control for the examination of dredging impacts.

Sediment supply

The primary condition which must be met for accretion to occur is the existence of a sufficient supply of sediment. The primary sources of allocthonous sediment for most marsh systems are (1) riverine sources, (2) off-shore sources, (3) barrier wash-over, (4) erosion of coastal cliffs, and (5) wind-blown sediments. Biogenic organic aggregates provide the major source of autochthonous sediments (Frey & Basan, 1978). The AICW in the study area does not receive significant input of sediment from riverine sources or experience substantial barrier island wash over and is not located near any coastal cliffs. Off-shore sources, wind-blown sediments, and organic aggregates are most probably the major potential sources of new sediment (personal observations, 1980-present). Dredged bed sediment also may contribute considerably to the sediment supply, both during the dredging process and later as dredged sediment is eroded from shoreline disposal areas. There is no indication of a change in sediment supply levels during the study period.

Sediment type

Channel margin sediments in the study area vary from coarse oyster shells to fine organic sediments. According to this variation in sediment, any location along the AICW channel margin can be placed into one of five different categories: intertidal bars, salt marsh, sandy dredge spoil disposal areas, uplands, or water (the mouths of tributaries or off-channel areas which join the main channel). Although these categories are somewhat subjective, they can be viewed as an indicator of both channel margin sediment type and the level of biological stabilization or destabilization. Intertidal bars contain mostly disarticulated oyster shells; marshes contain very fine sediments; spoil is generally sandy with some shell; uplands are sandy, but are usually reinforced with tree roots or seawalls. The 64.8 kilometers of channel margin examined in this study were classified as displayed in Table 1 below. Each sedimentary class can be expected to respond differently to erosive forces due to both the physical structure of the sediment and the levels of biological stabilization or destabilization.

Table 1: Summary of 1970/1971 channel margin classification

Margin classification	Margin length (km)	Proportion of margin length
intertidal bars	8.7	13%
marsh	24.8	38%
dredge spoil	19.3	30%
upland	6.1	9%
water	5.9	9%
Total	64.8	100%

Biological stabilization and destabilization

Estuarine organisms can have both positive and negative influences on the stability of channel margins. The major species responsible for shoreline and nearshore stabilization in the GTMNERR are smooth cordgrass, *Spartina alterniflora*, and the eastern oyster, *Crassostrea virginica*. Atlantic coast salt marshes, such those found in the GTMNERR, commonly consist of extremely fine unconsolidated silts and clays (Frey & Basan, 1978), the top several inches of which are reinforced by the rhizomatic mat of *Spartina alterniflora*. Personal observations suggest that marsh erosion in the reserve follows the general pattern described in the seminal work of Redfield (1972). Erosion of the sediment from under the root mat leaves the marsh surface unsupported and results in the mass wasting of large blocks of the vegetative mat and coherent sediment. This erosive process makes clear the fact that although *Spartina* roots do reinforce marsh sediments, they cannot prevent erosion in a high energy environment.

Oysters protect fine marsh sediments from erosive forces in a manner similar to cordgrass, but oysters are also not immune to damage from waves. Grizzle, Adams and Walters (2002) conducted a study of aerial photography in the Indian River Lagoon, on Florida's east coast, and observed widespread death of oyster bar margins, an occurrence they attributed to the action of boat wakes. Wakes have the potential to inhibit the settlement of larval oysters and physically move or smother adult oysters with sediment. Dead oyster bar margins similar to those discussed by Grizzle et al. (2002) are common in the GTMNERR. They appear much lighter in color than healthy bars and can be distinguished in aerial photographs. Informal analysis of aerial photos of the reserve suggests that all oyster bar margins with direct exposure to the navigation channel of the AICW could be classified as dead using Grizzle's criteria.

Biological destabilization, or bioturbation, involves physical disturbance of sediment by living organisms, such as the fiddler crab, *Uca pugnax* (Letzsch & Frey, 1980). Fiddler crab burrows penetrate marsh sediments and thus increase their susceptibility to erosion by waves or currents. Although native organisms such as *U. pugnax* may decrease the stability of sediments in stable ecosystems, lateral erosion and deposition are roughly equal even in their presence (Letzsch & Frey, 1980). Thus, in the absence of any drastic ecosystem changes, bioturbation should not be viewed as a primary cause of erosion. The same holds true for other examples of ecosystem change with the potential to alter marsh erosion rates. Periwinkle snails, *Littorina sp.*, have been observed to feed on *Spartina*; and in the absence of predation by blue crabs, *Callinectes sapidus*, populations of snails may have the potential to devastate *Spartina* marshes, destabilizing sediments and lowering deposition rates (Bertness & Silliman, 2002). Again, overall sedimentation rates should not be expected to change significantly unless there is a substantial change in trophic structure.

Alteration of the trophic structure of an ecosystem can cause otherwise innocuous processes, such as bioturbation or predation, to have drastic effects on the stability of the system. However, determination of the role of such processes in marsh erosion is difficult due to the natural complexity of ecosystems and the large amount of observational data necessary to ascertain if a change is occurring. No major changes in trophic structure, with clear potential to alter erosion rates, have been reported in the GTMNERR.

<u>The role of sea level</u>

Relative sea level rise can result from either an increase in eustatic sea level (the level of the ocean in relation to the land) or from subsidence of the land. Mean sea level is measured through analysis of tidal gauge data corrected to account for seasonal and interannual variation and change in land elevation. The lack of tidal data for any one location in the study area for any significant portion of the study period negates the possibility of conducting this type of analysis. However, a NOAA sea level trend analysis for a tidal gauge approximately 48 miles north of the study area reported an average rate of sea level rise of 2.43 millimeters/year, from 1928 to 1999 (NOAA, n.d. a). This rate is at the high end of the range of the estimated current global average rate of sea level rise of 1.0 to 2.4 millimeters/year (NOAA, n.d. b).

Sea level rise has been implicated as a causal factor in a number of studies of marsh erosion (Day et al., 1998; Downs et al., 1994; Hartig, Gornitz, Kolker, Mushacke, & Fallon, 2002; Kastler & Wiberg, 1996; Kearney, Grace, & Stevenson, 1988; Phillips, 1986a; Reed, 1988; Salinas, DeLaune, & Patrick, 1986). In these studies, subsidence and eustatic sea level rise often function in concert to increase erosion rates; but in several locations including Venice, Italy (Day et al., 1998) and Louisiana, (Salinas et al., 1986) subsidence appears to be the underlying cause of observed erosion. Subsidence is the decrease in elevation of sediments due to extraction of subsurface resources or geologic processes. There have been no recorded observations of subsidence in the reserve.

In cases of erosion exacerbated by eustatic sea level rise and those involving subsidence, the response of the marsh appears to be essentially the same. A simplified relationship of marsh elevation to relative sea level was presented by Redfield (1965), who found that if salt marsh surface accretion keeps pace with relative sea level rise, then the marsh will remain stable. This view was amended by Orson, Panageotou, and Leatherman (1985) and again by Schwimmer and Pizzuto (2000) who studied a rapidly eroding marsh in which the aggradation (vertical building) rate exceeded the rate of relative sea level rise. Schwimmer and Pizzuto propose that in the face of relative sea level rise a marsh can either (1) erode (retreat laterally), (2) prograde (build laterally), or (3) drown depending on local rates of relative sea level rise and marsh surface and nearshore sedimentation rates. Nearshore sedimentation is critical because it has the potential to alter bathymetry and thus affect the erosive impact of waves.

A marsh shoreline erodes, in the presence of relative sea level rise, when the nearshore sedimentation rate is less than the local rate of relative sea level rise and the rate of marsh aggradation is greater than the rate of relative sea level rise (i.e. the marsh builds upward fast enough to stay above water but erodes laterally). A shoreline progrades, in the presence of relative sea level rise, when the nearshore sedimentation rate and the rate of marsh aggradation are both greater than the local rate of relative sea level rise (i.e. the marsh not only builds upward fast enough to stay above water, but high nearshore deposition rates allow it to build laterally). A marsh drowns when the near shore sedimentation rate and the rate of marsh aggradation are both less than the local rate of relative sea level rise (i.e. the marsh cannot build upward fast enough to stay above water). The first indicator of drowning is the deterioration of the vegetative marsh mat due to excessive inundation. Where mat deterioration occurs, new areas of open water form and are then enlarged by waves in the direction of the predominant wind (Stevenson, Kearney, & Pendleton, 1985).

Considering these statements, if, in the presence of relative sea level rise, erosion is observed but drowning is not observed, as is the case in the GTMNERR, the marsh must be aggrading and erosion must therefore be caused by relatively low nearshore sedimentation rates. Nearshore sedimentation rates are influenced by wave climate and sediment supply (Schwimmer & Pizzuto, 2000), so erosion can be expected to be most severe in locations where sediment supply is lowest and wave energy is highest. Considering this relationship, sea level rise should not be considered a primary cause of erosion, but rather a secondary factor with the potential to increase the rate of erosion due to waves or nearshore currents.

Methods

The commonly used methods of measuring erosion rates can be grouped into two main classes, on-site data collection and measurement from compiled historical sources. The main advantage of on-site data collection is that change rates can be measured precisely, and change over short time periods can be quantified accurately; however, this method requires significant field work and, therefore, is not well suited to research involving time constraints or large study areas. Measurement from historical sources is a process which allows the intrusion of considerable error; however, this method allows for the relatively rapid assessment of change over large areas and time spans and does not require intensive field work. Due to time and budgetary constraints and the desire to study as large an area as possible, this study used methods involving measurement from complied historical sources.

Analysis of aerial photography, a method routinely used to analyze coastal geomorphic trends (see Cox, Wadsworth & Thomson, 2003, for a recent example), was used to measure the extent of erosion along the AICW in the southern section of the GTMNERR over the past thirty-one years. The Florida Department of Transportation (FDOT) Survey and Mapping Office provided digital versions of 1:24,000 scale, black and white aerial photography of the Flagler County portion of the study area taken in November and December of 1970 and in February of 2002. FDOT also provided 1:24,000 scale, black and white photography of the St. Johns County portion of the study area taken in April of 1971. Photography of the St. Johns County portion of the study area taken in 2002 was purchased from St. Johns County. Both sets of 2002 photography were received as digital orthophotos pre-rectified to geographic coordinate systems. All photo sets were scanned using a resolution of 2000 dots per inch to yield digital photo sets with a 0.3-meter pixel resolution. Environmental Systems Research Institute (ESRI) Arc Geographic Information System (GIS) software was used to georectify the 1970 and 1971 photos using the pre-rectified 2002 images. A minimum of 9 links was used in the rectification of each image and the mean root-mean-square (RMS) error for all rectified images was 3.3 meters. RMS error is the measure of uncertainty in geographic data promoted by the Federal Geographic Data Committee (FGDC, 2004). It is the square root of the mean squared differences in location between the data set being rectified (1970 and 1971 photography) and the established data set used as a base for rectification (2002 photography). The FGDC does not establish a specific threshold by which to judge RMS error; it instead suggests that users develop a standard sufficient for the purposes for which the data will be used and adhere to that standard.

Once photos were rectified, the channel margin in both the 2002 and the 1970/1971 photo sets were digitized to yield a digital line file. The channel margin was defined as the border of the major tidal channels of the GTMNERR. The margin should be distinguished from the edge of the navigation channel and from the channel shoreline. While the channel margin and the shoreline are often in the same location, there are also many locations in the study area where practically all of the energy generated in the channel dissipates on intertidal bars which can be over a hundred meters from dry land. When the shoreline and the channel margin were in the same place, the vegetation line was used to locate the channel margin. In unvegetated areas, margin definition was less precise. When gaps, such as tributary mouths or openings between dredge spoil islands were encountered, the shoreline was followed away from the main channel until the end of the erosive margin, as indicated by a white, sandy shoreline, was encountered (Figure 4).

The methods used by Kastler and Wiberg (1996) were used to ascertain the uncertainty involved in this digitization process. Three randomly selected, vegetated, one-kilometer margin reaches were digitized three times each and the mean distance between each successive digitization was calculated. This calculation yielded a mean digitization error of 3.9 meters. This number was combined with the 3.3 meter RMS error as the square root of the two squared numbers following the methods of Gaeuman, Schmidt, and Wilcock (2003), to yield a total estimated error of 5.1 meters (Figure 5).

While this error makes precise location of individual points difficult, it is essentially randomly distributed, so widespread changes in a single general direction are likely to be real. Additionally, this error only applies to vegetated margin types, including marsh, most dredge spoil disposal areas, and uplands. As exposure of intertidal bars varies with the tide, the degree to which they are distinguishable in aerial photographs varies depending on when the photos were taken. It was found that dead shell bars, which were significantly more common in the 2002 photographs, were much easier to discern than live oyster bars. Water margins, found in the mouths of tributaries along the channel, are also imprecise. Due to these differences, estimation of a reliable error rate in the delineation of intertidal bar and water margins is difficult.

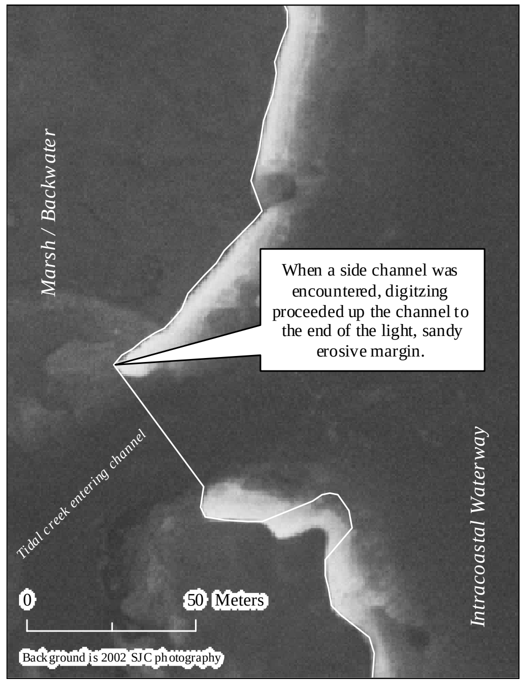


Figure 4: Digitizing the channel margin in the vicinity of a side channel

$$\sqrt{(digitizing\_error)^2 + (RMS\_error)^2} = Total\_estimated\_error$$

$$\sqrt{(3.9)^2 + (3.3)^2} = 5.1m$$

Figure 5: Estimation of error

The channel margin lines were manually attributed as water, intertidal bars, marsh, spoil or upland by referencing the 1970/1971 photo set, as displayed in Figure 6. Where margin type was uncertain, on-site ground truthing inspections were conducted. The margin classes are subjective; however, they are indicators of the predominant sediment type in the area and the level of biological stabilization.

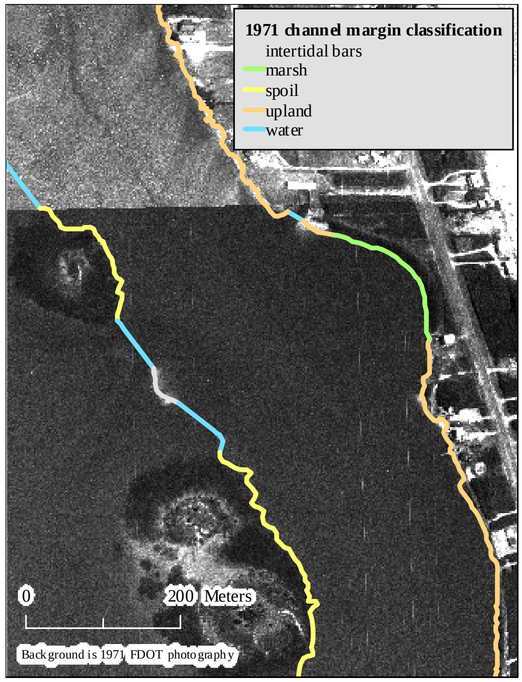


Figure 6: Classification of channel margin types

Once digitization and margin classification were complete, change in margin location was assessed using two separate methods: a polygon-based analysis of change in area, and a point-based analysis of lateral margin movement.

Polygon-based analysis

The polygon-based analysis was used to determine the total change in area of each margin classification as a result of erosion or accretion. Following the classification of the channel margin, the channel margin lines were used to create two polygons representing the major tidal channels in 1970/1971 and 2002. Using the methods of Gaueman et al. (2003), these polygons were clipped to create two new polygon files. One file contained all areas which were not part of the channel in 1970/1971 but were part of the channel in 2002, and thus represented erosion. The second file contained areas which were part of the channel in 1970/1971 but were not in 2002 and thus represented accretion. Examples of erosion and accretion polygons are displayed in Figure 7. Using GIS software, erosion polygons were manually categorized as one of the five margin types by spatially joining them to the file containing channel margin classification types. Accretion polygons, which were much less numerous, were categorized manually while referencing the 2002 photos (Figures 18-33). The total area of erosion and accretion of each margin classification was calculated.

Point-based analysis

The point-based method of analysis was structured to determine the rate of lateral erosion or accretion along the channel and to allow examination of rates of change in relation to a suite of indicator variables developed to ascertain the role of the various causal factors in erosion or accretion. Point files were constructed through an automated process which located points every 10 meters along the 64.8 kilometers of digitized channel margin in the study area for both the 1970/1971 and 2002 channel margin line files. This created two point files of approximately 6,480 points each (examples of which are displayed in Figure 7). If the points were found to lie on the margins of the previously created erosion polygons, the distance from each 1970/1971 point to the nearest point in the 2002 layer was recorded as a negative number. If the points were found to lie on the margins of the accretion polygons this distance was recorded as a positive number.

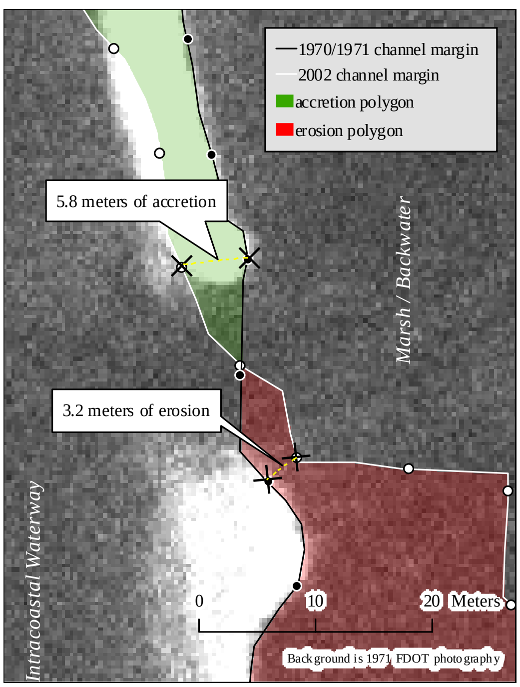


Figure 7: Methods used to measure erosion and accretion

The points, at which lateral movement of the channel margin was measured, were classified according to their characteristics which have the potential to influence erosion and accretion using automated geoprocessing techniques. Each point in the 1970/1971 file was dichotomously classified according to its exposure to wind waves formed by prevailing winds, its exposure to boat wakes generated by vessels in the AICW channel, its exposure to tidal currents likely to cause erosion, and its location north or south of the State Road 206 Bridge (as an indicator of dredging activity). Points were also classified according to channel margin type. In addition, the width of the entire 1970/1971 channel, as well as the distance between the 2002 channel margin and the edge of the AICW in 1999, were calculated. These indicator variables are summarized in Table 2.

Table 2: Indicators of factors affecting erosion and accretion

Variable	Continuous value mean ± stdev (min, max)	Category	Intended to quantify erosion due
channel margin classification	N/A	0 (water) 1 (intertidal bars) 2 (marsh) 3 (dredge spoil) 4 (upland)	sediment type and biological stabilization
exposure to wind waves	N/A	1 (margin facing predominant wind direction) 0 (margin not facing predominant wind direction)	wind waves
exposure to AICW channel	N/A	1 (exposed to boat wakes generated in AICW) 0 (unexposed to boat wakes generated in AICW)	boat wakes
entire 1970/1971 channel width (m)	426.2 ± 687.9 (91.1, 1290.5)	N/A	boat wakes
distance from 1999 AICW channel (m)	272.4 ± 711.1 (7.8, 773.0)	N/A	boat wakes
exposure to tidal currents	N/A	1 (likely to be effected by tidal currents) 0 (unlikely to be effected by tidal currents)	currents
radius of curvature (m) of the nine identifiable bends	789.1 ± 268.6 (439.3, 1195.1)	N/A	currents
location relative to SR206 bridge	N/A	1 (south of bridge - along dredged channel) 0 (north of bridge - along undredged channel)	dredging

Points were coded 1, as exposed to wind waves formed by the prevailing winds, if the margin faced any direction from 300 to 90 degrees. Unexposed points, where the margin faced from 90 to 300 degrees, were coded as 0. Figure 8 displays an example of wind exposure coding and presents a conceptual diagram used to estimate margin angle and subsequent exposure. Exposure was determined based on photographs at a scale of approximately 1:5,000 so minor variations, on the scale of several meters, are not reflected in this variable. Such precision would be prohibitively time consuming and would likely exceed the precision of the digitized channel margins.

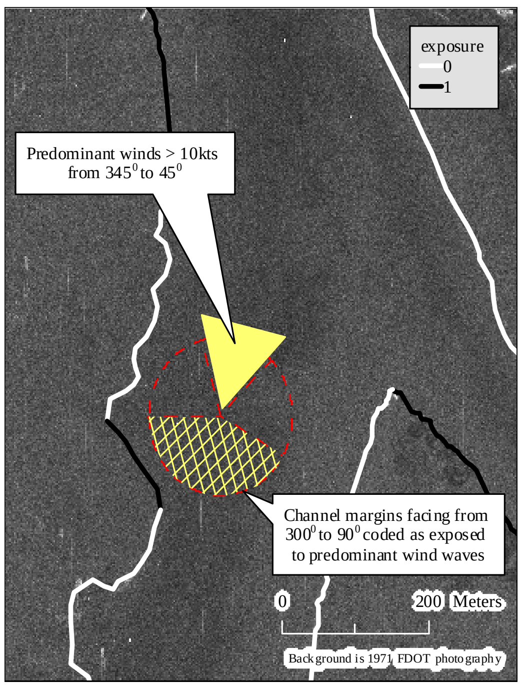


Figure 8: Coding of exposure to waves caused by predominant winds

Points were coded 1, as exposed to boat wakes, if a line drawn perpendicular to the centerline of the AICW navigation channel could pass through them without crossing a second channel margin (Figure 9). If points did not meet this condition they were coded 0 for this attribute. The same lines used in this test were used to measure the width of the 1970/1971 channel. Channel width was measured perpendicular to the centerline of the AICW at 10 meter intervals. Since the width measurement lines usually did not intersect the points where change was measured, channel margin points were assigned the width measurement which intersected the channel margin closest to their location. Points unexposed to boat wakes were excluded from the analyses involving channel width. Because boat wakes decay with distance from the sailing line of the boats which produce them, wake-caused erosion can be expected to be most severe when the entire tidal channel is narrower and wakes have less distance over which to dissipate before they impact the channel margin.

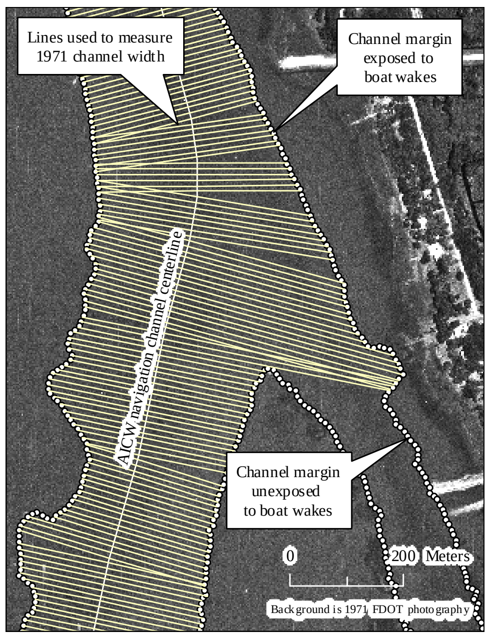


Figure 9: Determination of exposure to navigation channel boat wakes
and measurement of 1970/1971 channel width

The distance from the edge of the navigation channel, as defined by the location of United States Coast Guard navigation markers in 1999, to the channel margin was measured as displayed in Figure 10. This measurement serves as a third indicator of the influence of boat wakes on erosion rates. As with the channel width variable, points were assigned the measurement which intersected the channel margin closest to their location and points coded as unexposed to boat wakes were excluded. Erosion rates influenced by boat wakes can be expected to be highest where the navigation channel runs closest to the channel margin and wakes have the least time to dissipate.

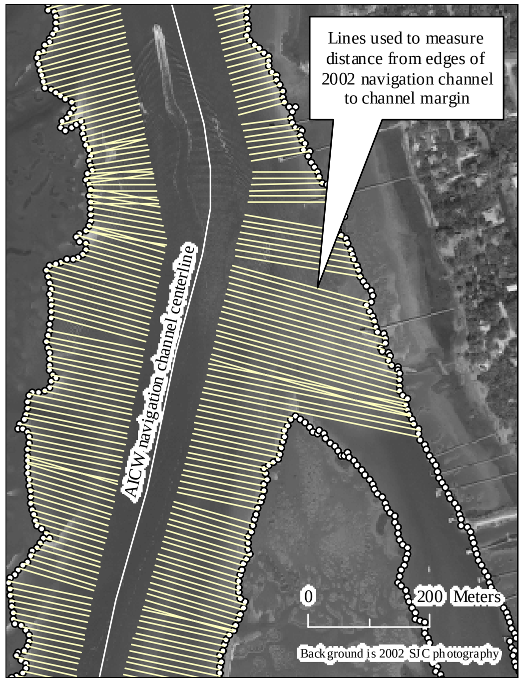


Figure 10: Measurement of distance from edge of 1999 navigation channel to channel margin

Points were coded 1, as exposed to tidal currents, if they were on the outside of one of the nine identifiable bends in the AICW channel in the study area. Points on the inside of bends or on straight reaches of margin were coded as 0. The radius of curvature, of all identifiable bends, was also recorded to serve as a secondary measure of erosion caused by tidal currents. The radius of curvature of a bend can be interpreted as the radius of the largest circle which fits the curve of a bend smoothly. In this study, Arc GIS software was used to fit an arc to each curve and determine its radius. In addition to these two indicators of tidal current-caused erosion, the bathymetric cross sections of the nine bends (taken from data provided by the St. Johns Water Management District) were examined for signs of active outer bank erosion, mainly a significant increase in depth towards the outside of the bend. Such erosion can be expected to be most severe in the tightest bends. Figure 11 shows an example of coding of the tidal current exposure variable and measurement of radius of curvature.

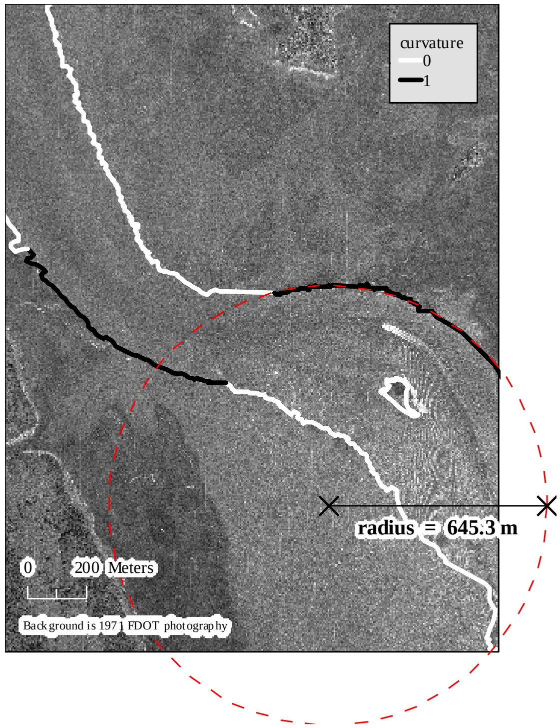


Figure 11: Coding of curvature variable and determination of radii of curvature

In addition to the variables discussed previously, the location of each point relative to the State Road 206 Bridge was also recorded as a binary variable to indicate presence or absence of dredging (south of bridge = 1, north = 0).

The 1970/1971 points, where lateral margin movement was measured, were analyzed to detect and examine relationships between accretion or erosion rate and each of the potential contributing factors in Table 2. Linear regression was used to examine the correlation between margin movement rates and causal factors measured on a continuous scale. The Kruskal-Wallis test, Tukey's studentized range test, and the Wilcoxon rank sum test were used to examine differences in rates of channel margin movement for independent variables measured on a categorical scale. All significant variables were entered into a multiple linear regression model to allow estimation of channel margin movement rates given different site characteristics. Kendall's Tau-b was calculated to overcome the weaknesses of least-squares regression as a measure of correlation between binary independent variables and a continuous response.

Results

Both polygon and point-based analysis techniques revealed high rates of channel margin erosion in the study area. Channel margins classified as intertidal bars, marsh, dredge spoil, and uplands all experienced net erosion. Channel margins classified as water were excluded from analyses due to the ambiguities involved in the interpretation of accretion and erosion of these areas. Exposure to wakes generated by vessels in the AICW was the causal factor most strongly correlated with higher rates of erosion. Detailed results of the polygon and point-based analyses further illustrate the extent of erosion and the relationship of erosion rates with causal factors.

Polygon-based analysis

The area of channel margin lost to erosion in the study area from 1970/1971 to 2002 was found to far exceed the area replaced through accretion. Instead of an accretion/erosion ratio of approximately 1 that would be expected in light of previous work (Letzsch & Frey, 1980), from 1970/1971 to 2002 the ratio of accretion to erosion in the study area was 0.13. The total tidal channel area, as defined by the digitized channel margins, expanded 11.4% from 656.0 hectares (1621.0 acres) in 1970/1971 to 730.7 hectares (1805.7 acres) in 2002. Excluding channel margins attributed as water, 68.2 hectares (168.6 acres) of marsh, intertidal bars, marsh, spoil areas, and uplands were lost to erosion and not replaced through accretion. These findings are summarized in Table 3 below.

Table 3: Summary of area eroded 1970/1971 to 2002

Margin classification	Proportion of margin length	Area in hectares [acres]					
		Erosion		Accretion		Net change	
intertidal bars	15%	21.0	[51.8]	0.1	[0.1]	-20.9	[-51.7]
marsh	42%	26.4	[65.2]	10.2	[25.2]	-16.2	[-40.1]
dredge spoil	33%	28.7	[71.0]	0.1	[0.2]	-28.7	[-70.8]
upland	10%	2.7	[6.7]	0.3	[0.8]	-2.4	[-6.0]
Total	100%	78.8	[219.1]	10.6	[26.2]	-68.2	[-168.6]

Point-based analysis

While information concerning the area of channel margin habitat eroded is useful in the evaluation of the ecological impacts of erosion, the approach used in this analysis obscures the impacts of specific causal factors. In order to discern the relative impact of individual potential causes, it is necessary to eliminate the spatial variability in exposure which occurs within individual polygons. Comparison of points along the channel margin in 1970/1971 and 2002 allows association of rates of change with discrete sets of causal factors. Table 4 summarizes the lateral erosion data obtained from point comparisons along all non-water margin types.

Table 4: Summary of lateral movement from 1970/1971 to 2002

Margin classification	Proportion of margin length	Count of measurement points	Mean linear movement (m)
intertidal bars	15%	870	-23.2
marsh	42%	2477	-9.3
dredge spoil	33%	1930	-16.7
upland	10%	613	-4.6
Total	100%	5890	-13.4

Comparison of Tables 3 and 4 reveals that although the largest loss to erosion in terms of area was from dredge spoil margins, intertidal bars were subject to a higher rate of lateral erosion. Upland areas experienced both the lowest level of loss of area and the lowest rate of lateral erosion. Marsh margins ranked third in both in terms of area eroded and lateral rate of movement. In Figure 12, rates of lateral erosion are depicted graphically according to margin classification.

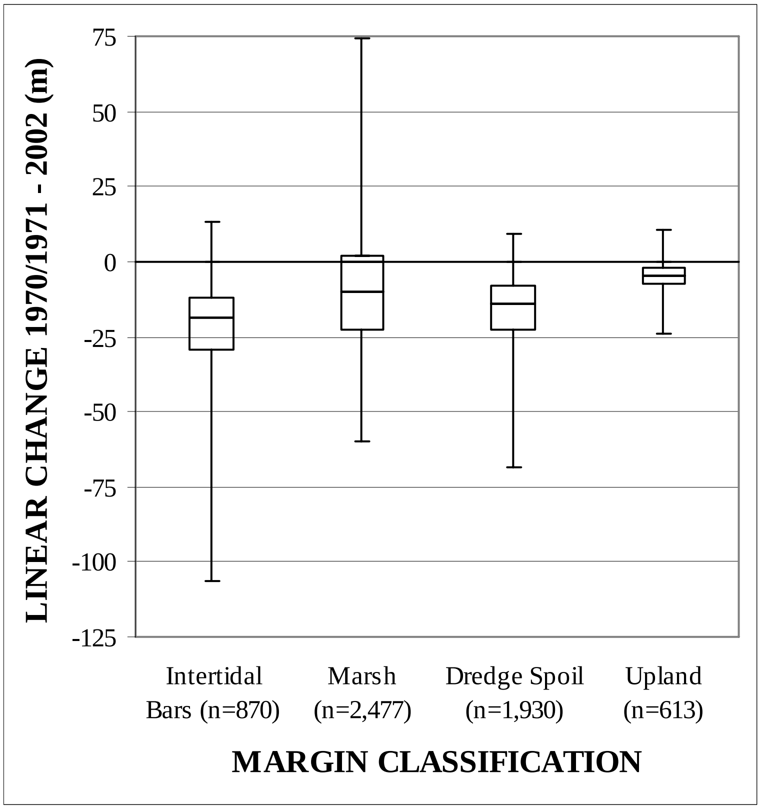


Figure 12: Minimum, maximum and quartile rates of lateral movement from 1970/1971 to 2002 classified by margin type

A Kruskal-Wallis test showed that the rate of channel margin movement of at least one of the margin classifications was significantly different ($p < 0.0001$) than the others. A subsequent Tukey's studentized range test was used to conduct pair-wise comparisons among all of the mean ranks of all of the margin classes. All comparisons showed significant differences ($p<0.05$).

Wilcoxon rank sum tests revealed significant differences ($p < 0.0001$) in the amount of lateral movement at points exposed and not exposed to both the AICW channel and waves generated by predominant winds. To discern the relative impact of these two factors, lateral rates of movement for points exposed to no significant causal factors, to only wind waves generated by predominant winds, to only boat wakes generated in the AICW channel and to both boat wakes and wind waves were compared. A Kruskal-Wallis test showed that the rate of movement for at least one of the causal factor combinations was significantly different ($p < 0.0001$) than the others. A Tukey's studentized range test revealed significant differences ($p<0.05$) in channel margin movement in all possible causal factor, pair-wise comparisons except the “exposed to no apparent causal factors” and the “exposed to wind waves only” categories (see dashed box in Figure 13). The fact that this comparison was not statistically significant may be associated with the relatively small sample size and limited fetch available at points exposed only to wind waves. These points were located along secondary channels and were protected from boat wakes and the longer fetch found in the AICW.

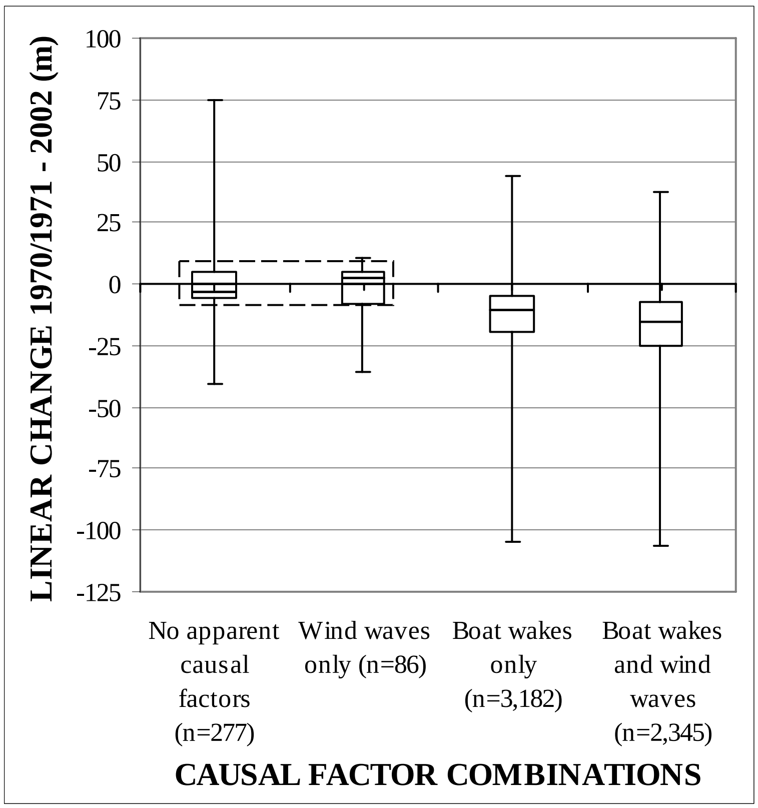


Figure 13: Minimum, maximum and quartile rates of lateral movement from 1970/1971 to 2002 classified by exposure to causal factors

In order to develop estimates of 1970/1971 to 2002 lateral movement, given variations in and interactions between margin type and exposure to causal factors, dichotomous variables for each margin type, for exposure to boat wakes generated in the AICW channel, and for exposure to wind waves generated by the predominant wind were entered into a least squares linear regression model (see Table 5).

Table 5: Regression of lateral movement on significant causal factors and margin type

Source	DF	F value	Pr > F
model	5	255.69	<0.0001
total	5889		
R-Square	0.18		

Variable	Coefficient	t value	Pr > |t|
intercept	8.30	8.57	<0.0001
intertidal bars	-17.56	-23.11	<0.0001
marsh	-5.65	-8.60	<0.0001
spoil	-10.88	-15.91	<0.0001
exposure to wind waves	-1.98	-5.04	<0.0001
exposure to boat wakes	-13.03	-16.29	<0.0001

All coefficients in this model are significant and the very large overall F-value reveals that the variance explained by the model is significantly greater than the variance due to model error. However, the R^2 value of 0.18 reveals that much of the variation in the rate of channel margin movement remains unexplained by the model. This unexplained variation may be due to the fact that the regression attempts to explain all of the variation in a continuous dependent variable with binary independent variables. It also could be a reflection of the use of blunt measures which do not capture small scale variation in bathymetry and sediment type, and thus do not precisely reflect the level of erosive energy at the channel margin.

Due to this unexplained variation, the model may not be suitable for predicting movement at individual points; however, it can be used to estimate mean rates of lateral movement based on exposure to causal factors and margin type. The data in Figure 14 were calculated using the regression coefficients. Mean rates of lateral movement for each exposure and margin combination, as estimated by the regression model, were multiplied by the total margin length. These products were then multiplied by the proportion of the entire margin classified as each margin type and as exposed to each combination of causal factors. The result is an estimate of the change in area of each margin type associated with each causal factor. This figure indicates that due to the number of points susceptible to boat wake erosion, the total loss in area associated with boat wake exposure is much greater than that associated with exposure to other factors.

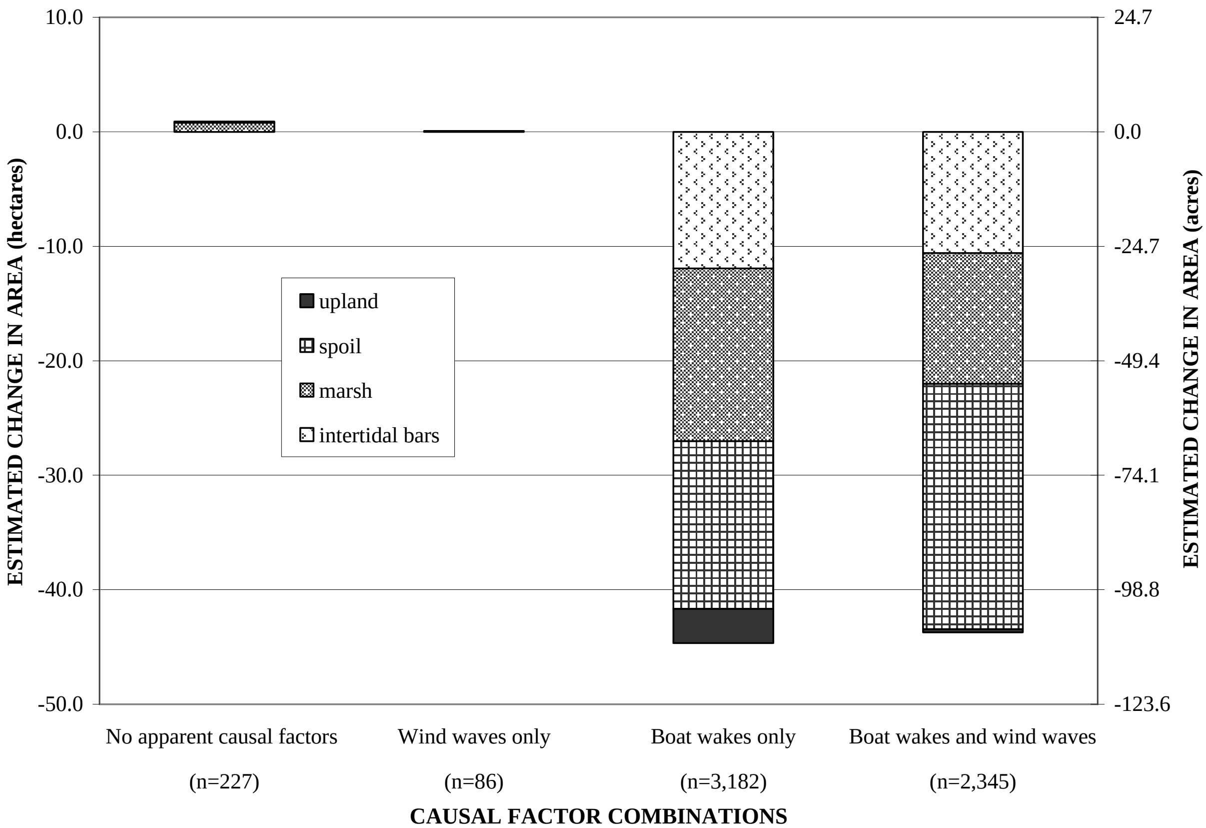


Figure 14: 1970/1971 to 2002 change in area estimated from rates of lateral movement

In order to circumvent the problem of the low explanatory power of the regression model resulting from the use of binary independent variables to explain a continuous dependent variable, the Kendall's Tau-b correlation coefficients were calculated for channel margin movement rate and all points exposed to each of the causal factor combinations (Table 6).

Table 6: Correlations of causal factors and channel margin movement

Variable	Kendall's Tau b coefficient	p value
exposure to wind waves	-0.14	<0.0001
exposure to boat wakes	-0.20	<0.0001

Kendall’s Tau-b can be interpreted as a measure of the percentage of variation in the dependent variable explained by the independent variable. While this non-parametric statistic is a more effective measure of correlation with binary independent variables than ordinary least-squares regression, it is limited in that it fails to account for interaction among the causal factors and the margin classification. It also does not help to overcome the coarseness in the measurement of the binary independent variables. These data constitute further evidence that simple exposure to boat wakes explains approximately 20% of the variation in channel margin movement.

Insignificant and marginally significant variables

Simple linear regression analysis revealed no significant correlations between channel margin movement and any of the three continuous causal variables, radius of curvature, distance from the 1999 AICW channel, and 1970/1971 channel width. A Wilcoxon rank sum test revealed no significant difference in the rates of movement for points coded as exposed or unexposed to significant tidal currents. Examination of bathymetric cross sections of the nine identifiable bends in the study area also provided no strong evidence of tidal current caused erosion.

The binary variable involving location relative to the State Road 206 Bridge, intended as an indicator of the impact of dredging, was found to be related to a small (2m over study period), but significant difference in margin movement. However, instead of erosion being more severe in dredged areas, it was actually less severe. There is no obvious explanation for this finding, but it could be related to the difference in the sediment type and level of shoreline stabilization in areas north and south of the bridge. The variable was not included in the final regression model because, although the coefficient was significant ($p<0.05$) its inclusion resulted in only a 0.0025 increase in the R^2 value.

Discussion

Channel margin erosion in the southern half of the GTMNERR from 1970/1971 to 2002 was severe and has most likely caused significant changes in the estuarine ecosystem. Lateral erosion was found to be significantly related to exposure to boat wakes generated in the AICW channel. Erosion was also found to be significantly related to exposure to wind waves generated by predominant winds; however, the effect of wind waves was significantly less than that of boat wakes.

The relatively low levels of correlation between the causal factors and erosion rates detected using linear regression and Kendall's Tau-b should not be viewed as an indication that boat wakes are not a primary cause of erosion. As stated, the reliance on binary variables and bluntness of measurement are two possible causes of the low R^2 of the regression model and these factors may also explain the relatively low Kendall's Tau-b coefficients.

A process of elimination of the likely causal factors also implicates boat wakes as the most significant cause of erosion. Because more erosion was estimated to have occurred in areas not exposed to waves generated by the predominant wind than in areas exposed to these wind waves, wind waves cannot be assumed to be the main cause of erosion. Since curvature was not significantly correlated with erosion rates and visual analysis of erosion patterns and bathymetric cross-sections did not reveal significant evidence of meander migration, currents can be rejected as a cause of erosion. The slightly lower rate of erosion in dredged areas south of the State Road 206 Bridge, suggests that dredging, too, does not exacerbated erosive processes.

Variation in sediment type, as indicated by channel margin classification, significantly influences erosion rates, but is not, in itself, a cause of erosion. Finally, biological change does not appear to be a major factor in high erosion rates because erosion was found to have occurred in all channel margin classification categories. This leaves boat wakes as the primary causal factor of erosion in the reserve. As displayed in Figure 14, above, the widespread susceptibility to boat wakes, alone, demonstrates the potential for vessel traffic to contribute significantly to erosion.

Further Research

Further research on channel margin erosion in the GTMNERR can take two main directions: (1) application of the methods used in this study to other areas of the reserve or other time periods or (2) a more in-depth study in the current study area aimed at establishing a stronger correlation between causal factors and erosion rates. Work using present methods could make use of photography from the 1990s, 1980s, 1970s, and 1940s and possibly T-sheet maps created by the United States Coast Survey in the early 1870s before the AICW was created. Such studies could also be extended to cover the northern portion of the reserve. More in-depth work aimed at establishing a stronger causal correlation could involve field measurement of wave energy and an attempt to correlate wave energy with fetch, nearshore bathymetric profile, local sediment type, and erosion rates. Such a study could develop a comparison of the net volumes of sediment transported by relatively small but frequent wind waves and larger but less frequent boat wakes.

In light of the evidence which suggests that overall high levels of erosion in the GTMNERR are related to exposure to boat wakes, the following chapter discusses strategies for managing erosion due to wake impacts.

CHAPTER 2

EROSION MANAGEMENT ALTERNATIVES

Introduction

Erosion management in coastal areas is most frequently discussed in relation to beach erosion. While the processes of beach and inshore channel margin erosion are similar, the low energy inshore environment and the distinct management goals make options which are generally undesirable in beach settings quite viable for inshore shoreline protection. With implementation in mind, methods of inshore erosion management are best grouped into two classes: (1) regulation-based alternatives, which address the cause of erosive forces and (2) stabilization-based alternatives, which address the effect of erosive forces. In the case of beach erosion, the human causes of erosion, frequently inlet stabilization, are often too firmly established to allow for regulatory management. Along inland waterways the main controllable cause of channel margin erosion is wake-producing vessel traffic. While dredging activity is also controllable, dredging does not presently appear to be a major cause of erosion in the GTMNERR. Regulatory options for erosion control in the GTMNERR must involve the regulation of navigational activities. Stabilization options include structural and non-structural measures. Structural stabilization includes the construction of physical structures, while nonstructural alternatives involve moving sediment or increasing natural stabilization. While structural options can exacerbate erosion and interrupt longshore sediment transport on a beach, they are less detrimental when used in controlling inshore erosion. The selection of erosion control strategies most well suited for use in an area depends mainly on the goal of erosion management in the locale.

The Goals of Inshore Erosion Management

Inshore erosion in the GTMNERR is an issue of concern because erosive processes are altering ecosystems of economic and environmental importance. The goal of erosion management activities depends to some degree on what interests are being represented. For example, pleasure boaters, fishermen, and waterfront homeowners may each have different feelings from one another, regarding erosion management. In order to develop a strong erosion management plan, it is important to involve all concerned parties. Not only is this type of planning process essential to ensure public acceptance of a management plan, it will also help to gain the cooperation of owners of submerged land in any stabilization efforts and will ease the enforcement of any regulation of boating activity. Given the necessary involvement of these and other local interests, a suitable management goal would be to "minimize channel margin erosion to the extent necessary to allow the recovery of altered shoreline and nearshore ecosystems, while accommodating the needs of diverse local interests to the extent possible." As evidence suggests, increased channel margin wave energy levels are the main cause of erosion in the GTMNERR; the key to limiting erosion is decreasing these energy levels. Achieving such a decrease on a scale as large as the entire GTMNERR is likely to involve the incorporation of both stabilization and regulation.

Stabilization Based Alternatives

As mentioned, stabilization based options include structural and non-structural measures. Non-structural strategies include less permanent structures which commonly make use of vegetation and other naturally occurring material. Structural measures involve the construction of permanent stabilization works. Both types of stabilization have advantages and disadvantages.

Non-structural, or soft, stabilization options are probably the most widely promoted and possibly the most widely used means of controlling inshore erosion. They are intended to physically resist erosive forces by stabilizing shoreline sediments. In estuaries, some of the first tools of those planning soft stabilization efforts are the organisms which naturally provide stabilization— the marsh grass, *Spartina alterniflora* (Knutson & Woodhouse, 1983), and oyster shells (Meyer, Townsend, & Thayer, 1997). The most obvious shortcoming of these strategies is the fact that they rely on the same biota that are being impacted by erosion to provide stability. If well-established marsh grasses and oyster bars are being eroded, then it is unlikely that new plantings of either will establish themselves before they, too, are eroded away. Stabilizing only the shoreline also fails to protect nearshore habitat, such as oyster bars, from increased wave energy.

Two studies which recognize the impermanence of vegetative plantings in areas of elevated wave energy are the works of Broome, Rogers & Seneca (1992) and Rogers (1994). Both of these reports provide extensive discussions of the combined use of vegetation and low cost, wooden breakwaters in controlling erosion in a North Carolina estuary. Breakwaters are structures built in the water, parallel to an eroding shoreline for the purpose of reducing wave energy. They present the main structural option for controlling erosion in the GTMNERR. Erosion control structures, such as groins and jetties, which are built perpendicular to the shoreline, are of little use in the inshore environment because these structures are designed to reduce longshore transport of sediment rather than to reduce wave energy.

With a few exceptions, breakwaters are a type of permanent stabilization, usually built from wood or stone. They extend from the bottom of a body of water to just below or well above the surface of the water. In addition to protecting shorelines, breakwaters also provide a hard substrate for the attachment of oysters and a refuge and foraging ground for fish. However, they have the potential to have unintended adverse effects on sedimentation or other ecological processes, and so they should be pilot tested before construction and used with caution. According to Dale Campbell, of the USCOE Panama City office, stone breakwaters are often opposed by boaters because of the potential hazards they pose to those who inadvertently leave the marked navigation channel (personal communication, September 10, 2004).

One example of a nonpermanent breakwater is the new product called WhisprWave®, developed by Wave Dispersion Technologies, Inc.. This structure is a floating plastic breakwater, which serves the same purpose as a permanent breakwater but has the advantages of being quicker to install and easier to relocate. Such a structure would also have the advantage of being less damaging in case of a vessel impact.

An example of a large, traditional, inshore breakwater project is offered by the 11,700 foot long stone breakwater constructed in Louisiana to protect eroding marshes bordering the Gulf Intracoastal Waterway from wake damage (Louisiana Coastal Wetlands Conservation and Restoration Task Force, 2001). An example from Florida, involving the same regulatory agencies which would be involved in a stabilization project in the GTMNERR, is Project Green Shores in Pensacola (Florida Department of Environmental Protection, 2005) (Figure 15).

Figure 15: Project Greenshores in Pensacola, Florida

While these projects are expected to significantly decrease marsh loss to erosion, they are costly. The Louisiana project cost about $137 per linear foot of breakwater. Although this cost also includes construction of stone terraces, to reduce available fetch in a portion of the protected marsh, building a similar protective structure for only half of the study area would cost about $15 million. Breakwater construction at lower cost has been shown to be possible.

In both coastal Louisiana (Steller, 1991) and Italy's Venice Lagoon (Scarton, Cecconi, Are, Day, & Rismondo, 2000), an innovative technique has been used to construct fence-type breakwaters from wood and brush. Both of these projects involved the construction of a sort of wooden bin between posts set into the bottom. In Italy, the fences were filled with willow and poplar bundles. In Louisiana, the fences were filled with discarded Christmas trees. This innovative reuse effort won a participating parish a national award for environmental sustainability (Kratch, 1996). High levels of volunteer participation resulted in the construction of 7,000 meters of fence for only $190,000 in 1991. The obvious drawback of these less costly fences is their durability. The breakwater in Italy received severe damage during a storm and a large portion of the sediment which had accumulated behind it was lost. Before construction of this type of breakwater, careful study should be undertaken to determine if the low cost is worth the lower durability and resulting higher maintenance costs. It is possible that a breakwater of this design could be an excellent pilot project to study the effects of breakwaters on local erosion rates before construction of a more permanent structure.

The high cost and potential adverse ecological impacts associated with stabilization, such as breakwaters, makes it unlikely that a significant portion of the GTMNERR channel margin environment will ever be protected by structures. This emphasizes the need for regulatory protective strategies.

Regulation Based Strategies

Regulation-based erosion management strategies address the cause of erosion without permanent physical alteration of the nearshore ecosystem. These strategies focus primarily on the reduction of boat wakes. The role of boat wakes in channel margin erosion rates can be expected to increase as the level of boat traffic in the reserve increases. There has been increase in boat registration in St. Johns and Flagler counties of over 400% since 1977 (Figure 16).

Boat traffic can be regulated in several ways to reduce margin erosion caused by wakes. As previously stated, factors influencing the erosive impact of boat wakes include the size of the wake, the water depth, the current direction and velocity, the morphology of the impacted bank, the presence of wind waves, and the distance of the vessel from the shore (Macfarlane & Renilson, 1999). Factors which can potentially be regulated include the distance of vessels from shore and factors such as vessel speed, hull form, draft, loading and trim which influence the size of the wake.

Vessel speed and distance from shore are the most obvious opportunities for regulation. Development of precise regulations may need to be supported by additional research linking wakes to habitat degradation in the GTMNERR. Such research would also help to clarify which vessels and what activities should be regulated. For example, is it more important to regulate less common displacement-hulled vessels that produce huge wakes or more common planing vessels that produce smaller wakes? Although such studies have been conducted elsewhere (Wilcox, n.d.), it is important to understand the impacts of the specific distribution of vessel types found in the GTMNERR.

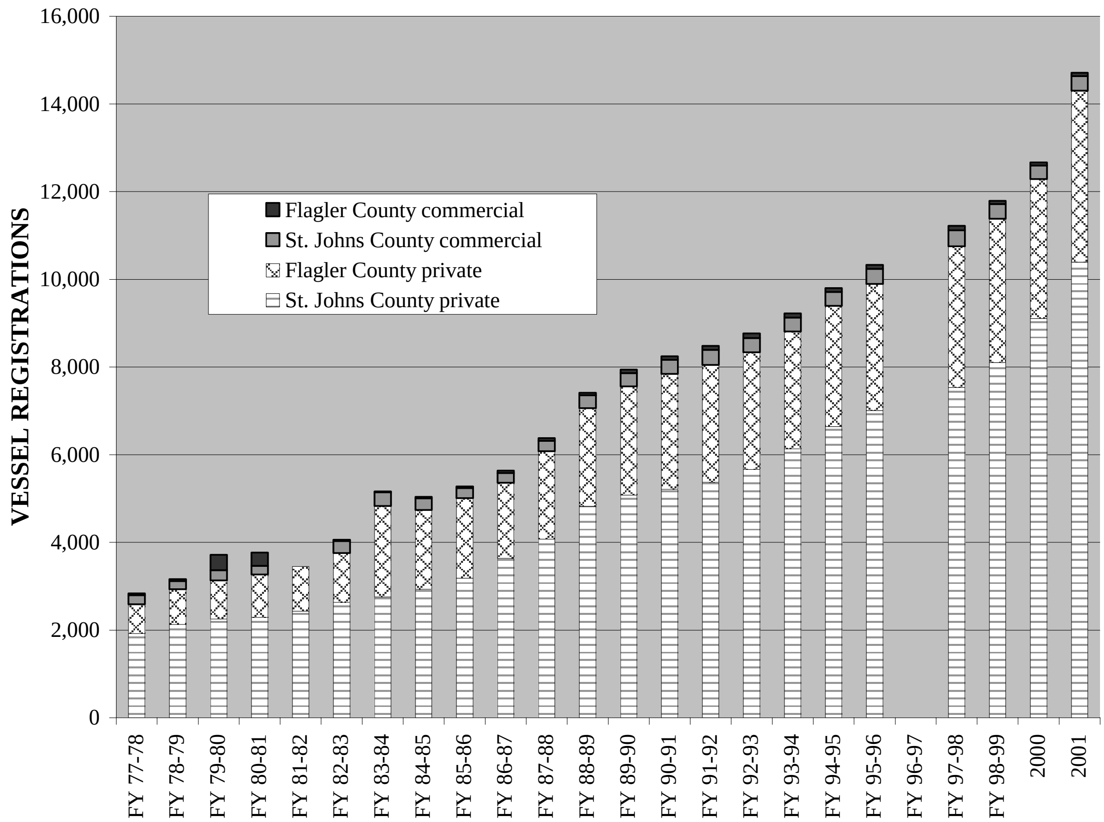


Figure 16: Boat registrations in Flagler and St. Johns Counties, 1977 to 2001
(Florida Statistical Abstract, 1977-2001)

Implementation of both stabilization-based plans and regulation-based plans will require significant planning. Before such a planning effort is undertaken, an attempt should be made to establish which private and governmental entities will need to be involved in the implementation process.

CHAPTER 3

POLICY GOVERNING IMPLEMENTATION OF MANAGEMENT ALTERNATIVES

Introduction

Given the evidence which implicates wakes from boat traffic as the primary factor in the observed channel margin erosion in the GTMNERR and the preceding discussion of possible measures which could be used to mitigate the effects of navigation on the AICW, it is useful to understand how such measures could be implemented. The options for implementation of stabilization plans and regulation plans differ considerably. Implementation of stabilization plans involves public participation and environmental permitting, while implementation of regulation is mainly a matter of law enforcement.

Implementation of Stabilization Plans

Implementation of stabilization plans is complicated by the fact that the AICW in the GTMNERR is constructed in waters of the United States within a right-of-way, composed of federally owned easements on state and private land. Although shoreline protection is a permitted activity for property owners within the right-of-way, a large scale public margin stabilization project, partially on private land, would be an involved process.

First, the project must be permitted under applicable federal and state regulations. Federal permitting authority to regulate construction in waters of the AICW stems from two main sources, Section 404 of the Clean Water Act (2005) and Section 10 of the Rivers and Harbors Act (2005). The Clean Water Act regulates placement of any type of fill, including materials used to build stabilization works, in the navigable waters of the United States. The Rivers and Harbors Act applies to projects which have the potential to obstruct navigation in the navigable waters of the United States. The USCOE is charged with the implementation of both of these statutes. If federal funding is used in the completion of a project or a federal permit is issued, completion of an Environmental Impact Statement, in compliance with the National Environmental Policy Act (2005), may also be required.

The State of Florida maintains an Environmental Resource Permitting (ERP) system, independent of the federal system. The ERP system, which is implemented by the Florida Department of Environmental Protection and the Florida Water Management Districts, regulates most major land alterations within the state including projects involving dredging and filling of waters or wetlands. Statutory authorization of the ERP program to regulate activity in wetlands is contained in Part IV of Chapter 373 of the Florida Statutes (2004). Issuance of an ERP permit from the state certifies not only that a project is compliant with state wetlands regulations, but also that it is consistent with the goals of the Florida Coastal Zone Management Program (Coastal Planning and Management, 2004). Although the USCOE issued a Statewide Programmatic General Permit to the State of Florida to avoid duplication in federal and state permitting procedures, regulation of breakwaters is specifically excluded from the scope of this permit (State of Florida, n.d.). Separate applications to the USCOE and the state are required to ensure compliance with the Clean Water Act (2005) and the Rivers and Harbors Act (2005). As nearshore and shoreline stabilization projects have been constructed in Florida (Florida Department of Environmental Protection, 2005), meeting the federal and state requirements is clearly possible with proper project design.

In addition to regulatory permits, proprietary authorization must also be obtained from involved parties. If the work is to take place within the AICW right-of-way, then the USCOE Real Estate Branch must authorize the use of an easement. If the work is to take place on submerged lands owned by the State of Florida, the state must issue a proprietary authorization for use as required in Chapter 253 of the Florida Statutes (2004). If the work is to take place on privately owned lands, consent must also be obtained from these land owners. According to David Roach, of the Florida Inland Navigation District (personal communication, January, 2005), the owners of the AICW right-of-way retain all rights to the land except those interfering with the navigation project. Once the consent of property owners and the USCOE Real Estate Branch is obtained and all applicable permits are acquired, construction can begin.

Implementation of Regulation Plans

Implementation of new navigation regulations is mainly a matter of enforcement, which is discussed below under Regulation of Navigation. Before discussing the implementation of a new set of regulations, it is important to understand the existing regulatory framework which establishes and supports the right to inshore navigation in the AICW.

<u>The Right to Inshore Navigation in Florida</u>

In Florida, and the United States as a whole, the right to navigate is protected by expressions of the Public Trust Doctrine which is rooted in the Roman Code of Justinian (Robert Deyle, personal communication, March, 2005) under which publicly useful bodies of water are preserved as public property. In Florida this authority is defined in a constitutional provision (FL Const. art. X, § 11) which declares that land beneath navigable waters is to be publicly held, and not for sale (Reimer, 2001). Navigable water bodies are defined in case law as any bodies, which in 1845, at the time of statehood, were "capable of being used" for transportation. The ordinary high water line defines the extent of public ownership. In the case of saltwater bodies, this high water line is statutorily defined as the "mean high water line," a location that can be established from local tidal gages (Reimer, 2001). The Atlantic Intracoastal Waterway, which is of particular concern, is a federal waterway, and so the right to navigation is based on federal navigational servitude as established in the Commerce Clause of the United States Constitution (U.S. Const. art. I, §8). As demonstrated, the right to navigate is firmly based in both the federal and state constitutions.

<u>Support of Inshore Navigation</u>

Governmental support of navigation mainly consists of developing, marking, and maintaining inshore channels. The 1927 Rivers and Harbors Act (2005) assigned the federal government the role of constructing and maintaining the navigation channel of the Intracoastal Waterway (Florida Inland Navigation District, 1967a). The USCOE is assigned the responsibility for the physical construction work and for cooperating with state and local authorities in planning and project development (Florida Inland Navigation District, 2002).

In Florida, the Florida Inland Navigation District (FIND), established by the state legislature as an independent special district in 1927, helps to provide necessary rights-of-ways and land for channel dredging spoil disposal areas, to the federal government, free of charge (Florida Inland Navigation District, 2002). FIND is composed of eleven Florida east coast counties: Duval, St. Johns, Flagler, Volusia, Brevard, Indian River, St. Lucie, Martin, Palm

Beach, Broward, and Miami-Dade. The district is governed by an eleven member Board of Commissioners, one from each county in the district, appointed by the Governor (Florida Inland Navigation District, 2002). According to Franklin Morrison, with the Jacksonville District of the USCOE, the local port authorities cooperate with both the USCOE and FIND in funding local navigational projects and the acquisition of dredge material management sites (personal communication, November 20, 2003). Supported by an array of state and federal legislation, the channel of the Intracoastal Waterway forms the backbone of inland marine navigation along Florida's east coast.

Regulation of Navigational Activities

Once the right to navigate is established and the creation and maintenance of a waterway, which can support modern navigation, is ensured, the conditions are such that the environmental conflicts begin to occur. As boat traffic on Florida's waterways continues to increase, the need to regulate boating in order to moderate environmental degradation will increase. Federal, state, and local authorities share an interest in the regulation of marine navigation, but the legal authority of these entities to enact such regulation differs substantially.

Federal Regulation

The ability of the federal government to regulate marine navigation is established jointly in the Commerce Clause of the United States Constitution, previously cited as establishing the federal right to navigation, and the Property Clause of the Constitution (U.S. Const. art. IV, §3). The Commerce Clause gives the government the right to regulate maritime activity in waters of the United States based on the "federal navigational servitude" and this basis for regulation has been supported by the courts (Gibbons v. Ogden, 1984). The authority to restrict navigation based on the reasoning that the U.S. has the right to make rules governing conduct on federal property and adjacent non-federal property, as described in the Property Clause, has also been upheld (McGrail v. Babbitt, 1997). The implementation of these constitutional authorities has been delegated to a number of federal agencies.

Brooks (2000) discusses six federal agencies with potential power to regulate navigation in Florida waters, the United States Coast Guard (USCG), the USCOE, the Fish and Wildlife Service (USFWS), the National Marine Fisheries Service (NMFS), the National Park Service

(NPS), and NOAA. The powers of NOAA and the NPS are restricted to national marine sanctuaries and national parks, respectively (Brooks, 2000). Although the Fort Matanzas National Monument borders the study area, its small size makes any regulation within its boundaries insignificant in terms of protecting the resources of the GTMNERR as a whole. While the GTMNERR is administered jointly by NOAA and the State of Florida, it is not a marine sanctuary, and thus NOAA is also unlikely to have significant regulatory authority over activities in the reserve. The USFWS and the NMFS derive broad authority from the Endangered Species Act (2005) and the Marine Mammal Protection Act (2005) to regulate activity which may impact endangered species or marine mammals. This authority has been largely delegated to the State of Florida, which makes use of it in regulation of boating activities for the protection of the West Indian Manatee (Florida Manatee Sanctuary Act, 2004). However, regulation related to endangered species does not appear to have immediate application to the current issue of channel margin protection. The power of the USCOE to restrict navigation is generally limited to issues of military operations and national security (Brooks, 2000). The limitations on the previously discussed agencies leave the USCG as the federal body with the most power to affect meaningful regulation within the GTMNERR. The Coast Guard has authority to restrict vessels operating in the navigable waters of the United States for "environmental purposes" (Ports and Waterways Safety Program, 2005) and to restrict vessels from "safety zones" for safety or environmental purposes (Navigation and Navigable Water Rule, 2005).

State Regulation

State regulation of inshore navigation in Florida is accomplished through the statutory grant of police powers and the Public Trust Doctrine, as defined in the State Constitution (FL Const. art. X, §11). Such regulation is implemented by the Board of Trustees of the Internal Improvement Trust Fund, the Florida Fish and Wildlife Conservation Commission (FWCC), and the Florida Department of Environmental Protection (FDEP). However, only the FWCC and FDEP have power to restrict navigation for environmental purposes.

The FWCC uses its statutory authority, under the Florida Manatee Sanctuary Act (2004), to restrict and exclude vessels to ensure manatee protection. This authority has been upheld in court (Marine Industries Ass'n of South Florida, Inc. v. FDEP, 1996). Perhaps this power has the potential to be extended to ensure the protection of other environmental entities.

The FDEP has the authority to restrict motorized watercraft within state-defined canoe trails (Recreational Trails System, 2004), but at this time there are no such trails within the study area.

Local Regulation

Local governments in Florida, through exercise of their police power, have the authority to restrict the operation of vessels, within water bodies in their jurisdiction, through local law or ordinance. These local regulations cannot conflict directly with state or federal laws and cannot pertain to vessels operating within the AICW (Vessel Safety, 2004).

The restriction on local laws regulating activities in the Intracoastal Waterway makes significant local regulation of inshore boating activity along much of Florida's east coast very difficult. Particularly in regions such as northern Flagler County or southern St. Johns County, where practically all inshore navigation takes place in the Waterway, local governments are left with few means to restrict boating activity. In situations such as these, any significant restriction on navigation on the AICW will have to occur on the federal or state level.

CONCLUSION

Erosion along the margin of the Atlantic Intracoastal Waterway channel in the Guana Tolomato Matanzas Estuarine Research Reserve is drastically altering nearshore habitat and resulting in substantial ecological degradation. From 1970/1971 to 2002 nearly 70 hectares (170 acres) of nearshore intertidal bars, marsh, dredge spoil disposal areas, and uplands have been lost to erosion. Analysis of erosive trends suggests that increased nearshore wave energy caused by boat wakes is the primary cause of this erosion; however, further research may be necessary to accurately relate wake energy to erosion rates. Such work should be followed by the development and implementation of a plan intended to address the problem of erosion.

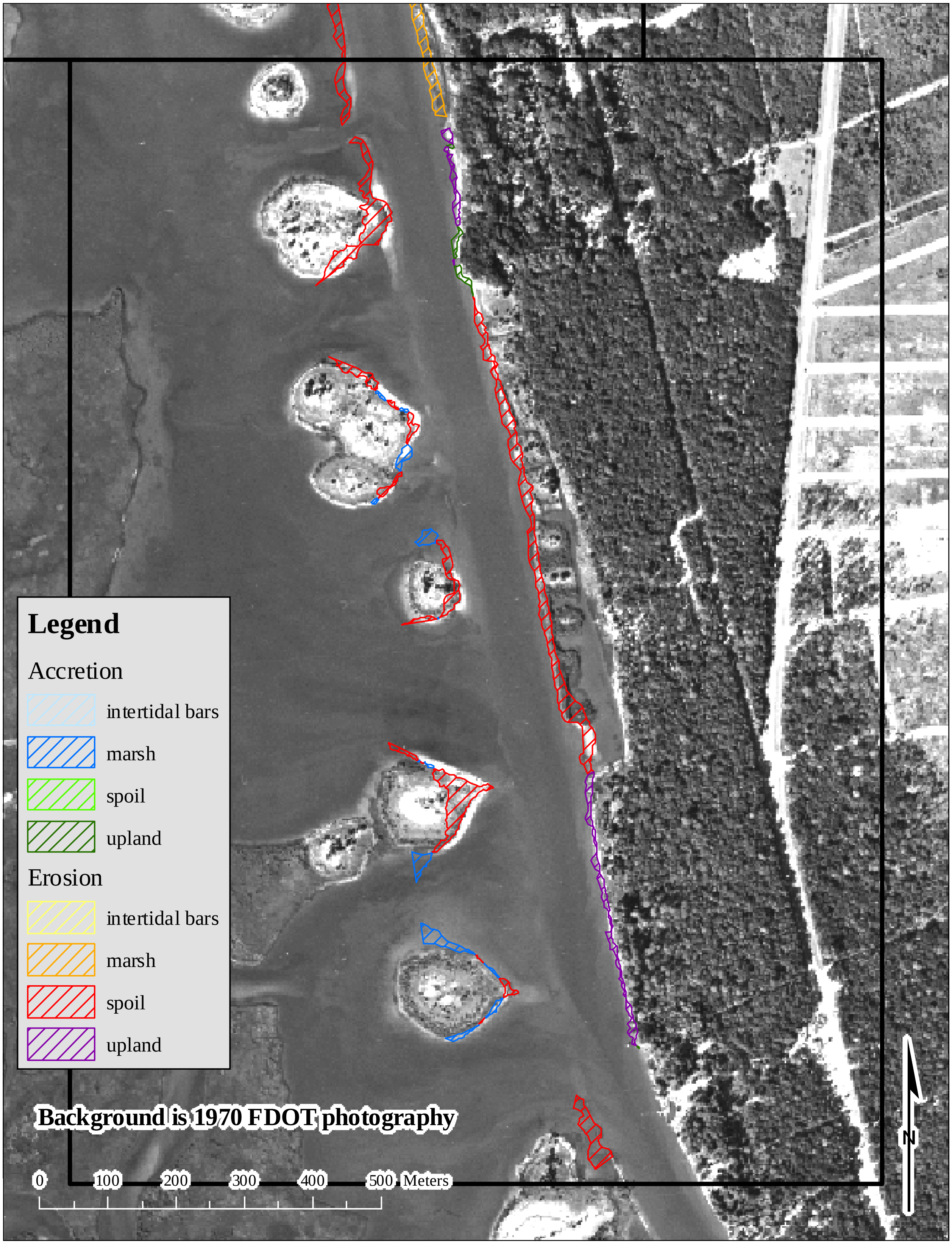
A management plan developed to address the problem of margin erosion in the GTMNERR should focus primarily on minimizing nearshore wave energy levels and perhaps using nearshore stabilization techniques as a remediation tool where impacts have been most severe. Regulation of navigation on the Intracoastal Waterway would most likely be implemented by the State of Florida and thus involve enforcement by the Florida Fish and Wildlife Conservation Commission. As no clear statutory authority for such regulation exists, extension of existing legislation or introduction of new state legislation may be necessary. Implementation of the stabilization portion of such a plan would involve meeting federal and state permitting requirements and obtaining the consent of involved land owners. Failure to implement such a plan is likely to allow current rates of habitat degradation to continue and, therefore, has the potential to undermine the intent of the GTMNERR as a National Estuarine Research Reserve (National Estuarine Research Reserve System, 2005(b)).

GLOSSARY

accretion	The process of accumulation of sediment deposited by wind or water
accretion polygons	A closed, two-dimensional figure with at least three sides representing an area where accretion has occurred
aggradation	The process of a vertical increase in the elevation of a landform due to sediment deposition
AICW	Atlantic Intracoastal Waterway
allochthonous sediment	Sediment introduced from outside the system
autochthonous sediment	Sediment generated within the system
bathymetric profile	A cross section showing the elevation of the bottom of a body of water
bioturbation	Disruption caused by biological activity
erosion	Removal of sediment by wind or water
erosion polygons	A closed, two-dimensional figure with at least three sides that represents an area where erosion has occurred
eustatic sea level rise	A worldwide fluctuation in sea-level; as opposed to local or regional change
fetch	The distance wind blows across the surface of a body of water to generate waves
GTMNERR	Guana Tolomato Matanzas National Estuarine Research Reserve
longshore sediment transport	The physical movement of sediment along a shoreline by currents running parallel to the shore
NERR	National Estuarine Research Reserve
organic aggregates	Macroscopic particulate matter of biological origin
predation	An interaction which involves one organism eating another
rhizomatic mat	A structure formed by the interwoven underground stems of plants
riverine	Of or related to a river
subsidence	The decrease in the elevation of a landform
surface accretion	Synonymous with aggradation
tidal prism	The difference in the volume of water in a body between high and low tides
trophic structure	The network of interrelationships in a biological community based on the transfer of energy

APPENDIX

Figure 17: Index of plates



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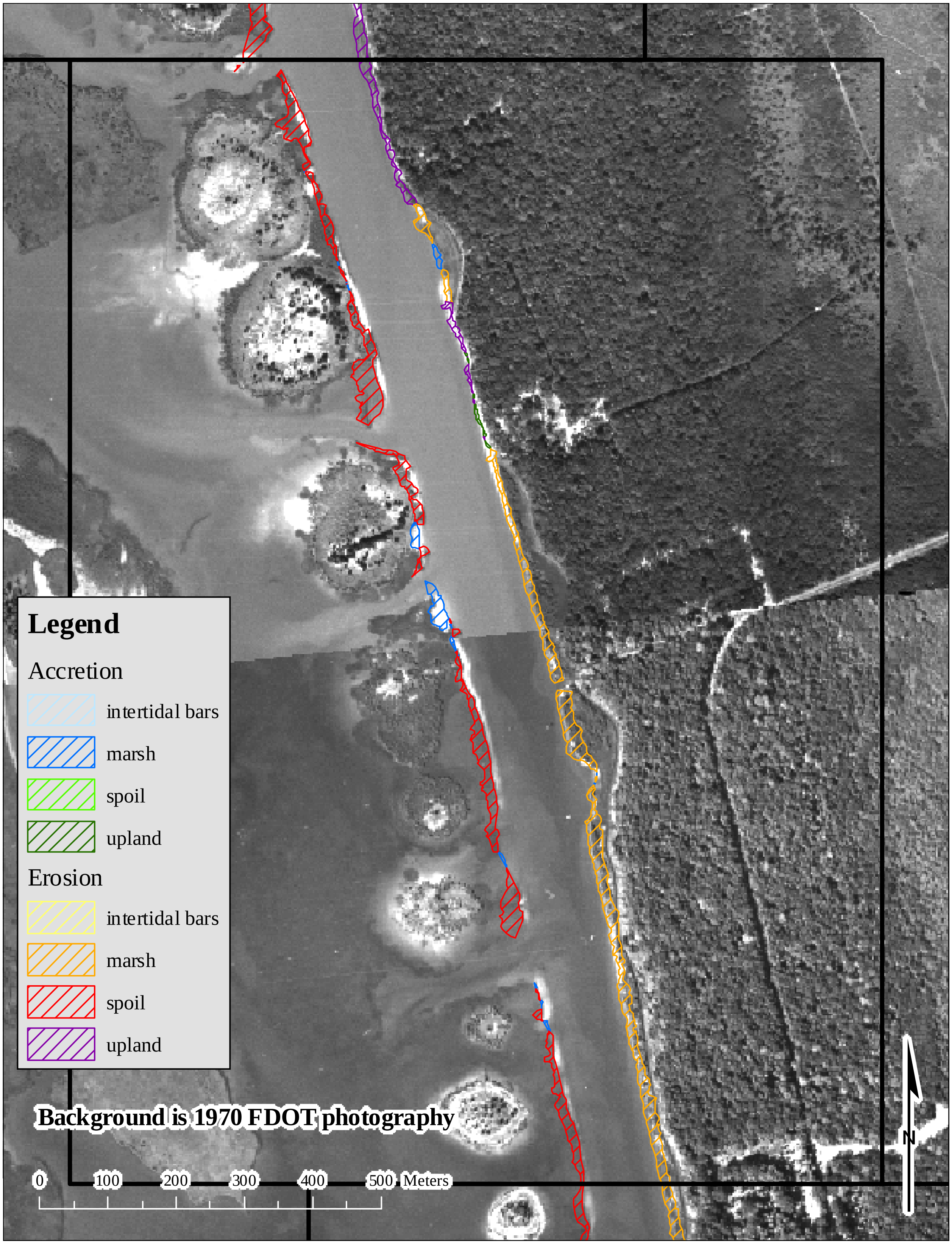

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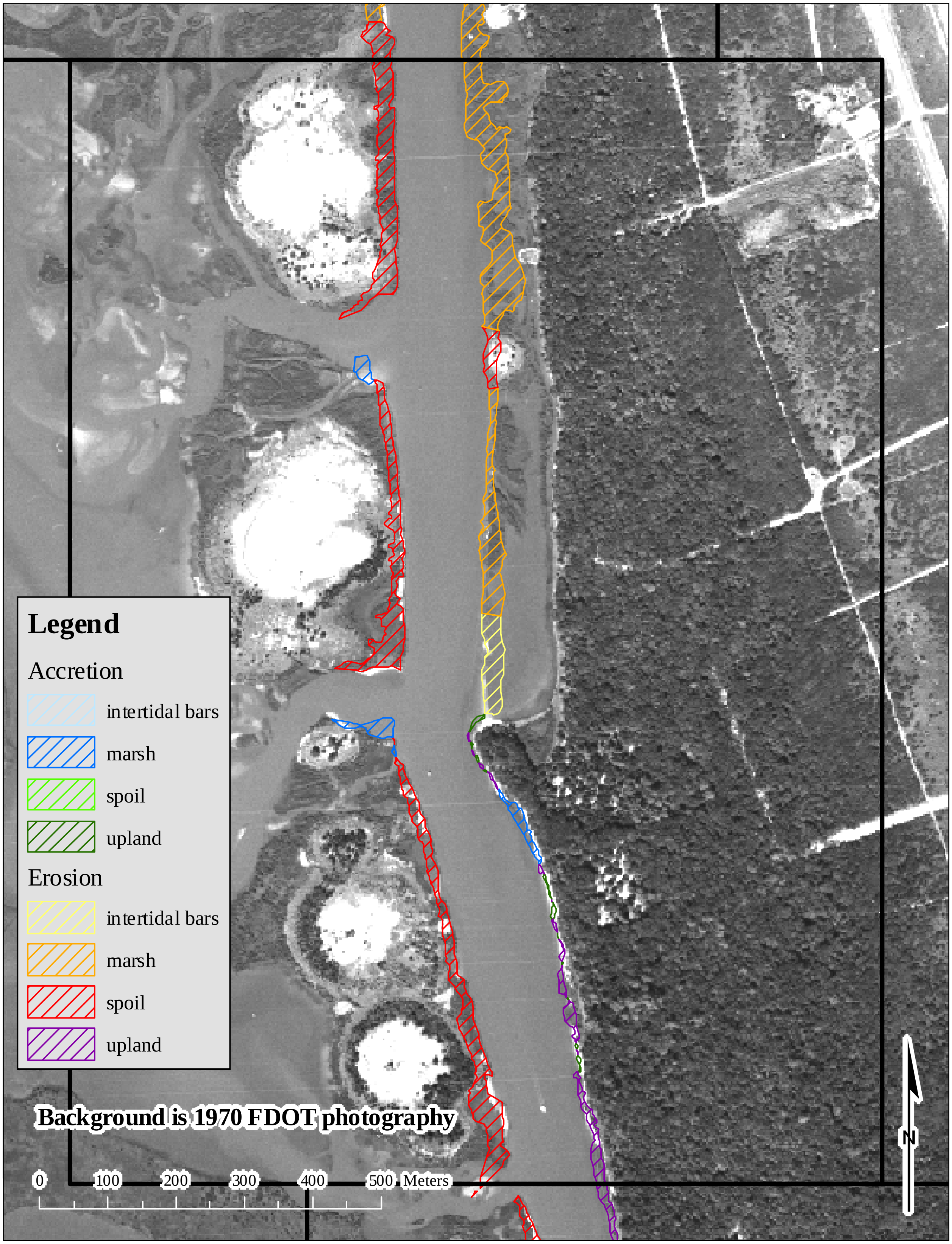

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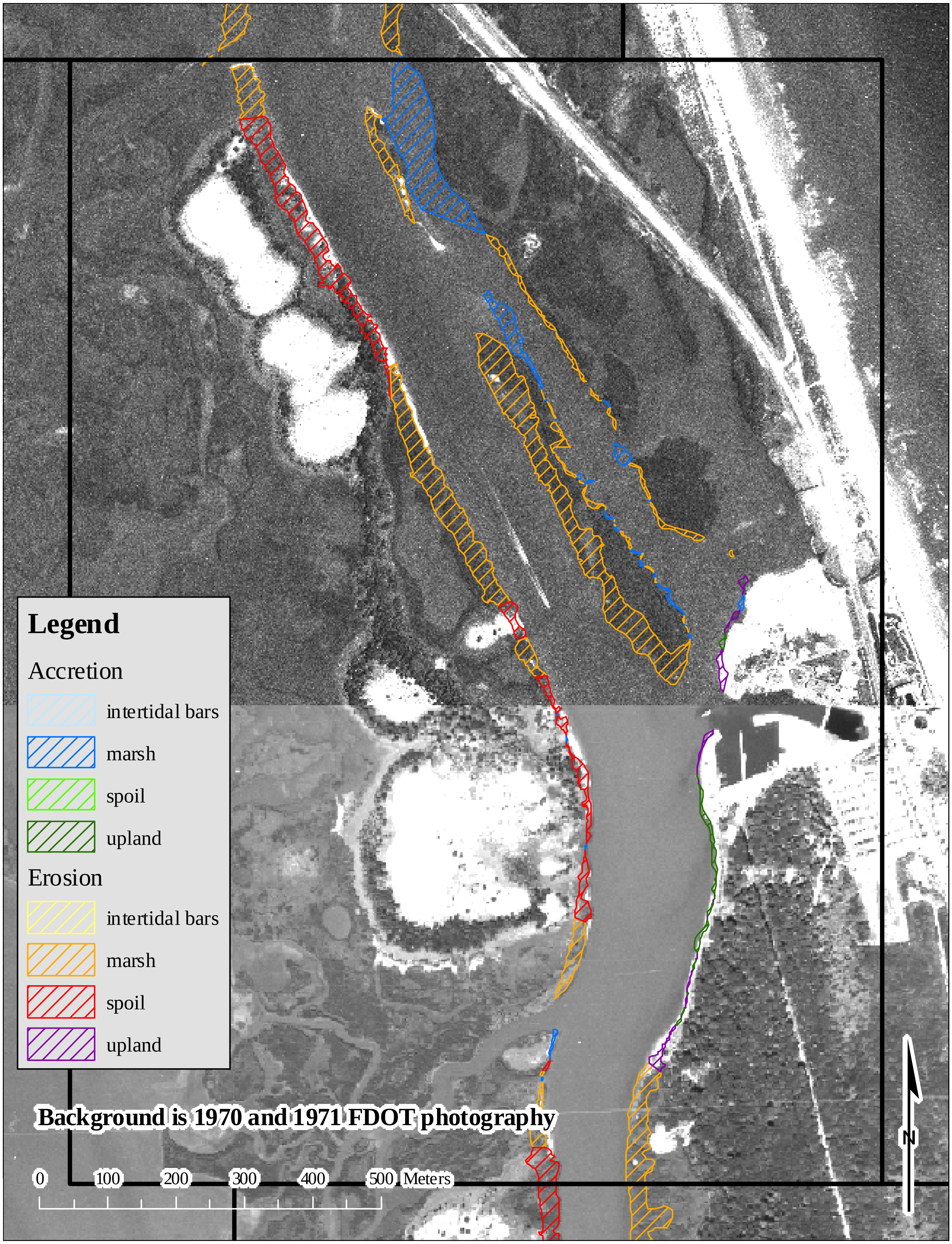

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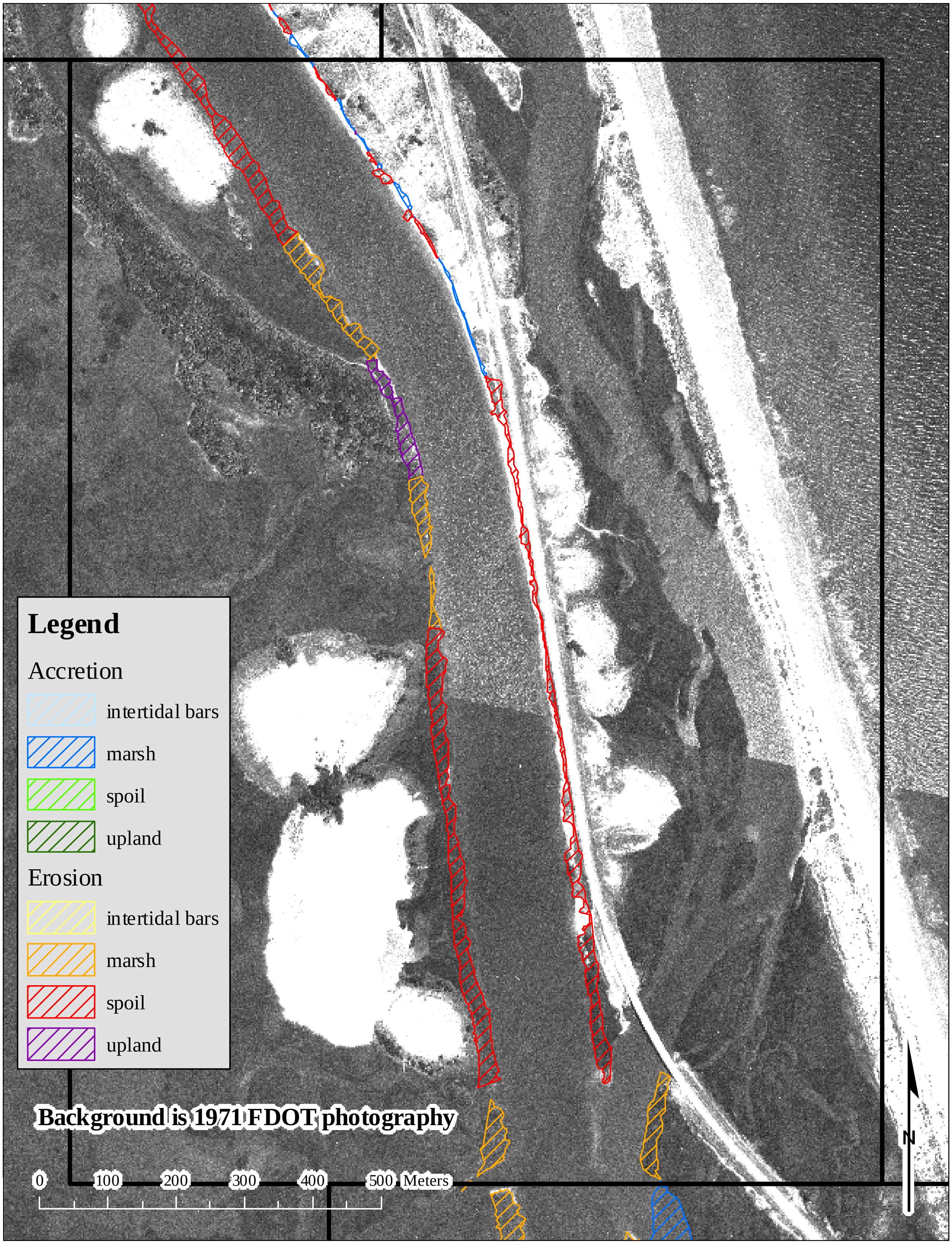

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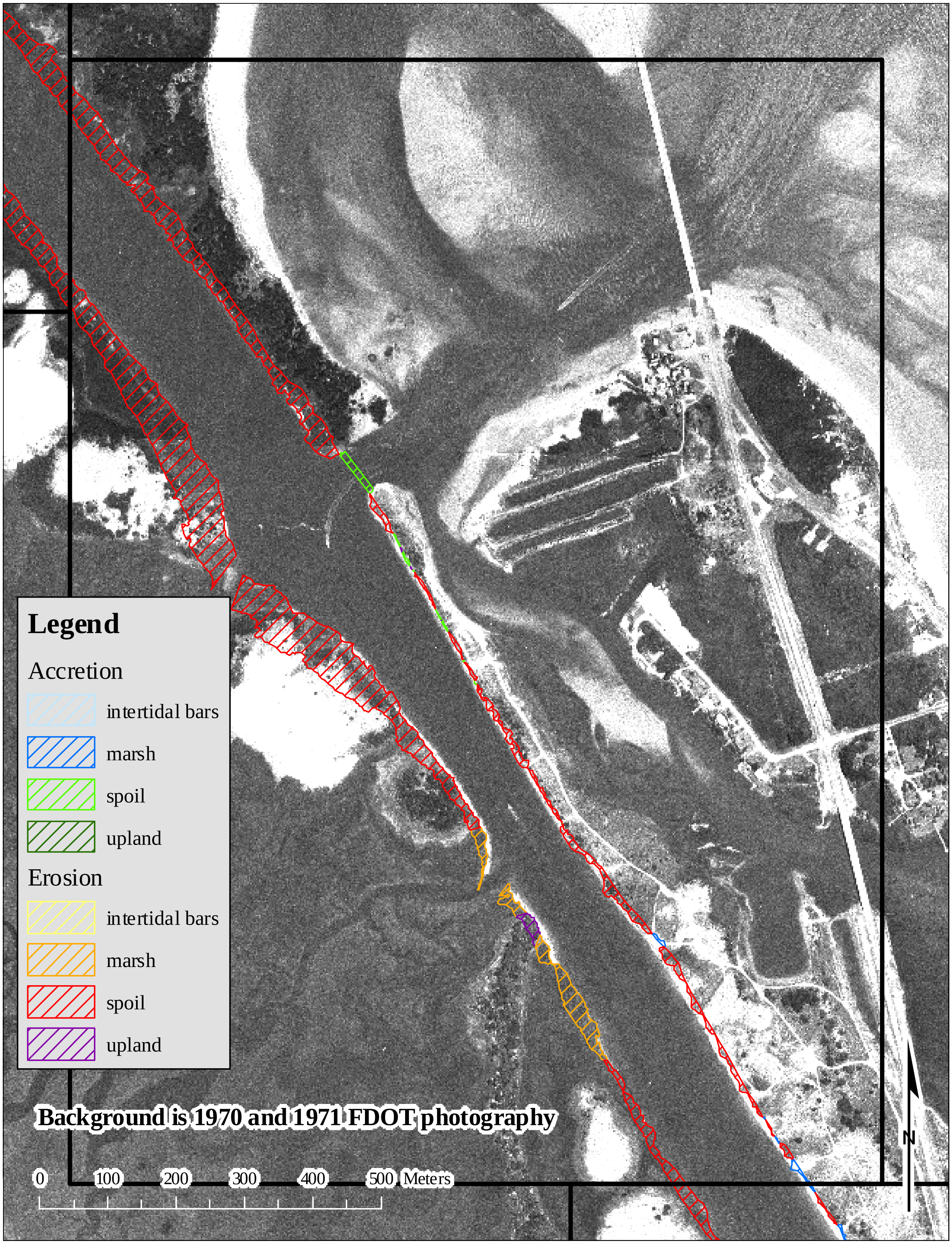

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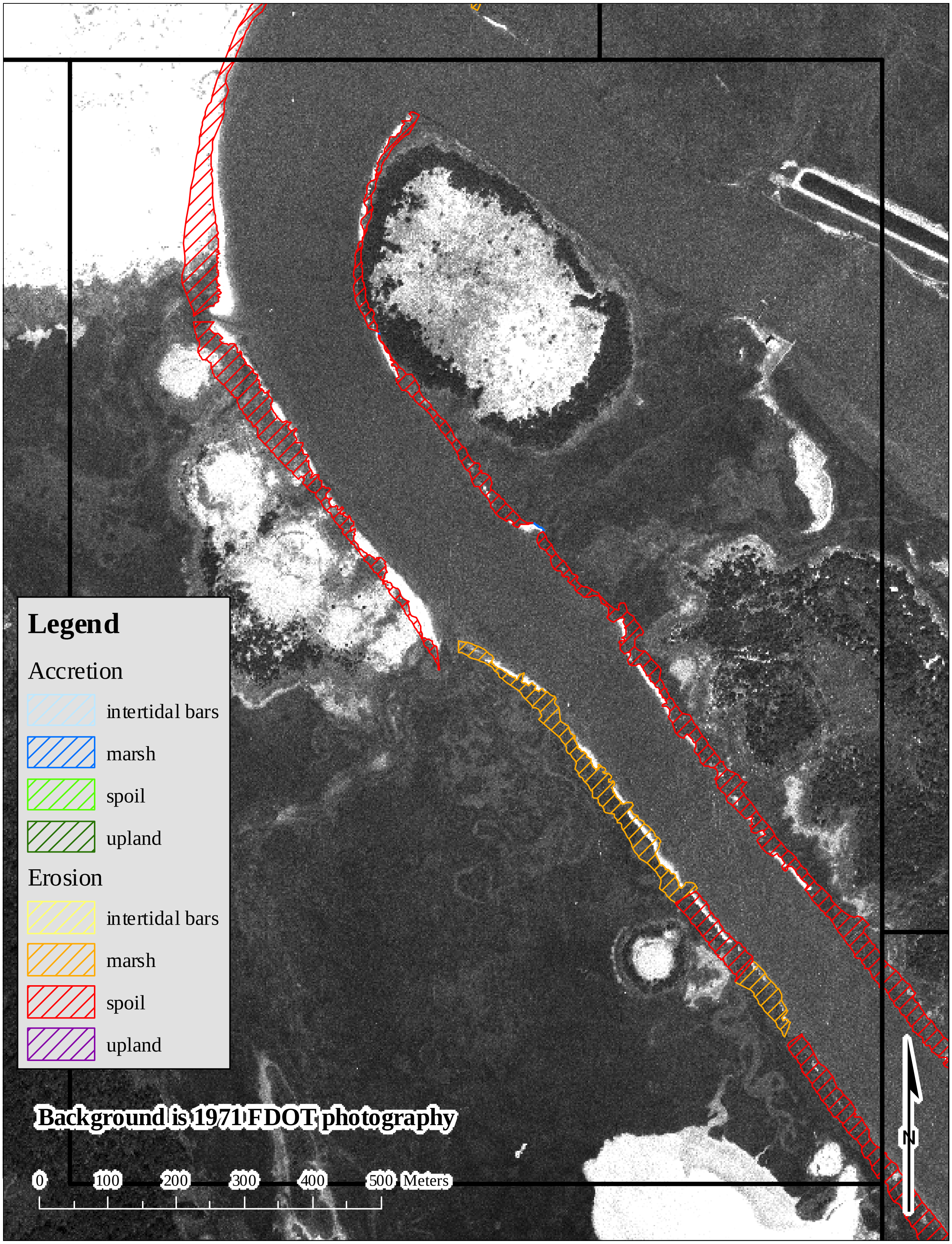

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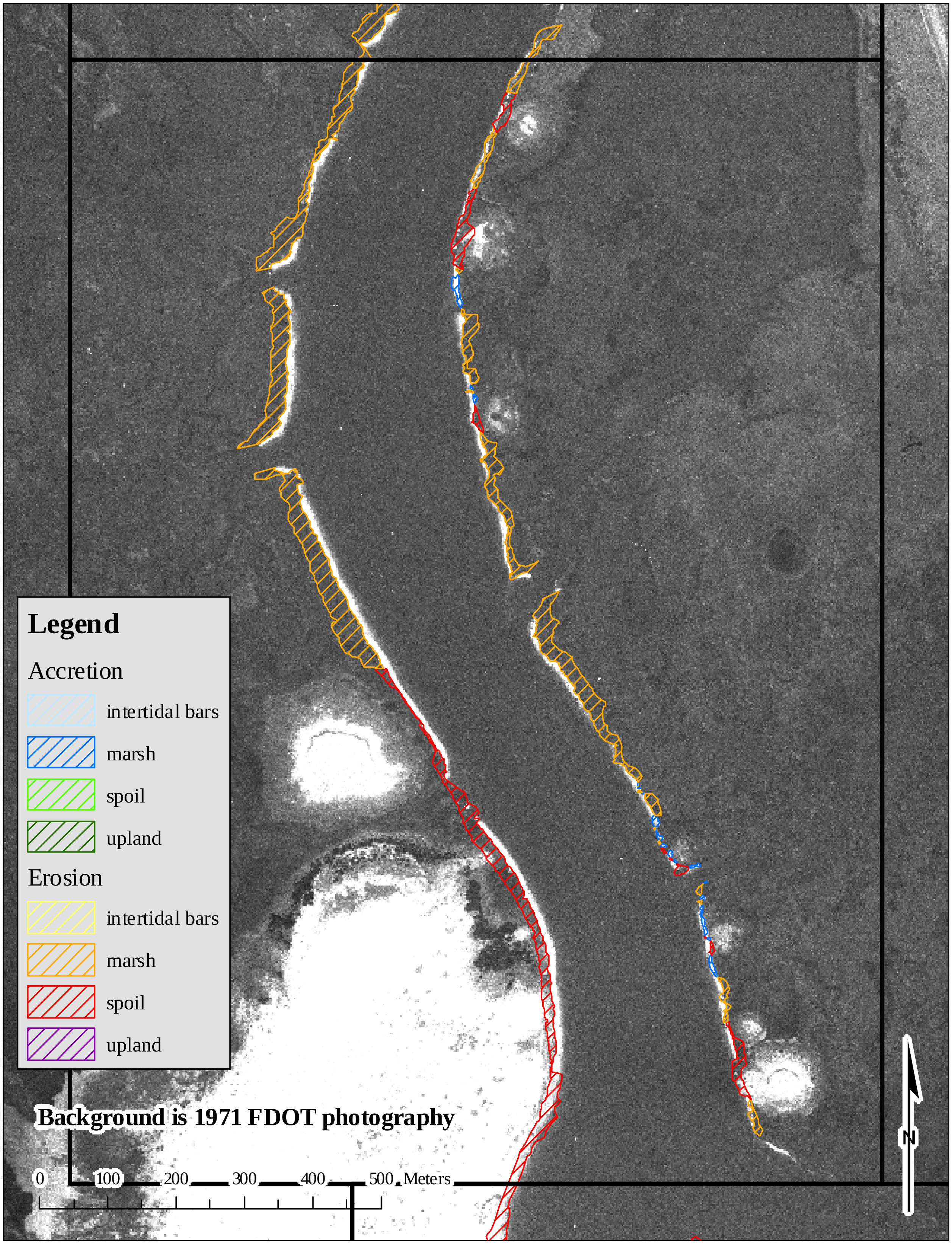

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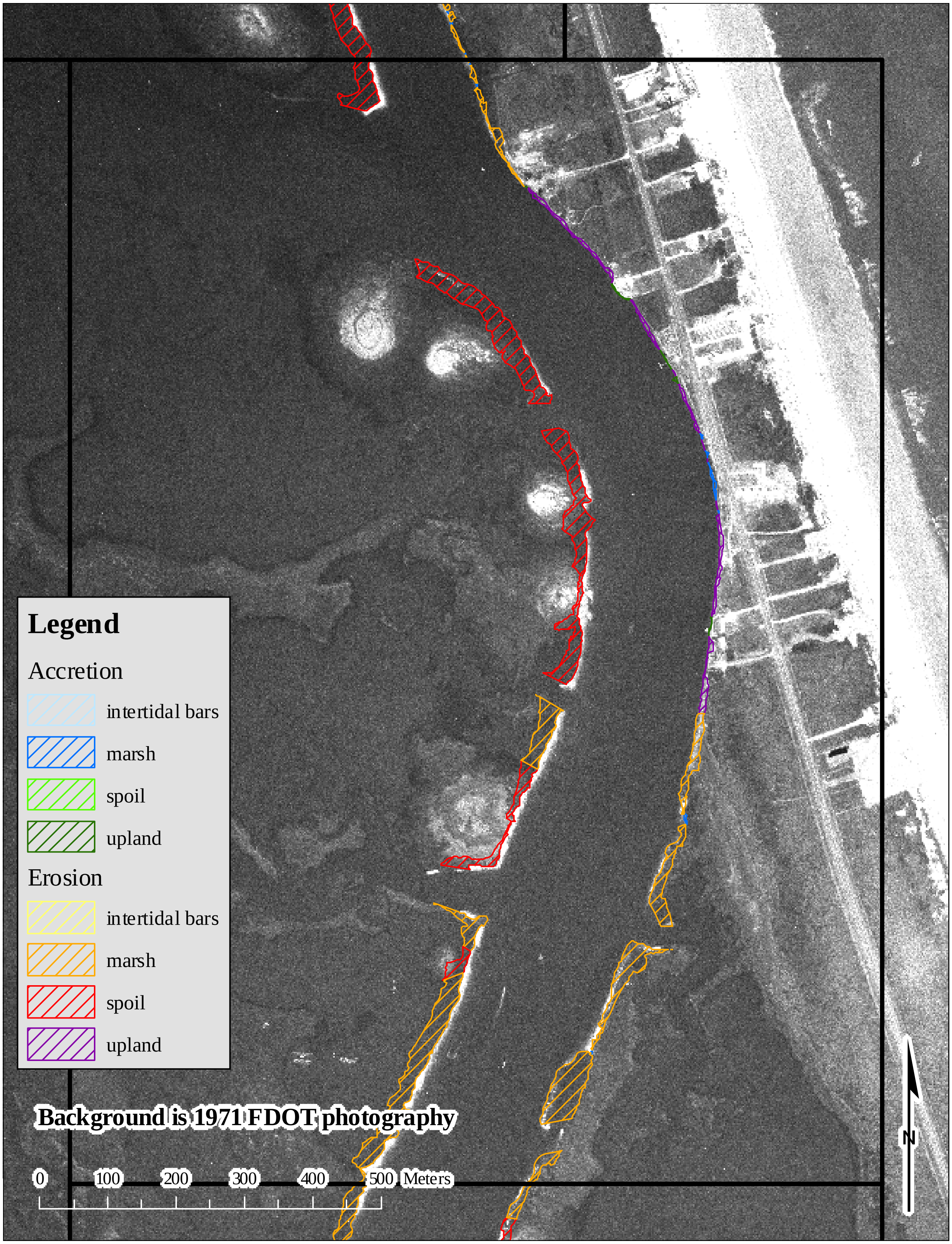

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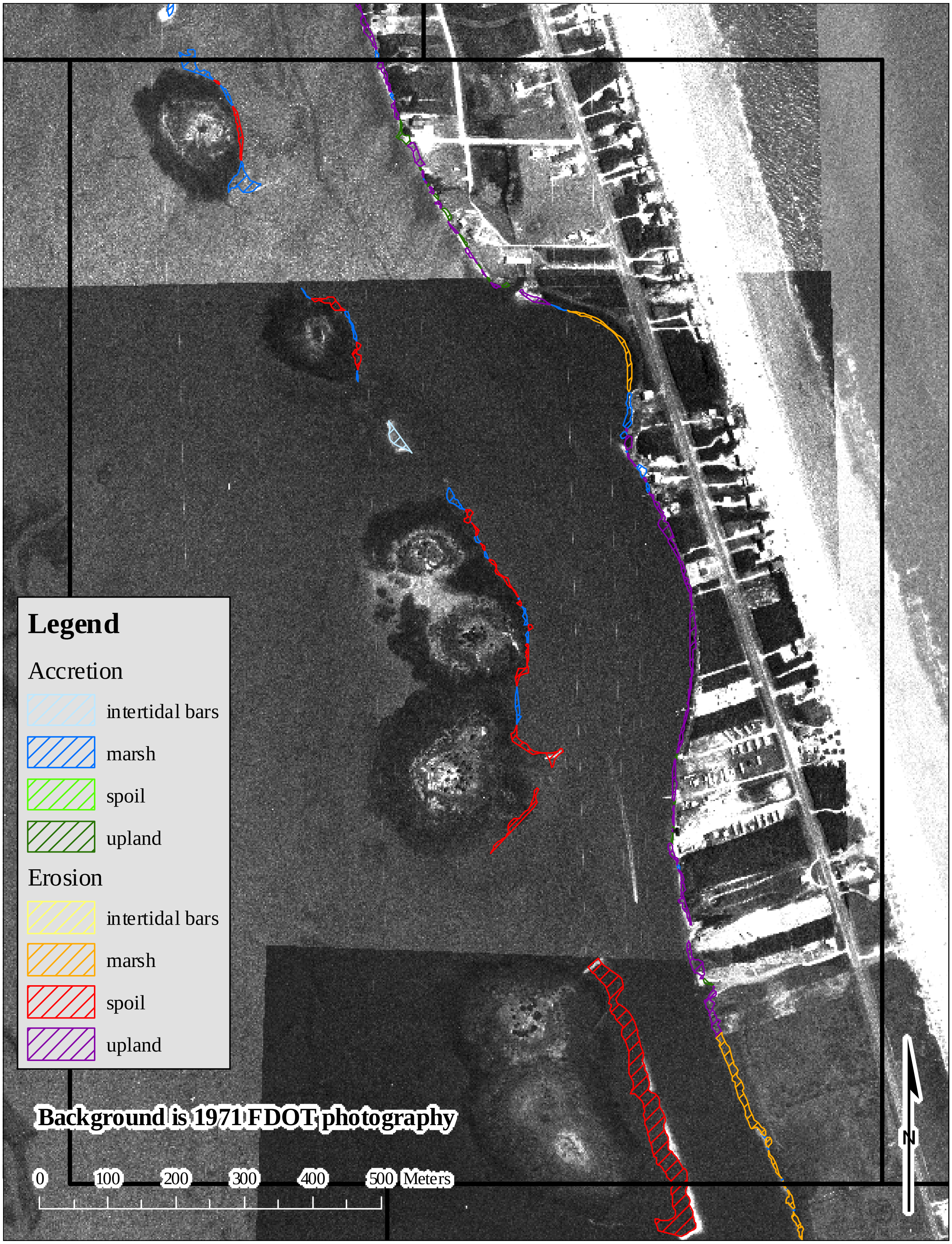

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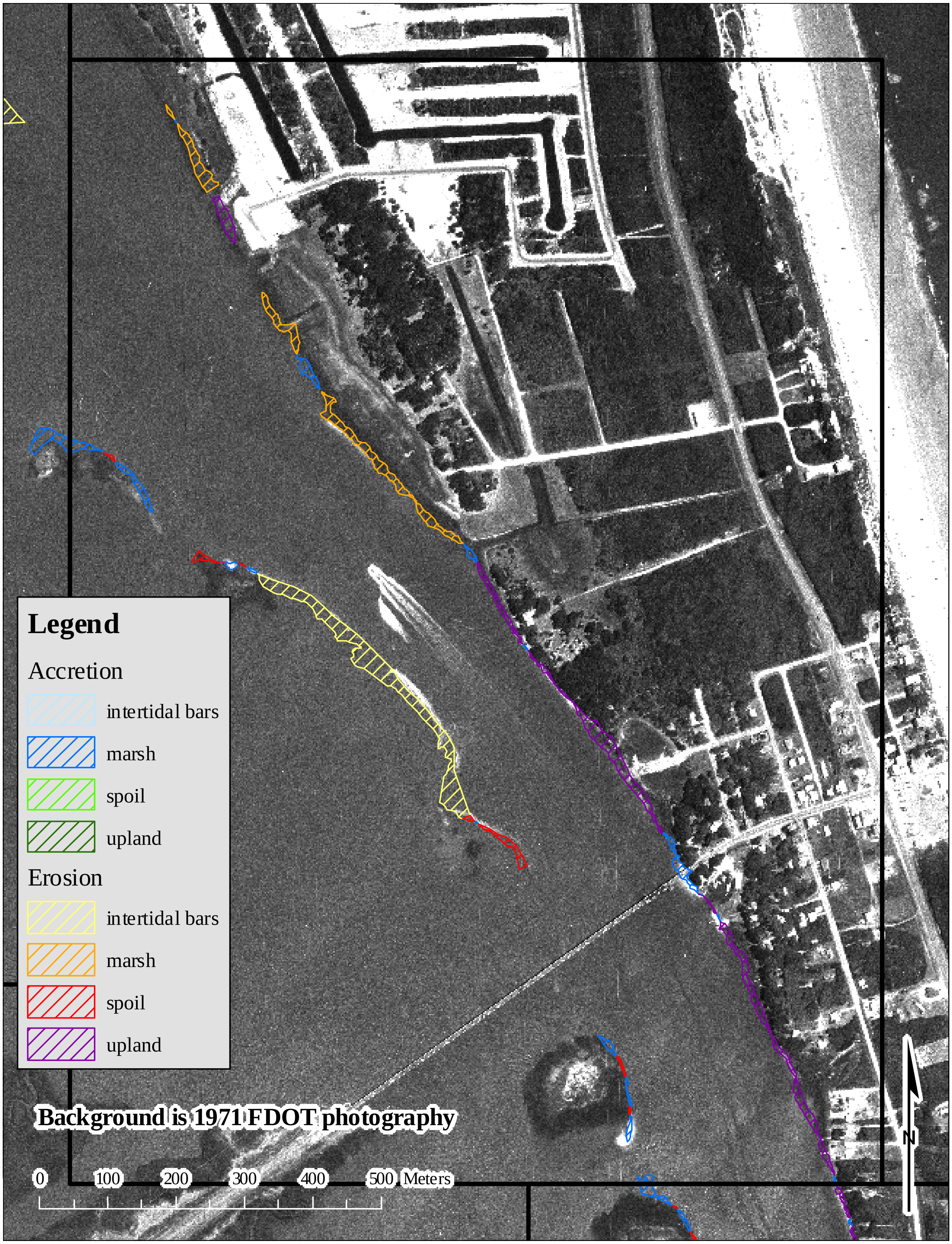

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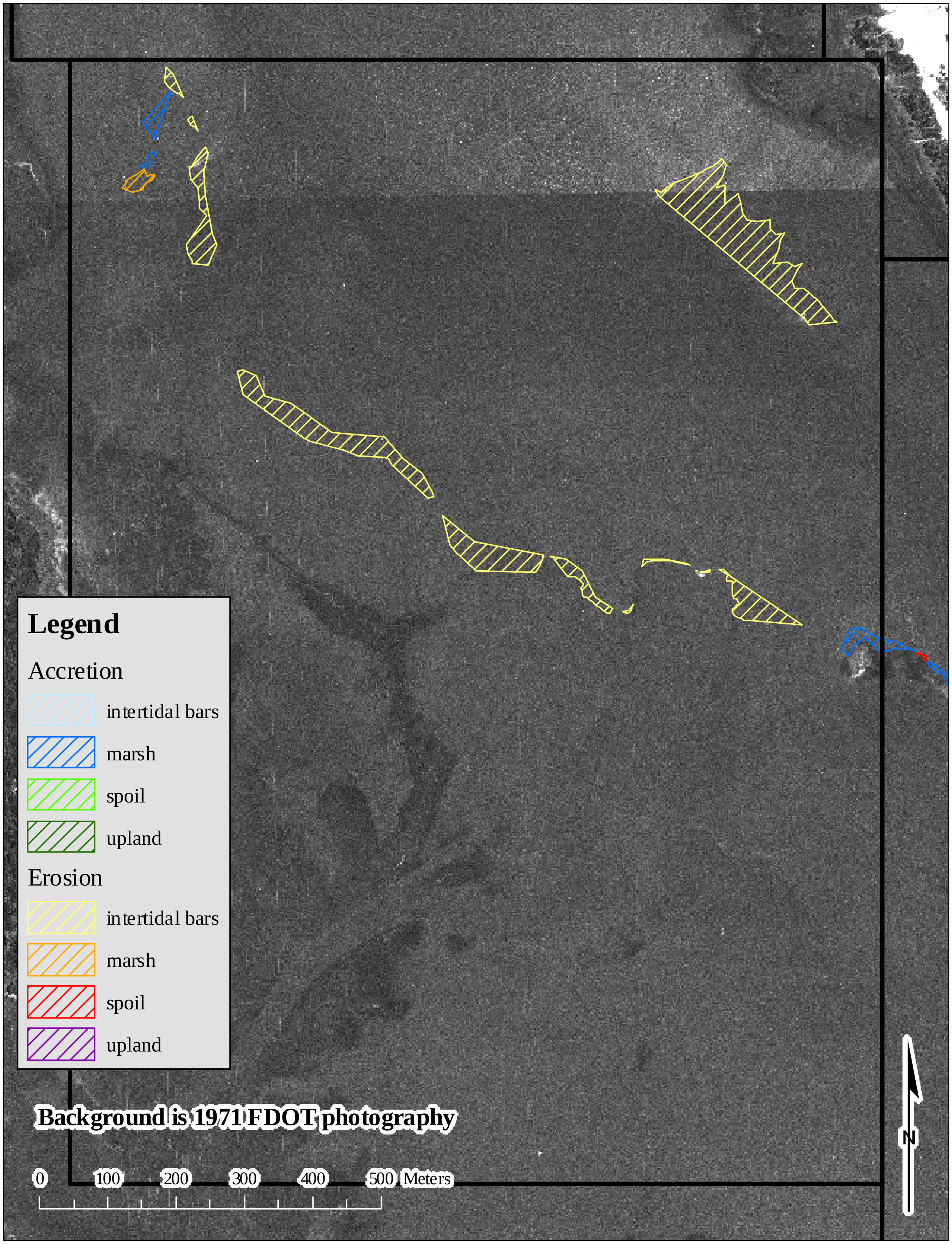

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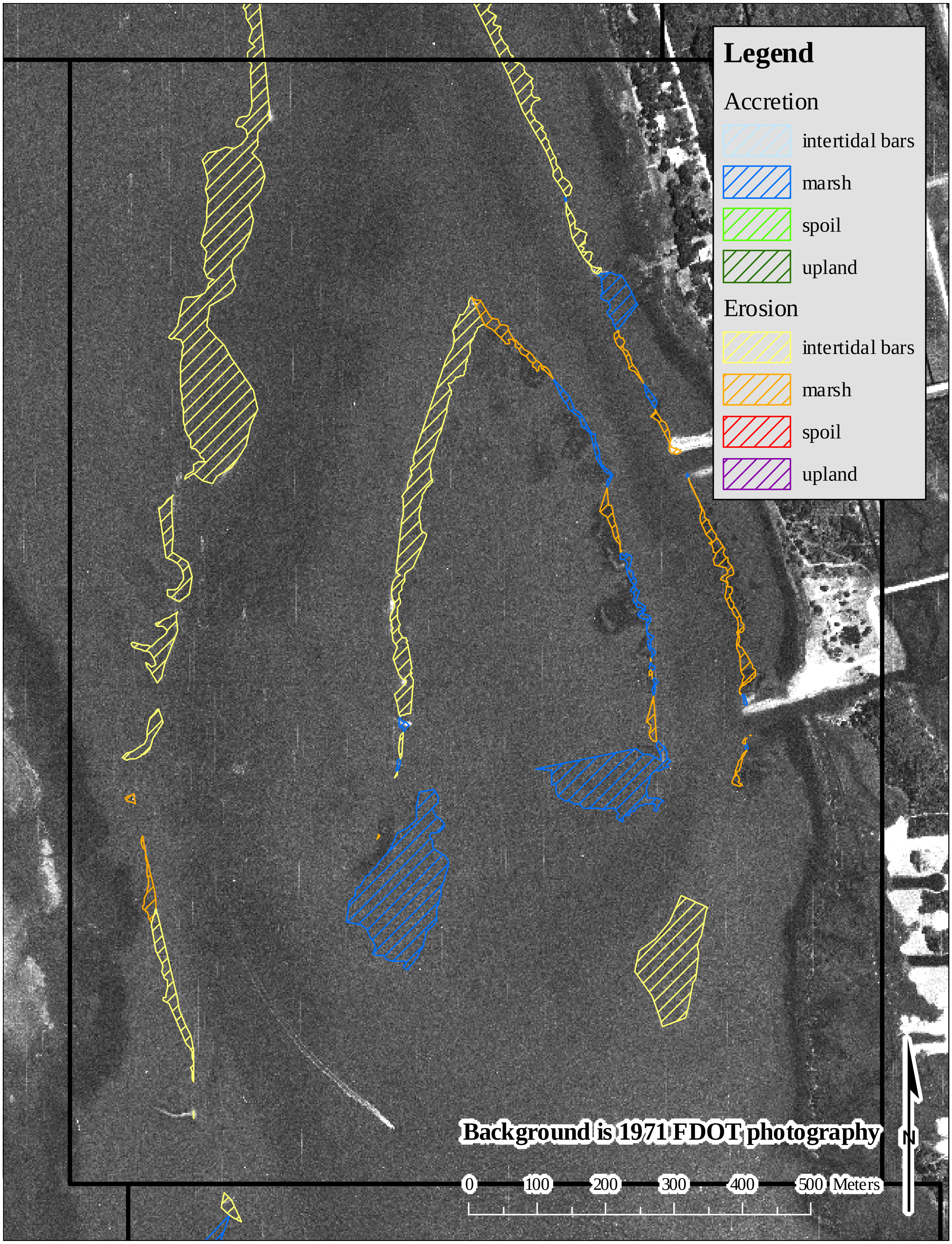

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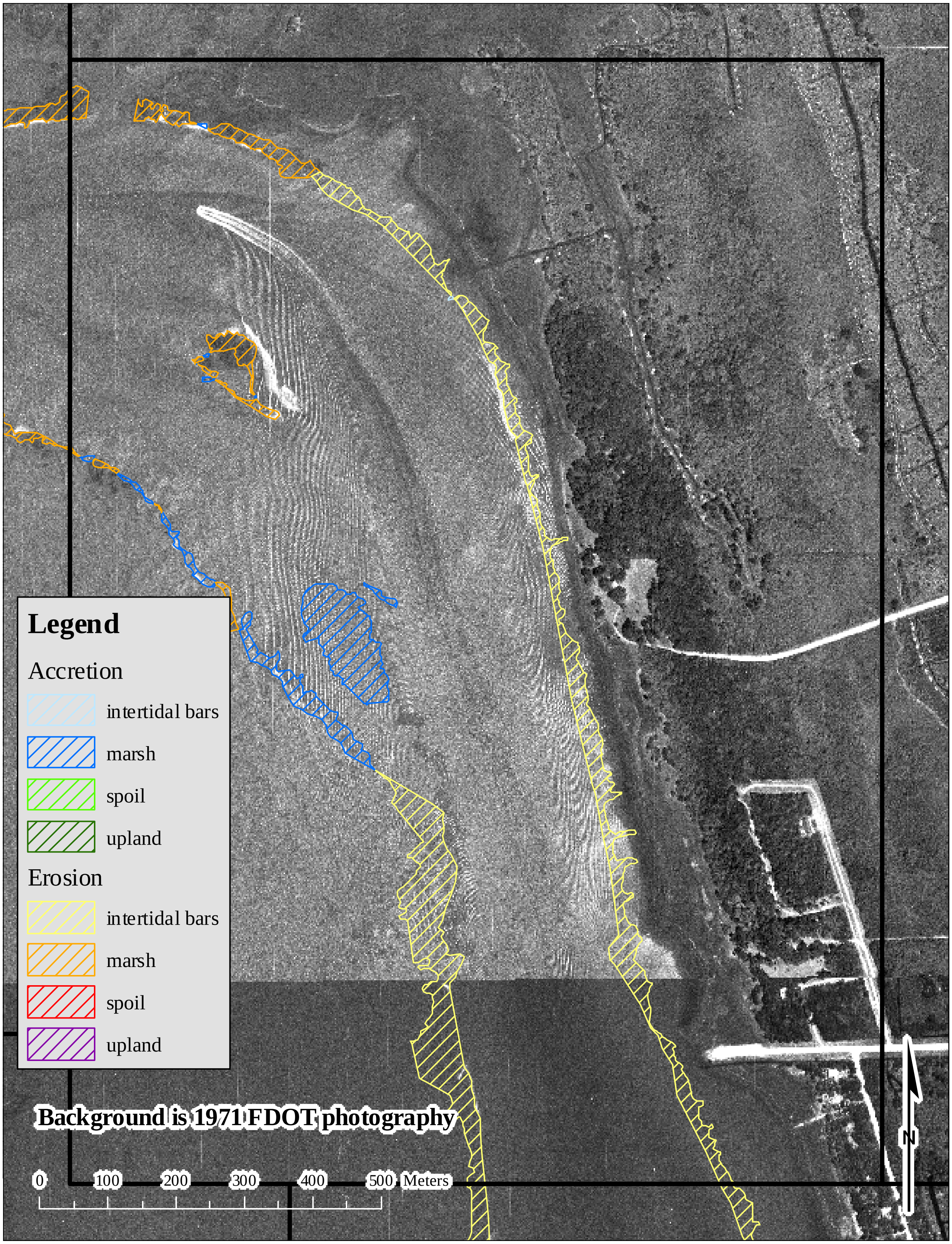

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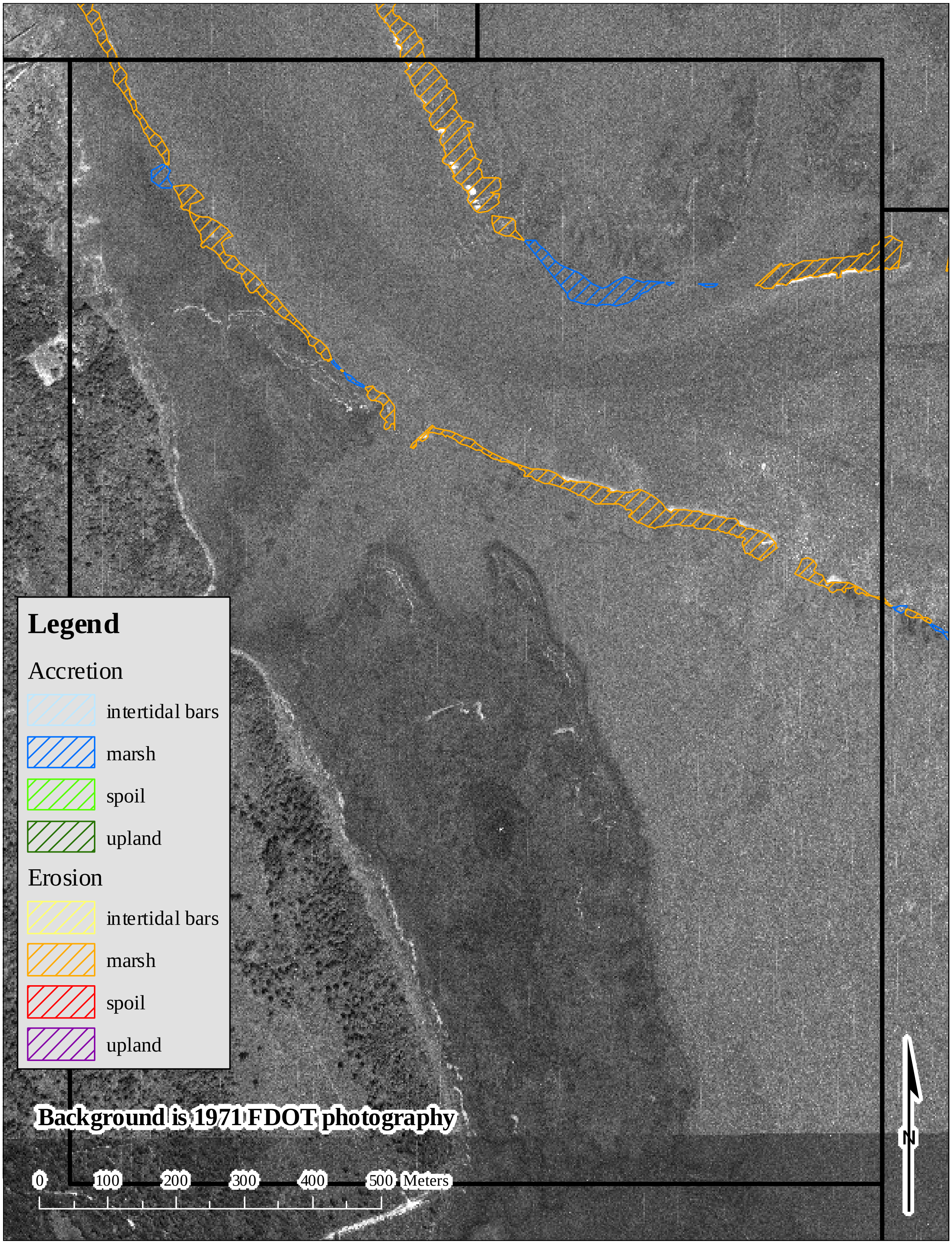

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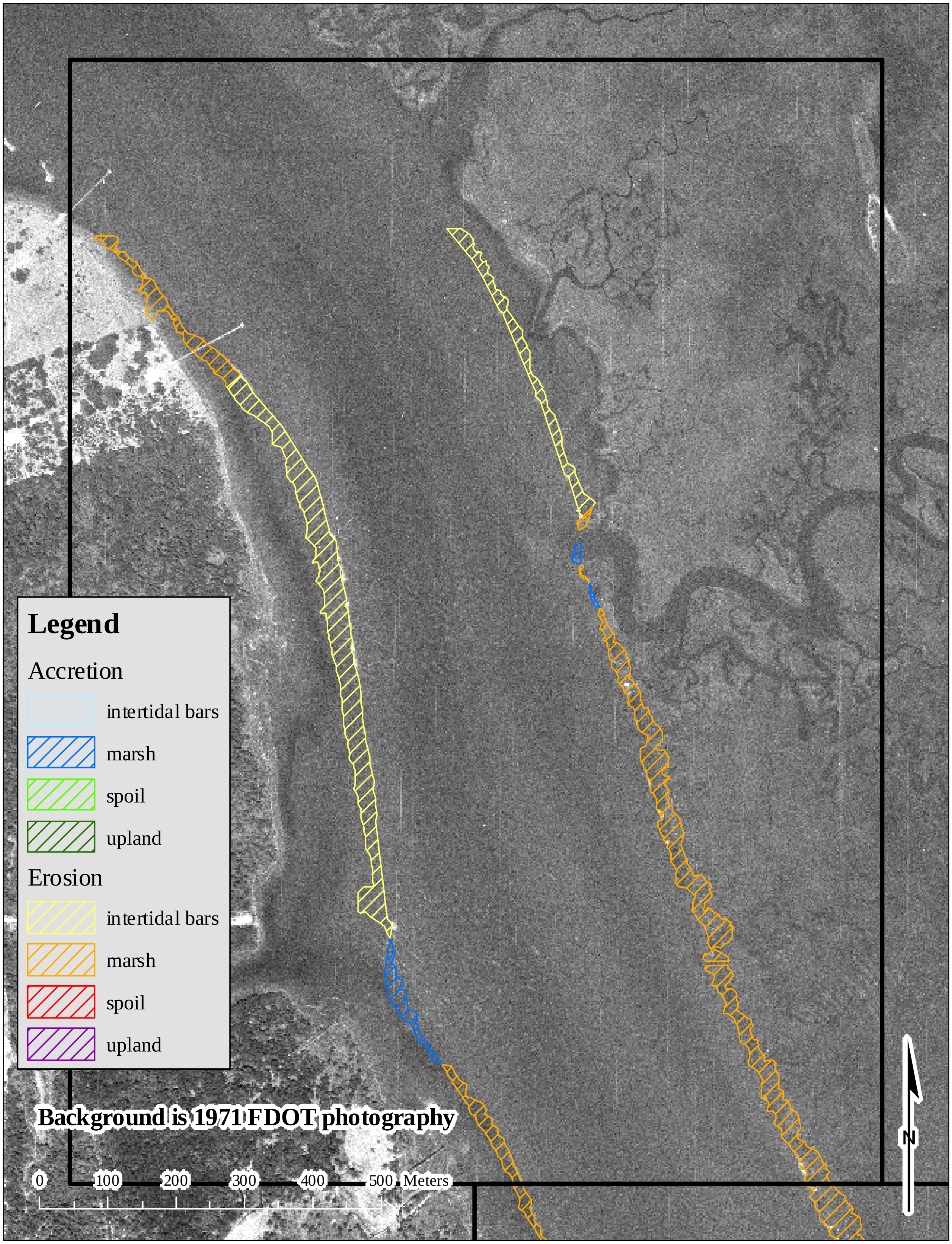

Figure 33: Plate 16

REFERENCES

Beatley, T., Brower, D. J., & Schwab, A. K. (2002). *An introduction to coastal zone management*. Washington, DC: Island Press.

Bertness, M., & Silliman, B. (2002). Fewer blue crabs, more periwinkle snails make salt marshes blue. *Water Environment & Technology, 14*(12), 24-25.

Brooks, J. L. (2000). Federal, state and local authority to restrict or exclude vessels in Florida waters. In, *Recreational boating waterway management and the environment* Tallahassee: Florida Bar.

Broome, S. W., Rogers, S. M., & Seneca, E. D. (1992). *Shoreline erosion control using marsh vegetation and low-cost structures*. Raleigh, NC: Albemarle-Pamlico Estuarine Study : University of North Carolina Sea Grant College Program.

Clean Water Act, 33 U.S.C.S. §1344 *et seq.* (2005).

Coastal planning and management, FL Stat. Chapter 380 Part II (2004).

Cox, R., Wadsworth, R. A., & Thomson, A. G. (2003). Long-term changes in salt marsh extent affected by channel deepening in a modified estuary. *Continental Shelf Research, 23*(17-19), 1833-1846.

Day J.W., J., Scarton, F., Rismondo, A., & Are, D. (1998). Rapid deterioration of a salt marsh in Venice Lagoon, Italy. *Journal of Coastal Research, 14*(2), 583-590.

Doane, S. N., Wells, L. E., & Merman, L. (1998). Quantification of wetland loss through time in San Pablo Bay, California based on GIS analysis of GPS, air photo, and historical map data. *Abstracts with Programs - Geological Society of America, 30*(7), 139.

Downs, L. L., Nicholls, R. J., Leatherman, S. P., & Hautzenroder, J. (1994). Historic evolution of a marsh island: Bloodsworth Island, Maryland. *Journal of Coastal Research, 10*(4), 1031-1031-1044.

Endangered Species Act, 16 U.S.C.S. §1533 (d) (2005)

Federal Geographic Data Committee (FGDC) Subcommittee for Base Cartographic Data. (2004, February 11). Geospatial positioning accuracy standards, part 3: national standard for spatial data accuracy. Retrieved March 15, 2005, from http://www.fgdc.gov/standards/documents/standards/accuracy/chapter3.pdf

Flagler County. (2004). *Flagler County Code, Appendix C, Art. VI, Sect.2.* Retrieved 2004 from http://library2.municode.com/gateway.dll/FL2/florida2/1801/1802?f=templates&fn=default.htm&npusername=12218&nppassword=MCC&npac_credentialspresent=true&vid=default

FL Const. art. X, § 11.

Florida statistical abstract. (1977-2001). Gainesville, FL: University of Florida Press.

Florida Department of Environmental Protection. (2005, March 11). Project Greenshores: Site 2. Retreived March 15, 2005 from http://www.dep.state.fl.us/northwest/ecosys/section/greenshores.htm

Florida Inland Navigation District. (2002). *Florida inland navigation district management letter.*, 2003 from http://www.aicw.org/financials/mgmtletter2002.htm

Florida Inland Navigation District. (1967). *The story of F.I.N.D., Florida inland navigation district, Fernandina Beach to Miami, Florida; the Florida section of Atlantic Intracoastal Waterway, Trenton, N.J. to Miami, Fla*. Riviera Beach, FL: FIND.

Florida Manatee Sanctuary Act, FL Stat. §370.12(2) (2004)

Frey, R. W., & Basan, P. B. (1978). Coastal salt marshes. In R. A. Davis, & P. B. Basan (Eds.), *Coastal sedimentary environments* (2nd rev., expand ed.) (716). New York: Springer Verlag.

Gaeuman, D.A., Schmidt, J.C., & Wilcock, P.R. (2003). Evaluation of in-channel gravel storage with morphology-based gravel budgets developed from planimetric data. Journal of Geophysical Research, 108, F1.

Gibbons v. Ogden, 22 U.S. (9 Wheat) 1 (1984).

Grizzle, R.E., Adams, J.R., & Walters, L.J. (2002). Historical changes in intertidal oyster (Crassostrea virginica) reefs in a Florida lagoon potentially related to boating activities. *Journal of Shellfish Research, 21*(2), 749.

Grossfeld, S. (1997, Feb 5). An eye in the sky over Venice city to use satellite to monitor water traffic, limit erosion. *Boston Globe,* pp. A1:A2..

Guana Tolomato Matanzas Reserve. (2004, February 18). *Guana tolomato matanzas reserve, Florida - welcome page.* Retrieved October 6, 2004 from http://nerrs.noaa.gov/GTM/welcome.html

Hartig, E. K., Gornitz, V., Kolker, A., Mushacke, F., & Fallon, D. (2002). Anthropogenic and climate-change impacts on salt marshes of Jamaica Bay, New York City. *Wetlands, 22*(1), 71-89.

Hershberger, D. A., & Ting, F. C. K. (1996). Study of wind waves in the Gulf Intracoastal Waterway at Aransas National Wildlife Refuge. *Journal of Waterway, Port, Coastal and Ocean Engineering, 122*(5), 239-239-244.

Kastler, J., & Wiberg, P. (1996). Sedimentation and boundary changes of Virginia salt marshes. *Estuarine, Coastal & Shelf Science, 42*(6), 683.

Kearney, M. S., Grace, R. E., & Stevenson, J. C. (1988). Marsh loss in Nanticoke estuary, Chesapeake Bay. *Geographical Review, 78*(2), 205-220.

Kennish, M. J. (2002). *Impacts of motorized watercraft on shallow estuarine and coastal marine environments*. Lawrence, KS: Coastal Education and Research Foundation.

Knutson, P. L., & Woodhouse, W. W. (1983). *Shore stabilization with salt marsh vegetation*. Fort Belvoir, Va.: U.S. Army, Corps of Engineers, Coastal Engineering Research Center.

Kratch, K. (1996). River ecology, coastal projects win sustainability awards. *Water Environment & Technology, 8*, 28.

Leopold, L.B., Wolman, M.G., & Miller, J.P. (1992). *Fluvial Processes in Geomorphology.* New York: Dover.

Letzsch, W. S., & Frey, R. W. (1980). Deposition and erosion in a Holocene salt marsh, Sapelo Island, Georgia. *Journal of Sedimentary Petrology, 50*(2), 529-542.

Louisiana Coastal Wetlands Conservation and Restoration Task Force. (2001, July). GIWW - Perry Ridge West Bank Stabilization (CS-30). Retrieved March 15, 2005, from http://www.lacoast.gov/news/press/2001-12-12b/cs30-factsheet.pdf

Macfarlane, G. J., & Renilson, M. R. (1999). Wave wake - a rational method for assessment. In, *Royal Institution of Naval Architects International Conference on Coastal Ships and Inland Waterways,* London: Royal Institution of Naval Architects.

Management and Storage of Surface Waters, FL Stat. Chapter 373 Part IV (2004).

Marine Industries Ass'n of South Florida, Inc. v. Fl. Dept. of Environmental Protection, 672 So. 2d 878 (Fla. App. 4 Dist. 1996).

Marine Mammal Protection Act, 16 U.S.C.S. § 1361 et seq. (2005).

Maynord, S. T., United States Army Corps of Engineers, Alaska District, Alaska Dept. of Fish and Game, Habitat and Restoration Division, Alaska Division of Parks and Outdoor Recreation, Engineer Research and Development Center (U.S.) & Coastal and Hydraulics Laboratory (U.S.). (2001). *Boat waves on Johnson Lake and Kenai River, Alaska.* Retrieved 2004 from http://libweb.wes.army.mil/uhtbin/hyperion/CHL-TR-01-31.pdf; Electronic Name: IARC:CHL-TR-01-31.pdf

McGrail v. Babbitt, 986 F. Supp 1386, 1394 (US Southern Dist. 1997).

Meyer, D. L., Townsend, E. C., & Thayer, G. W. (1997). Stabilization and erosion control value of oyster clutch for intertidal marsh. *Restoration Ecology, 5*(1), 93-93-99.

Montague, C. L., & Wiegert, R. G. (1990). Salt marshes. In R. L. Myers, & J. J. Ewel (Eds.), *Ecosystems of Florida* (pp. 481--516). Orlando, FL: University of Central Florida Press.

National Environmental Policy Act, 42 U.S.C.S. §4321 et seq. (2005).

National Estuarine Research Reserve System. (2004). *National Estuarine Research Reserve System strategic plan 2003 – 2008.* Retrieved September 23, 2004, 2004 from http://nerrs.noaa.gov/Background_StrategicPlan.html

National Estuarine Research Reserve System, §16 USCS 1461 (b)(2)(B) (2005).

National Estuarine Research Reserve System, §16 USCS 1461 (f)(3)(A) (2005).

National Oceanographic and Atmospheric Administration. (2003). *Climatic summary table.* Retrieved October 22, 2004 from http://seaboard.ndbc.noaa.gov/data/climatic/SAUF1.pdf

National Oceanographic and Atmospheric Administration. (n.d. a). *Mean sea level trend 8720220 Mayport, Florida.* Retrieved October 17, 2004 from http://co-ops.nos.noaa.gov/sltrends/sltrends_station.shtml?name=Mayport&state=Florida&stnid=8720220&start_yr=1928&end_yr=1999&slt=2.43&sterr=0.18

National Oceanographic and Atmospheric Administration. (n.d. b). *Mean sea level trends.* Retrieved October 17, 2004 from http://co-ops.nos.noaa.gov/sltrends/slrmap.shtml

Navigation and Navigable Waters Rule. 33 C.F.R. § 165.20 (2005).

Orson, R., Panageotou, W. & Leatherman, S.P. (1985). Response of tidal marshes of the U.S. Atlantic and Gulf Coasts to rising sea levels. *Journal of Coastal Research*, *1*(1), 29-37.

Phillips, J. D. (1986a). Coastal submergence and marsh fringe erosion. *Journal of Coastal Research*, *2*(4), 427-436.

Phillips, J. D. (1986b). Spatial analysis of shoreline erosion, Delaware Bay, New Jersey. *Annals - Association of American Geographers*, *76*(1), 50-62.

Ports and Waterways Safety Program, 33 U.S.C.S. §1222 et seq. (2005).

Raines, B. (2003, April 12). Boat wakes take toll on state's coastal rivers. *The Associated Press State & Local Wire*, Retrieved September 22, 2004, from the LexisNexis database.

Recreational Trails System, FL Stat. §260.017 (2004)

Redfield, A.C. (1965). Ontogeny of a salt marsh estuary. *Science*, *147*(3653), 50-55.

Redfield, A. C. (1972). Development of a New England salt marsh. *Ecological Monographs, 42*(2), 201-237.

Reed, D. J. (1988). Sediment dynamics and deposition in a retreating coastal salt marsh. *Estuarine, Coastal and Shelf Science, 26,* 67-79.

Reimer, M. K. (2001). The public trust doctrine: Historic protection of Florida's navigable rivers and lakes. *The Florida Bar Journal,* 10-20.

Rivers and Harbors Act, 33 U.S.C.S. §403 *et seq.* (2005).

Rogers, S. M.. (1994). *Marsh grass protection with low-cost breakwaters, shoreline erosion control demonstration final project report for albemarle-pamlico estuarine study*. Raleigh, NC: Seagrant.

Salinas, L. M., DeLaune, R. D., & Patrick, W. H. J. (1986). Changes occurring along a rapidly submerging coastal area: Louisiana, USA. *Journal of Coastal Research, 2*(3), 269-284.

Scarton, F., Cecconi, G., Are, D., Day J.W., J., & Rismondo, A. (2000). Effects of an intertidal sediment fence on sediment elevation and vegetation distribution in a Venice (Italy) lagoon salt marsh. *Ecological Engineering, 16*(2), 223-233.

Schwimmer, R. A. (2001). Rates and processes of marsh shoreline erosion in Rehoboth Bay, Delaware, U.S.A. *Journal of Coastal Research, 17*(3), 672-683.

Schwimmer, R. A., & Pizzuto, J. E. (2000). A model for the evolution of marsh shorelines. *Journal of Sedimentary Research, Section A: Sedimentary Petrology and Processes, 70*(5), 1026-1035.

State Lands. FL Stat. § 253.03(7)(b) (2004).

State of Florida. (n.d.). *State programmatic general permit.* Retrieved March 15, 2005 from http://www.dep.state.fl.us/water/wetlands/forms/spgp/spgpiii.doc

Steller, D. L. (1991). Christmas tree fences: Their use in marsh erosion control. *Wetlands Restoration and Creation, 18*, 143-153.

Stevenson, J. C., Kearney, M. S., & Pendleton, E. C. (1985). Sedimentation and erosion in a Chesapeake Bay brackish marsh system. *Marine Geology, 67*(3-4), 213-235.

U.S. Const. art. 1, § 8.

U.S. Const. art. IV, §3

U.S. Environmental Protection Agency. (2004). *Administration to reaffirm commitment to no net loss of wetlands and address approach for protecting isolated waters in light of supreme court ruling on jurisdictional issues.* Retrieved October 10, 2004 from http://www.epa.gov/epahome/headline2_011003.htm

Vessel Safety, FL Stat. § 327.60(1) (2004).

Wave Dispersion Technologies, Inc. (n.d.). Retrieved March 15, 2005 from http://www.whisprwave.com

Wilcox, D. (n.d.). *Effects of recreational boating on the upper Mississippi River system.* U.S. Army Corps of Engineers, St. Paul District. Retrieved from http://www.mvp.usace.army.mil/docs/nav/effects.pdf

Williams, H. E. L. (1993). Shoreline erosion at Mad Island Marsh Preserve, Matagorda county, Texas. *The Texas Journal of Science, 45*(4), 299-310.

Zabawa, C., Ostrom, C., Byrne, R. J. & Maryland Coastal Resources Division. (1980). *Final report on the role of boat wakes in shore erosion in Anne Arundel County, Maryland*. Annapolis, MD: Tidewater Administration, Maryland Dept. of Natural Resources.

BIOGRAPHICAL SKETCH

Frank Price was born in Tallahassee Memorial Hospital in 1978. In 1980 he moved to St. Augustine where he grew up surfing at Butler Beach and fishing in the Matanzas River. He moved back to Tallahassee in 1996 to earn a bachelor's degree in Environmental Studies with a minor in Biology. He has been employed by Florida State University, North Carolina State University, and Environmental Planing and Analysis (a private environmental consulting firm). Currently he works for the U.S. Geological Survey in Tallahassee where he assists with interdisciplinary research on the Apalachicola River. Upon graduation he plans to pursue a career in coastal resource management in the southeastern U.S.