Environmental Sensitivity Index Maps:
Classifications Crosswalk Project

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Prepared for:

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Introduction

Environmental Sensitivity Index (ESI) maps provide a concise summary of coastal resources that are at risk if an oil or chemical spill occurs nearby. When a spill occurs, ESI maps can help responders reduce the environmental impacts due to the spill and the cleanup efforts. Additionally, planners can use ESI maps before a spill happens to identify sensitive locations, establish protection priorities, and identify protection and cleanup strategies. The development of an ESI database has been standardized in the ESI Guidelines (Petersen et al., 2019), now in its 4th edition. A fundamental component of the ESI is the shoreline classification and ranking scale, which classifies shoreline segments based on their morphology, exposure, and other factors, and ranks these classes by their sensitivity to spilled oil. The ESI shoreline classification and ranking scale has been in use since the late-1970s. Rankings range from 1 – least vulnerable, to 10 – most sensitive, with a variety of qualifiers unique to the geographic region. The scale (Table 1) incorporates the following considerations:

1. Shoreline type (substrate, grain size, origin)
2. Exposure to wave energy
3. Biological productivity and sensitivity
4. Ease of cleanup

Prediction of the behavior and persistence of oil in shoreline habitats is based on an understanding of the dynamics of the coastal environments, not just the substrate type and grain size. The intensity of energy expended upon a shoreline by wave action and/or currents directly affects the persistence of stranded oil. The need for shoreline cleanup activities is determined, in part, by the slowness of natural processes in removal of oil stranded on the shoreline. The potential for biological injury and ease of cleanup of spilled oil are also important factors in the ESI shoreline ranking. Thus, shorelines exposed to high levels of physical energy and low biological activity rank low on the scale, whereas sheltered shorelines with associated high biological activity have the highest ranking.

Urban development, storms, and other natural processes can impact coastal environments in ways that may change the shape and type of shoreline. Thus, ESI maps need to be updated regularly to reflect these changes. For example, devastating winds and flooding from Hurricane Sandy impacted and altered coastal shorelines along the East Coast. Following Sandy, ESI maps were updated for eleven Atlantic coast states. Some ESI maps, such as in many areas of Alaska, are outdated due to the current availability of higher-resolution shoreline and imagery datasets.

To improve the efficiency and accuracy of updating and classifying the ESI shoreline, as well as enable the use of these data by a broader community of users, the National Oceanic and Atmospheric Administration's (NOAA) National Ocean Services' (NOS) Office of Response and Restoration (OR&R) Emergency Response Division (ERD) investigated the potential of converting ("crosswalking") other shoreline morphology data and classification systems to the ESI scale, as well as crosswalking the ESI data to other classification systems. These other datasets and systems include the NOAA Continuously Updated Shoreline Product (CUSP), NOAA Coastal and Marine Ecological Classification Standard (CMECS), NOAA U.S. Great Lakes Hardened Shorelines Classification, and NOAA Fisheries ShoreZone classification system. Additionally, ERD investigated the potential for the use of developing methods and techniques to segment and classify shorelines more efficiently. Research Planning, Inc. was contracted to undertake this work. This report summarizes the results of this investigation. Each crosswalk system or evaluated mapping method is presented in the following sections.

Table1. Currently used ESI shoreline classes.

ESI Code	Environment Code	Description
1A	E/L	1A: Exposed rocky shores
1A	R	1A: Exposed rocky banks
1B	E/L/R	1B: Exposed, solid man-made structures
1C	E/L/R	1C: Exposed rocky cliffs with boulder talus base
2A	E	2A: Exposed, wave-cut platforms in bedrock
2A	L	2A: Shelving bedrock shores
2A	R	2A: Rocky shoals and bedrock ledges
2B	E	2B: Exposed scarps and steep slopes in mud/clay
3A	E	3A: Fine- to medium-grained sand beaches
3B	E	3B: Scarps and steep slopes in sand
3B	L	3B: Eroding scarps (unconsolidated sediment)
3B	R	3B: Exposed, eroding banks (Unconsolidated Sediment)
3C	E	3C: Tundra cliffs
4	E	4: Coarse-grained sand beaches
4	L	4: Sand beaches
4	R	4: Sand bars and gently sloping banks
5	E/L	5: Mixed sand and gravel beaches
5	R	5: Mixed Sand and gravel bars and gently sloping banks
6A	E/L	6A: Gravel beaches
6A	E	6A: Gravel beaches (granules/pebbles) – used in Alaska
6A	R	6A: Gravel bars and gently sloping banks
6B	E/L/R	6B: Riprap
6C	E	6C: Gravel beaches (cobble/boulder) – used in Alaska
6D	E	6D: Boulder rubble
7	E/L	7: Exposed tidal flats
8A	E/L	8A: Sheltered scarps (bedrock/mud/clay)
8A	E	8A: Sheltered impermeable rocky shores
8B	E/L/R	8B: Sheltered, solid man-made structures
8B	E	8B: Sheltered, permeable, rocky shores
8C	E/L/R	8C: Sheltered riprap
8D	E	8D: Sheltered rocky rubble shores
8E	E	8E: Peat shorelines
8F	R	8F: Vegetated, steeply sloping bluffs
9A	E	9A: Sheltered tidal flats
9A	L	9A: Sheltered sand and mud flats
9B	E/L/R	9B: Sheltered, vegetated low banks
9C	E	9C: Hypersaline tidal flats
10A	E	10A: Salt- and brackish-water marshes
10B	E/L/P/R	10B: Freshwater marshes
10C	E/L/P/R	10C: Swamps
10D	E/L/P/R	10D: Scrub-shrub wetlands
10E	E	10E: Inundated low-lying tundra
10F	E	10F: Mangroves

Crosswalk: NOAA Continually Updated Shoreline Product (CUSP)

The NOAA Continually Updated Shoreline Product (CUSP) was created to deliver continuous shoreline with frequent updates to support various GIS applications. It is a mean high-water proxy shoreline based on vertical modeling or image interpretation using water-level stations or shoreline indicators and includes all national shoreline that has been verified by contemporary imagery and shoreline from other non-NOAA sources. The CUSP shoreline is often used as the primary dataset for creating an ESI vector shoreline. Although it has less stringent data acquisition requirements and quality control measures than other methods, it usually has a more accurate shoreline than many other datasets when compared to the most recent imagery and is developed at a higher-resolution scale than other datasets (1:1,000 – 1:24,000). CUSP is also available for most of the continental U.S. and portions of Hawaii, Pacific Islands, Alaska, Puerto Rico, and the U.S. Virgin Islands.

CUSP contains two attributes that are useful for shoreline classification. One is the source date (SRC_DATE) that can be used to filter data that have been added after the previous classification effort (if there is one). The other attribute describes the artificial (man-made) or natural characteristics of a shoreline segment (ATTRIBUTE). Many of these attributes can be crosswalked directly to ESI types (Table 2). However, the permeability of most of the artificial ATTRIBUTE values is not indicated, except for rip rap and groins, which are permeable structures and ramps, slipways, and drydocks which are impermeable. Breakwater is typically but not always impermeable. Bulkheads/sea walls and wharfs are usually impermeable but may be composed of rip rap or have rip rap at the base.

Although CUSP has a wetland value (“Natural.Apparent.Marsh Or Swamp”), it does not distinguish between salt marsh (10A), freshwater marsh (10B), swamp (10C), or scrub/shrub wetland (10D). It also does not include distinct values for any of the other natural ESI types that include 19 out of the 29 ranking values. Finally, CUSP provides information about one shoreline type per segment while the ESI classification system allows for up to three shoreline types per segment. Thus, although the CUSP shoreline is often used as the vector shoreline for ESI maps, the CUSP attributes are not sufficient to completely classify the ESI type of a given shoreline segment. They can be used, however, to pre-classify some shoreline segments and serve as a guide during the manual classification process. CUSP attributes may be more useful if used in tandem with other datasets or model outputs to refine some of the natural categories.

Table 2. NOAA Continually Updated Shoreline Product (CUSP) ATTRIBUTE crosswalk to ESI.

ATTRIBUTE	ESI Exposed	ESI Sheltered	Comments
Breakwater.Bare	6C	8C	breakwater in CUSP is not always impermeable
Groin.Bare	6C	8C	
Jetty.Bare	1B or 6C	8B or 8C	
Man-made	1B or 6C	8B or 8C	
Man-made.Bulkhead Or Sea Wall	1B	8B	
Man-made.Bulkhead Or Sea Wall.Ruins	1B or 6C	8B or 8C	ruins may appear more like riprap
Man-made.Drydock.Permanent	1B	8B	
Man-made.Ramp	1B	8B	
Man-made.Rip Rap	6C	8C	
Man-made.Slipway	1B	8B	
Man-made.Wharf Or Quay	1B	8B	
Man-made.Wharf Or Quay.Ruins	1B or 6C	8B or 8C	ruins may appear more like riprap
Natural.Apparent.Marsh Or Swamp	10A or 10B	10A or 10B	in Alaska, these are marshes
Natural.Glacier	N/A	N/A	not mapped in ESI
Natural.Great Lake Or Lake Or Pond	N/A	N/A	not mapped in ESI
Natural.Great Lake Or Lake Or Pond.Approximate	N/A	N/A	not mapped in ESI, though some are connected to open water
Natural.Mean High Water			could be any natural, non-wetland category
Natural.Mean High Water.Approximate			could be any natural, non-wetland category
Natural.Mean Water Level			could be any natural, non-wetland category
Natural.River Or Stream			could be any natural, non-wetland category
Natural.River Or Stream.Approximate			could be any natural, non-wetland category
Undetermined			

Crosswalk: NOAA Great Lakes Hardened Shoreline (GLHS)

The NOAA Great Lakes Hardened Shoreline (GLHS) dataset was created for the NOAA Office for Coastal Management and in partnership with the United States Army Corps of Engineers to support detailed shoreline mapping of the U.S. Great Lakes shorelines. The data were created by digitizing shoreline using NAIP imagery from 2014 through 2017, then compared with oblique imagery to determine structure condition and quality and were intended to be used at a map scale of 1:2,000 based on 1-meter spatial resolution or better aerial imagery. Like CUSP, the GLHS shoreline can be used as the primary dataset for creating an ESI vector shoreline. Either the CUSP or the GLHS shorelines are likely the most accurate shoreline available for the Great Lakes, though the relative accuracy of each of these sources differs by location according to age and source imagery.

The GLHS database consists of multiple attributes that are useful for shoreline classification. The shoreline type (Shoreline_Type) describes the artificial or natural characteristics of a shoreline segment. The primary and secondary structure type attributes (Structural_Type_Primary and Structural_Type_Secondary) describe the type of structure for artificial shoreline types. The primary and secondary structure condition attributes (Structural_Condition_Primary and Structural_Condition_Secondary) describe the condition of artificial structures. These attributes each contain a numeric code, each of which has an accompanying description.

As with CUSP, some of the Shoreline Types can be directly crosswalked to ESI (Table 3). The Structural Type attributes can help further refine some of the artificial types, but the permeability is not always indicated. Four Structural Type codes (300, 301, 302, 303) are described as rip rap, thus any shoreline segment with this classification can be crosswalked to the ESI type 6B or 8C, depending on the exposure. GLHS also follows CUSP with no distinction between freshwater marsh (10B), swamp (10C), or scrub/shrub wetland (10D). Instead, GLHS distinguishes wetlands by their location and/or exposure: Open Shoreline/Shore Wetlands (180, 181) and Rivermouth/Sheltered Wetlands (182).

Crosswalk: ShoreZone

As described in the most recent ShoreZone Protocol (Cook et al., 2017), the NOAA Fisheries ShoreZone data is a coastal aerial imaging, classification, and mapping system used to inventory alongshore and across-shore geomorphological and biological attributes of the shoreline. ShoreZone oblique aerial imagery is acquired at low altitudes during the lowest tides of the year. The imagery is used to partition a digital shoreline into relatively environmentally homogeneous segments called ShoreZone units and is then used to describe the physical and biological attributes of each unit. ShoreZone datasets cover the Pacific coast from Oregon to Alaska and are used in much the same way as ESI maps: for coastal planning, identification of vulnerable resources, oil spill response planning, habitat modeling, recreational planning, and scientific research.

The ShoreZone attributes, BC_CLASS (Coastal Class) and EXP_BIO (Exposure), form the basis of the ESI crosswalks in previous ShoreZone protocol documents. After evaluating all the attributes in ShoreZone, we agree with using these as a starting point (Table 4). But these two attributes alone do not provide a direct crosswalk for all SZ BC_CLASS/EXP_BIO combinations. Thus, we determined that some of the other ShoreZone attributes such as Bioband, Form and Material attributes could further refine some of the conversions (Figure 1). However, it may require developing complex correlations between these attributes.

Table 3. NOAA Great Lakes Hardened Shoreline (GLHS) crosswalk to ESI codes.

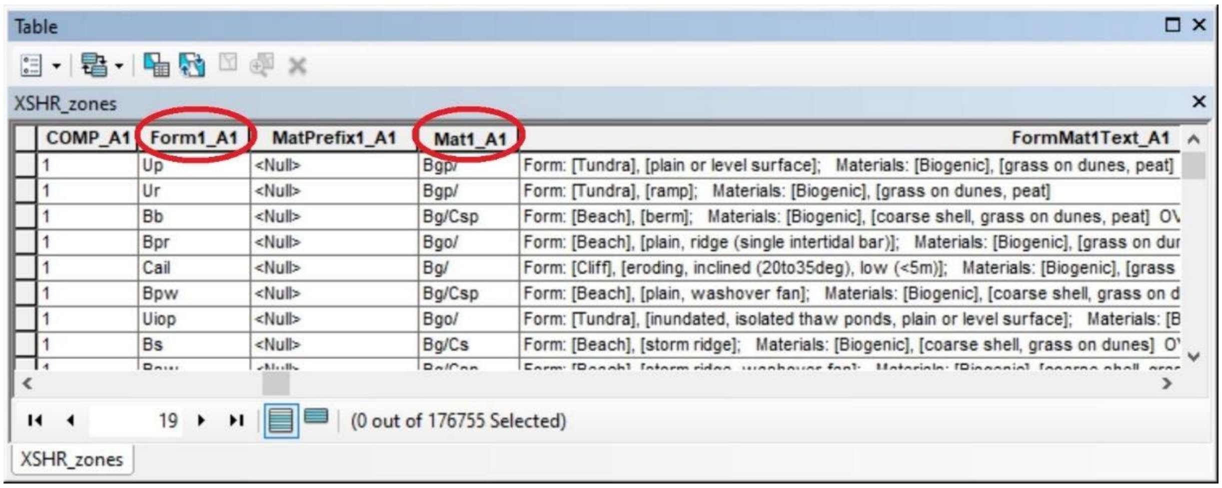
Shoreline_Type_Description	Structural_Type_Primary_Description	Structural_Type_Secondary	Exposure**	ENVIR	ESI	Comments
Sand or Cohesive Bluffs (Till or Lacustrine)			E,S	L,R	3B	
Homogeneous Bluffs (sand content 0-20%)			E,S	L,R	3B	
Homogeneous Bluffs (sand content 20-50%)			E,S	L,R	3B	
Homogeneous Bluffs (sand content >50%)			E,S	L,R	3B	
Composite Bluffs (sand content 0-20%)			E,S	L,R	3B	
Composite Bluffs (sand content 20-50%)			E,S	L,R	3B	
Composite Bluffs (sand content >50%)			E,S	L,R	3B	
Sand Bluffs (composition unknown)			E,S	L,R	3B	
Cohesive Bluffs (composition unknown)			E,S	L,R	*	
Marine / Leda Clay Bluffs			E,S	L	2B	
Marine / Leda Clay Bluffs			E,S	L	2B	
Low Bank			E,S	L,R	*	no direct correlation
Glacial Till Low Bank / Low Plain			E,S	L,R	*	no direct correlation
Composite Low Bank / Low Plain			E,S	L,R	*	no direct correlation
Sandy Low Bank / Low Plain			E,S	L,R	*	no direct correlation
Leda/Marine Clay Low Bank /Low Plain			E,S	L,R	*	no direct correlation
Creek Bank (applies to narrow creek channels where mapping extends inland)			E,S	L,R	*	
Baymouth Barrier Complex			E,S	L,R	*	
Baymouth - Barrier (fronting wetlands or shallow embayments, estuaries)			E,S	L,R	*	
Sandy Beach / Dune Complex			E,S	L,R	*	3A, 4 or 5 - though no direct correlation found
Sandy Beach / Dune (relict deposits, areas with no new deposition)			E,S	L,R	*	3A, 4 or 5 - though no direct correlation found
Artificial Depositional (e.g., jetty, groin fill)			E	L,R	1B/5,6B/5*	sand/gravel in front of man-made
Artificial Depositional (e.g., jetty, groin fill)			S	L,R	8B/5,8C/5*	sand/gravel in front of man-made
Natural Depositional (areas with active supply/deposition)			E,S	L,R	*	
Erosional Beach (beach undergoing active erosion due to LST)			E,S	L,R	*	
Pocket Beach			E,S	L,R	*	
Coarse Beaches			E,S	L,R	4	
Gravel Beaches			E,S	L,R	6A	
Shingle / Cobbles			E,S	L,R	6A	
Boulder Beaches			E,S	L,R	6D	

Shoreline_Type_Description	Structural_Type_Primary_Description	Structural_Type_Secondary	Exposure**	ENVIR	ESI	Comments
Bedrock (Resistant)			E	L,R	1A,2A*	
Bedrock (Resistant)			S	L,R	8A*	
Bedrock (Resistant) no overburden			E	L,R	1A,2A*	
Bedrock (Resistant) no overburden			S	L,R	8A*	
Bedrock (Resistant) with glacial overburden			E,S	L,R	*	
Bedrock (Resistant) with sand overburden			E,S	L,R	*	
Bedrock (Erosive)			E,S	L,R	*	
Bedrock (Erosive) no overburden			E,S	L,R	*	
Bedrock (Erosive) with glacial Overburden			E,S	L,R	*	
Bedrock (Erosion) with sand overburden			E,S	L,R	*	
Open Shoreline Wetlands			E,S	L,R	10B,10C,10D*	
Open Shore Wetlands			E,S	L,R	10B,10C,10D*	
Rivermouth / Sheltered Wetlands			E,S	L,R	10B,10C,10D*	
Artificial	Boat Launch Ramps		E	L,R	1B	
Artificial	Boat Launch Ramps		S	L,R	8B	
Artificial High Quality Well Engineered	Revetment, well engineered, well maintained		E	L,R	1B,6B*	
Artificial High Quality Well Engineered	Revetment, well engineered, well maintained		S	L,R	8B,8C*	
Artificial High Quality Well Engineered	Seawalls / Bulkheads, well engineered, well maintained		E	L,R	1B	
Artificial High Quality Well Engineered	Seawalls / Bulkheads, well engineered, well maintained		S	L,R	8B	
Artificial High Quality Well Engineered	Jetties, well engineered, well maintained (Perpendicular shore protection)		E	L,R	1B,6B*	
Artificial High Quality Well Engineered	Jetties, well engineered, well maintained (Perpendicular shore protection)		S	L,R	8B,8C*	
Artificial High Quality Well Engineered	Offshore / Marina Breakwaters, well engineered, well maintained	000	E,S	L,R	*	could be riprap, solid structure, engineered bank, etc.
Artificial High Quality Well Engineered	Offshore / Marina Breakwaters, well engineered, well maintained	201	E	L,R	1B,6B*	usually riprap on the outside, solid structure on the inside
Artificial High Quality Well Engineered	Offshore / Marina Breakwaters, well engineered, well maintained	201	S	L,R	8B,8C*	could be riprap, solid structure
Artificial High Quality Well Engineered	Offshore / Marina Breakwaters, well engineered, well maintained	211	E	L,R	1B	
Artificial High Quality Well Engineered	Offshore / Marina Breakwaters, well engineered, well maintained	211	S	L,R	8B	
Artificial High Quality Well Engineered	Beach Nourishment, well engineered, well maintained		E,S	L,R	4	
Artificial High Quality Well Engineered	Slope Grading / Bluff Stabilization, well engineered, well maintained	000	E,S	L,R	*	
Artificial High Quality Well Engineered	Slope Grading / Bluff Stabilization, well engineered, well maintained	201,211	E	L,R	6B	
Artificial High Quality Well Engineered	Slope Grading / Bluff Stabilization, well engineered, well maintained	201,211	S	L,R	8C	
Artificial High Quality Well Engineered	Boat Launch Ramps, well engineered, well maintained		E	L,R	1B	

Shoreline_Type_Description	Structural_Type_Primary_Description	Structural_Type_Secondary	Exposure**	ENVIR	ESI	Comments
Artificial High Quality Well Engineered	Boat Launch Ramps, well engineered, well maintained		S	L,R	8B	
Artificial Good Quality Well Engineered	Revetment, well engineered, well maintained	000	E,S	L,R	*	could be riprap, solid structure, engineered bank, etc.
Artificial Good Quality Well Engineered	Revetment, well engineered, well maintained	201,211,231,241,281,282,301	E	L,R	6B	
Artificial Good Quality Well Engineered	Revetment, well engineered, well maintained	201,211,231,241,281,282,301	S	L,R	8C	
Artificial Good Quality Well Engineered	Revetment, well engineered, well maintained	212	E	L,R	1B,6C*	could be riprap, solid structure, engineered bank, etc.
Artificial Good Quality Well Engineered	Revetment, well engineered, well maintained	212	S	L,R	8B,8C*	could be riprap, solid structure, engineered bank, etc.
Artificial Good Quality Well Engineered	Revetment, well engineered, well maintained	252	E,S	L,R	4	
Artificial Good Quality Well Engineered	Revetment, well engineered, well maintained	271,272	E,S	L,R	9B	
Artificial Good Quality Well Engineered	Seawalls / Bulkheads, well engineered, well maintained	000,201,203,211,222	E	L,R	1B,6C*	could be riprap, solid structure
Artificial Good Quality Well Engineered	Seawalls / Bulkheads, well engineered, well maintained	000,201,203,211,222	S	L,R	8B,8C*	could be riprap, solid structure
Artificial Good Quality Well Engineered	Seawalls / Bulkheads, well engineered, well maintained	212	E	L,R	6B	
Artificial Good Quality Well Engineered	Seawalls / Bulkheads, well engineered, well maintained	212	S	L,R	8C	
Artificial Good Quality Well Engineered	Seawalls / Bulkheads, well engineered, well maintained	213,241	E	L,R	1B	
Artificial Good Quality Well Engineered	Seawalls / Bulkheads, well engineered, well maintained	213,241	S	L,R	8B	
Artificial Good Quality Well Engineered	Seawalls / Bulkheads, well engineered, well maintained	251,252	E,S	L,R	4	
Artificial Moderate Quality Moderately Engineered			E	L,R	1B,6C*	could be riprap, solid structure
Artificial Moderate Quality Moderately Engineered			S	L,R	8B,8C*	could be riprap, solid structure
Artificial Poor Quality Poorly Engineered			E	L,R	1B,6C*	could be riprap, solid structure
Artificial Poor Quality Poorly Engineered			S	L,R	8B,8C*	could be riprap, solid structure
Unknown						
<>	LIKE '%Rip Rap%' (300,301,302,303)	300,301,302,303	E	L,R	6B	should be riprap but does not always correspond
<>	LIKE '%Rip Rap%' (300,301,302,303)	300,301,302,303	S	L,R	8C	should be riprap but does not always correspond

Table 4. ShoreZone crosswalk to ESI.

Substrate	BC_CLASS and BC_CLASS_desc		ESI Exposed	ESI Sheltered	Other information needed
Rock	1	Rock Ramp wide	2A	2A	
	2	Rock Platform wide	2A	2A	
	3	Rock Cliff	1A	8A	
	4	Platform w sand beach wide	3A/2A, 4/2A	3A/2A, 4/2A	sediment size (sand) & order
	5	Rock Platform narrow	2A	2A	may be other shoreline type
Rock + Sediment	6	Ramp w gravel beach wide	6A/2A, 6B/2A	6A/2A, 6B/2A	sediment size (sand) & order
	7	Platform w gravel beach wide	6A/2A, 6B/2A	6A/2A, 6B/2A	sediment size (sand) & order
	8	Cliff w gravel beach	1C, 1A/6A, 1A/6B	8A/6A, 8A/6B	sediment size (sand) & order
	9	Ramp w gravel beach	6A/2A, 6B/2A	6A/2A, 6B/2A	sediment size (sand) & order
	10	Platform with gravel beach	6A/2A, 6B/2A	6A/2A, 6B/2A	sediment size (sand) & order
	11	Ramp w gravel & sand beach wide	5/2A	5/2A	order
	12	Platform w G&S beach wide	5/2A	5/2A	order
	13	Cliff w gravel/sand beach	1A/5	8A/5	
	14	Ramp w gravel/sand beach	6A/2A, 6B/2A	6A/2A, 6B/2A	sediment size (sand) & order
	15	Platform with gravel/sand beach	6A/2A, 6B/2A	6A/2A, 6B/2A	sediment size (sand) & order
	16	Ramp w sand beach wide	3A/2A, 4/2A	3A/2A, 4/2A	sediment size (sand) & order
	17	Platform w sand beach wide	3A/2A, 4/2A	3A/2A, 4/2A	sediment size (sand) & order
	18	Cliff w sand beach	1A/3A, 1A/4	8A/3A, 8A/4	sediment size
	19	Ramp w sand beach narrow	3A/2A, 4/2A	3A/2A, 4/2A	sediment size (sand) & order
	20	Platform w sand beach narrow	3A/2A, 4/2A	3A/2A, 4/2A	sediment size (sand) & order
Sediment	21	Gravel flat wide	7	9A	
	22	Gravel beach narrow	6A, 6B	6A, 6B	sediment size
	23	Gravel flat or fan	7	9A	
	24	Sand & gravel flat or fan	7	8A	
	25	Sand & gravel beach narrow	5	5	
	26	Sand & gravel flat or fan	7	9A	
	27	Sand beach	3A, 4	3A, 4	sediment size
	28	Sand flat	7	9A	
	29	Mudflat	7	9A	
	30	Sand beach	3A, 4	3A, 4	sediment size
Estuarine	31	Organics/Fines	10A, 10B, 10D	10A, 10B, 10D	wetland type
Anthropogenic	32	Man-made permeable	6C	8C	
	33	Man-made impermeable	1B	8B	
Current-Dominated	34	Channel			Need materials or form
Ice	35	Glacial ice shoreline	NA	NA	
Lagoon	36	Lagoon	NA	NA	
Periglacial/ Permafrost	37	Inundated tundra	10E	10E	
	38	Ground ice slumps			Need materials or form
	39	Low vegetated peat	8E	8E	



COMP_A1	Form1_A1	MatPrefix1_A1	Mat1_A1	FormMat1Text_A1
1	Up	<Null>	Bgp/	Form: [Tundra], [plain or level surface]; Materials: [Biogenic], [grass on dunes, peat]
1	Ur	<Null>	Bgp/	Form: [Tundra], [ramp]; Materials: [Biogenic], [grass on dunes, peat]
1	Bb	<Null>	Bg/Csp	Form: [Beach], [berm]; Materials: [Biogenic], [coarse shell, grass on dunes, peat] O
1	Bpr	<Null>	Bgo/	Form: [Beach], [plain, ridge (single intertidal bar)]; Materials: [Biogenic], [grass on du
1	Cail	<Null>	Bg/	Form: [Cliff], [eroding, inclined (20to35deg), low (<5m)]; Materials: [Biogenic], [grass
1	Bpw	<Null>	Bg/Csp	Form: [Beach], [plain, washover fan]; Materials: [Biogenic], [coarse shell, grass on d
1	Uiop	<Null>	Bgo/	Form: [Tundra], [inundated, isolated thaw ponds, plain or level surface]; Materials: [B
1	Bs	<Null>	Bg/Cs	Form: [Beach], [storm ridge]; Materials: [Biogenic], [coarse shell, grass on dunes] O

(0 out of 176755 Selected)

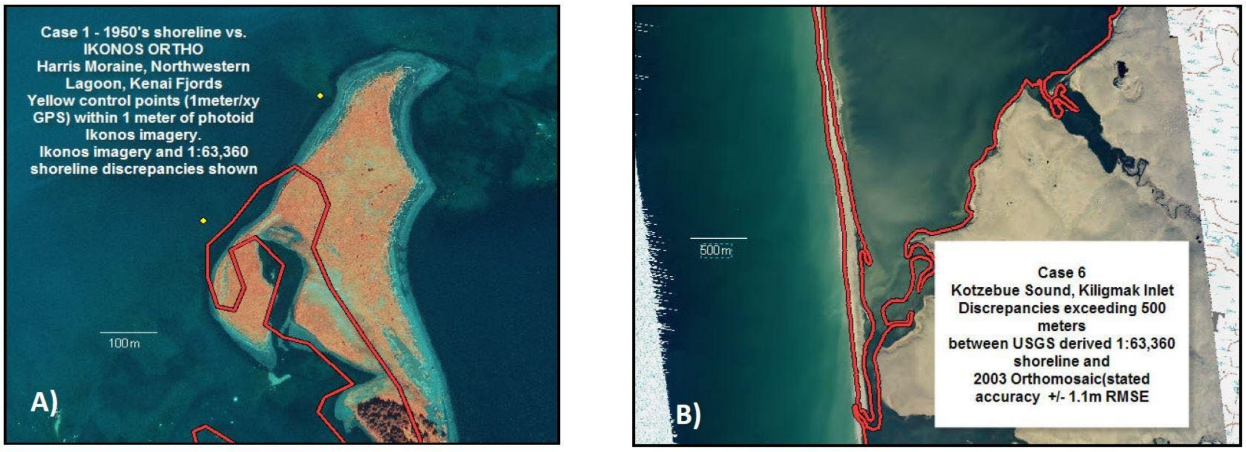
Figure 1. A sample of some of the form and material attributes in ShoreZone.

The spatial framework of ShoreZone is dependent on the digital shoreline. The 2017 ShoreZone Protocol states that in Alaska, "the operational standard for most ShoreZone mapping is the NOAA Coast63 shoreline which is a rough cartographic representation of the Mean High Water line derived primarily from United States Geological Survey (USGS) topographic maps at 1:63,360 scale," much of which is "based on ca. 1950 aerial photographs." Over 11% of the ShoreZone shoreline in Alaska is derived from Coast63. Dates for approximately 72% of sources for Alaska ShoreZone shoreline have been determined and range from 1942 to 2021, and over 18% are older than 1955. Dates for Washington ShoreZone shoreline range from 1994 to 2000, and dates for Oregon range from 2011 to 2014.

Older datasets present a variety of issues that make them incompatible for use as the primary ESI vector shoreline. Several of these older areas in ShoreZone were examined in more detail and compared to more recent ESRI World Imagery. As seen in the examples that follow, the ShoreZone shoreline is sometimes very coarse and/or does not match what is seen in the more recent satellite imagery (Figure 2). In some areas, there is a noticeable shift between the ShoreZone shoreline and what is seen in the imagery (Figure 3), most likely due to a datum transformation issue. In the 2017 ShoreZone Protocol, the resolution issue was addressed. The discrepancies are thus noted in the ShoreZone database by the SHORE_PROB attribute.


WV02 Imagery 2017/2022

Figure 2. A comparison of ShoreZone (blue) and the 2017/2022 WV02 ESRI World Imagery.


Case 1 - 1950's shoreline vs. IKONOS ORTHO
Harris Moraine, Northwestern Lagoon, Kenai Fjords
Yellow control points (1meter/xy GPS) within 1 meter of photoid Ikonos imagery.
Ikonos imagery and 1:63,360 shoreline discrepancies shown

Case 6
Kotzebue Sound, Kiligmak Inlet
Discrepancies exceeding 500 meters
between USGS derived 1:63,360 shoreline and
2003 Orthomosaic(stated accuracy +/- 1.1m RMSE

Figure 3. Discrepancies between the Coast 63 digital shoreline and satellite imagery for two National Parks in Alaska. A) Kenai Fjords and B) Kotzebue Sound. From Figure 9 in Cook et al. (2017).

Crosswalk: NOAA Coastal and Marine Ecological Classification Standard (CMECS)

The Coastal and Marine Ecological Classification Standard (CMECS) provides a national standard for describing coastal and marina ecological features. CMECS is designed to meet the varied needs of a broad audience. CMECS characterizes the marine and coastal environment as distinct environmental units with two attributes based on two settings and four components (Figure 4). The two broad-based settings attributes, the Aquatic Setting (AS) and Biogeographic Setting (BS), offer alternate but complementary approaches for partitioning the marine and coastal environment. The various components, Biotic Component (BC), Geoform Component (GC), Substrate Component (SC), and Water Column Component (WC) provide specific tools for describing observations. CMECS users may employ one or both settings and one or more components to classify environmental units. CMECS components include a variety of modifiers to enhance the specificity and detail of resulting descriptions and classifications. As part of this investigation, we investigated both the potential to crosswalk existing shoreline and intertidal habitat data utilizing the CMECS standard to the ESI shoreline classification.

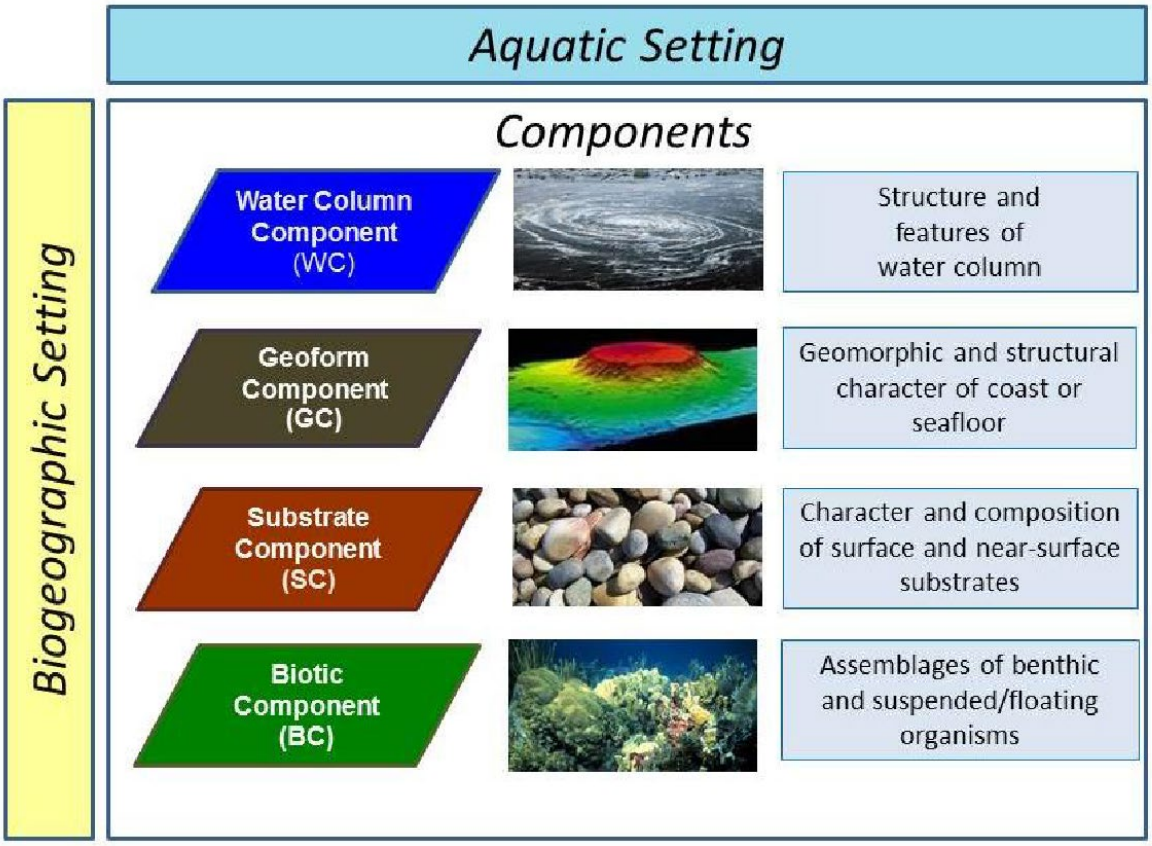
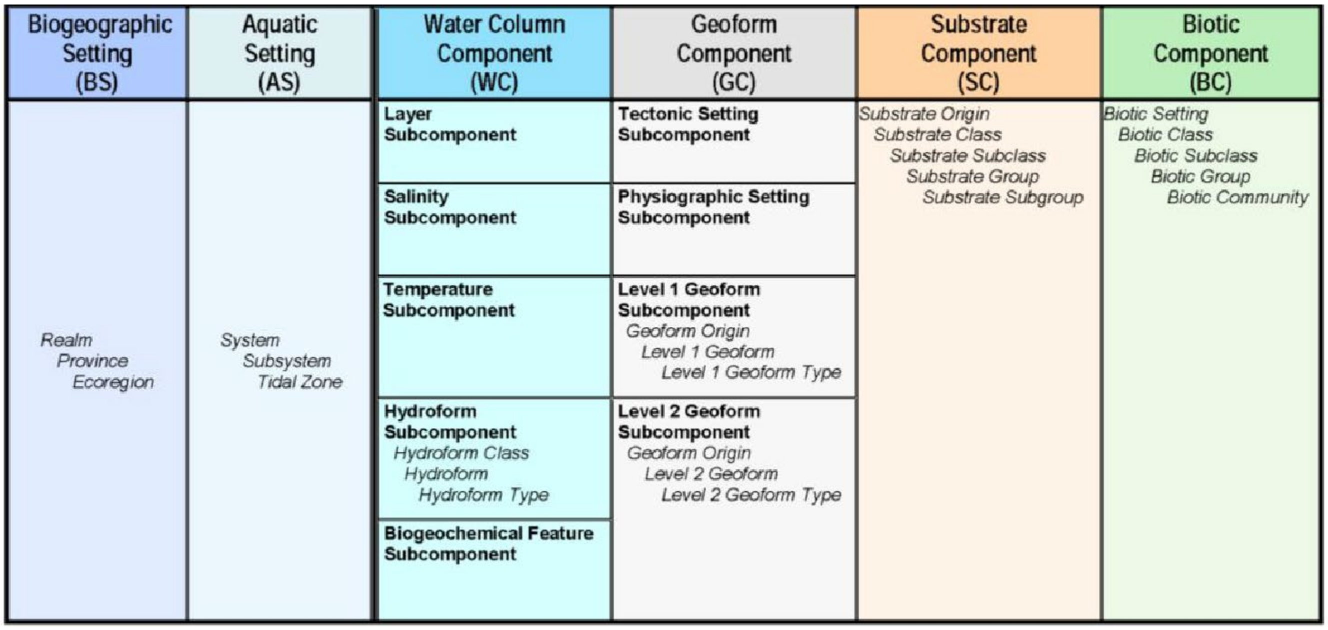


Figure 4. CMECS Settings and Components.

The AS is comprised of three hierarchical levels (System, Subsystem, and Tidal Zone) and provides the context for all CMECS components. It distinguishes oceans, estuaries and lakes, deep and shallow waters, and submerged and intertidal environments within which more refined classification of geological, physicochemical, and biological information can be organized. The BS is based on the *Marine Ecoregions of the World* (MEOW) and uses a nested, three-tiered system of realms, provinces, and ecoregions (moving from larger-scale to smaller-scale units) to describe the biogeographic elements of the estuarine system and the marine nearshore and offshore subsystems. MEOW (Spalding et al., 2007) does not extend inland to include freshwater systems. CMECS is currently using an approach taken by Abell et al. (2008) as an interim means for defining biogeographic units in the Great Lakes.

The BC is a hierarchical classification that identifies (a) the composition of floating and suspended biota and (b) the biological composition of coastal and marine benthos. The GC describes the major geomorphic and structural characteristics of the coast and seafloor. This component is divided into four subcomponents that describe Tectonic and Physiographic Settings and two levels of Geoform elements that include geological, biogenic, and anthropogenic geoform features. The SC describes the composition and size of substrate materials in all CMECS systems. This component is hierarchical and encompasses substrates of geologic, biogenic, and anthropogenic origin. Particle size classes conform to those developed by Wentworth (1922) and substrate mixes conform to the standard described by Folk (1954). Finally, the WC describes the water column in terms of vertical layering, water temperature and salinity conditions, hydroforms, and biogeochemical features. Modifiers allow users to further subdivide water column units. Units within the BC and SC are organized into traditional hierarchical frameworks; however, this is not the case for the WC and the GC. Units within each of the latter overlap significantly in nature and do not lend themselves to hierarchies (Figure 5).



Biogeographic Setting (BS)	Aquatic Setting (AS)	Water Column Component (WC)	Geoform Component (GC)	Substrate Component (SC)	Biotic Component (BC)
Realm *Province* *Ecoregion*	*System* *Subsystem* *Tidal Zone*	**Layer Subcomponent**	**Tectonic Setting Subcomponent**	*Substrate Origin* *Substrate Class* *Substrate Subclass* *Substrate Group* *Substrate Subgroup*	*Biotic Setting* *Biotic Class* *Biotic Subclass* *Biotic Group* *Biotic Community*
		Salinity Subcomponent	**Physiographic Setting Subcomponent**		
		Temperature Subcomponent	**Level 1 Geoform Subcomponent** *Geoform Origin* *Level 1 Geoform* *Level 1 Geoform Type*		
		Hydroform Subcomponent *Hydroform Class* *Hydroform* *Hydroform Type*	**Level 2 Geoform Subcomponent** *Geoform Origin* *Level 2 Geoform* *Level 2 Geoform Type*		
		Biogeochemical Feature Subcomponent			

Figure 5. CMECS Settings and Components. AS, BS, BC, and SC are internally hierarchical. WC and GC include non-hierarchical subcomponents.

Each CMECS component is autonomous (i.e., designed to be classified and mapped independently of the others), but components can be combined as necessary, depending on application. This is analogous to combining information from independent land cover, landform, and soil classifications (in terrestrial classifications) to describe specific locations on land. Environmental units may be spatially represented as points, lines, polygons, and grids according to CMECS. In practice, however, most local or regional data utilizing the CMECS standard consist of polygons or grids, rather than linear features.

The attributes present in CMECS data permit a crosswalk from the CMECS standard to the ESI classification system. The table in Appendix A (see accompanying MS Excel spreadsheet) describes this crosswalk in detail. Each ESI classification was reviewed for its description and prior usage. Next, the CMECS document and spreadsheet were reviewed to determine if any of the CMECS units met the description of the ESI classification. Most ESI classifications could be found within CMECS; however, there were several ESIs that currently do not have any CMECS unit in Appendix A.

CMECS is not necessarily a shoreline classification system, though it can be used for that purpose. While a crosswalk of CMECS to ESI is possible, use of CMECS-compliant data for this purpose is presently limited, due to high variability in level of classification detail, spatial data representation format, and spatial scale in various CMECS data sets. These characteristics make it difficult to identify datasets that fit the level of classification for the crosswalk and at a spatial scale required for ESI products. Based on CMECS data available at the time of publication, a more likely use of data utilizing this standard would be for benthic habitat information rather than shoreline classification.

National ESI to CMECS Conversion

Though use of crosswalked CMECS data as a source of ESI shoreline classification data may be limited, ESI shoreline data are well suited to be crosswalked to the CMECS standard which may broaden their utility. To investigate this potential, RPI generated a merged national ESI shoreline including all available ESI shoreline data in the continental United States (CONUS) converted to the CMECS standard. Shorelines in the Great Lakes, Alaska, Hawaii, and other U.S. territories were excluded to focus on the core marine and estuarine environments of the US. To accomplish this task, existing merged national ESI shoreline data were obtained from NOAA (NOAA ERD, 2017). This shoreline was then updated with any published ESI shoreline data more recent than the publication of the master shoreline data – specifically, data from East Florida. Data at the margins of all atlas boundaries were then edge-matched, giving preference to more recent shoreline data. Finally, this updated master CONUS-wide ESI shoreline dataset was split into three separate adjoining datasets to reduce total size of files and ease processing: the Pacific coast, the Atlantic coast, and the Gulf of Mexico and Florida. The boundary between the Gulf of Mexico data and Atlantic data was placed at the border between Florida and Georgia along the St. Mary’s River to avoid splitting individual states or ESI atlas source data (Figure 6).

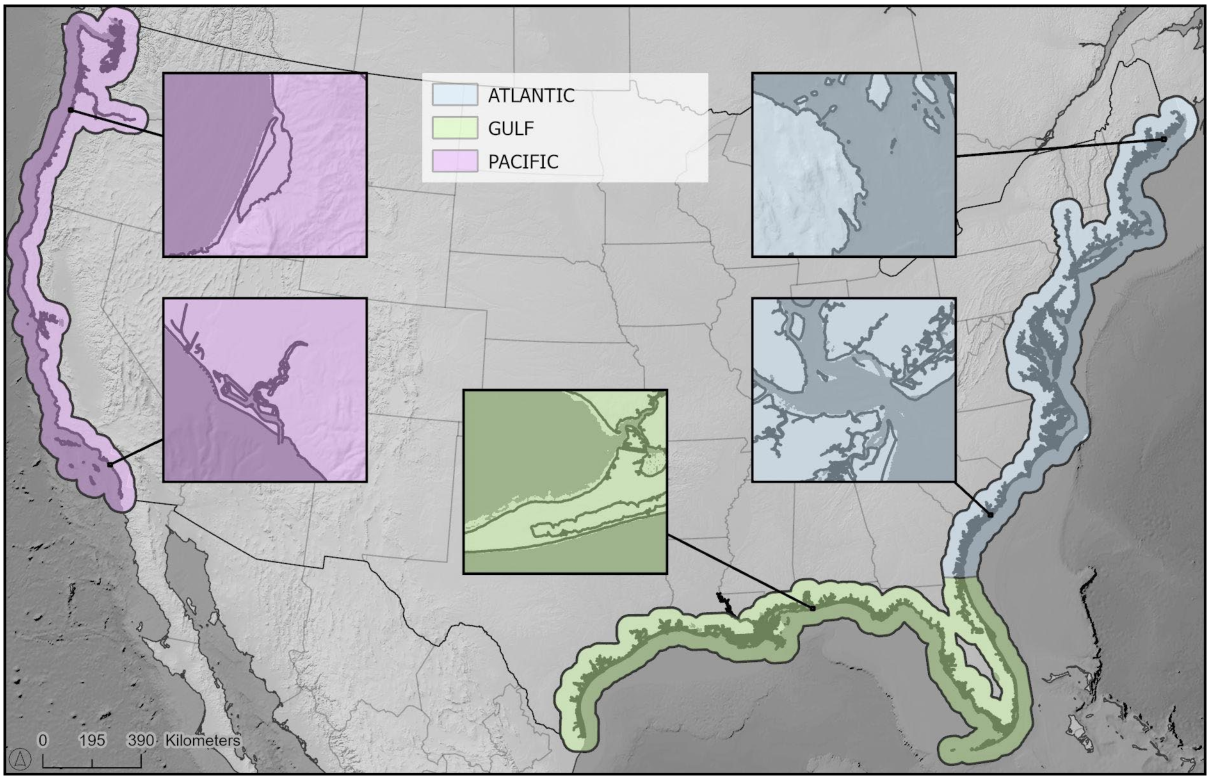


Figure 6. Extent and regional divisions of updated master CONUS-wide ESI shoreline dataset.

Shoreline features in the updated master CONUS-wide ESI shoreline dataset classified according to the ESI standard were crosswalked to the CMECS as follows. We firstly developed overlay polygons to assign multiple broad-scale attributes required by CMECS to all shoreline segments in the updated master CONUS-wide ESI shoreline dataset. These overlay polygons were based upon unique combinations of the input data, and modified for the purposes of intersection with the shoreline database to ensure that all shoreline segments were contained within the intended update polygon. These polygons also describe spatially constrained landscape-level geomorphological structures into which individual shoreline segments may be grouped. These large features—generally on the scale of dozens or hundreds of square kilometers – are then further grouped and assigned unique Aquatic and Biogeographic Setting (AS and BS) attributes.

Each overlay polygon was assigned to a biogeographic setting per CMECS after the approach described by Spalding et al. (2007) in Marine Ecosystems of the World (MEOW) to characterize Biogeographic Settings occurring in the Estuarine System and in the Marine Systems. These overlay polygons were also assigned to an aquatic setting. Overlay polygons were constructed to partition all shoreline segments into either marine or estuarine systems as required by CMECS after the FGDC (2012). This process was complex. The definition, and thus spatial extent, of an estuary, whilst seemingly simple, has been subject to substantial ambiguity by researcher and discipline (Pritchard, 1967; Kjerfve, 1989; Fairbridge, 1980). For this purpose, the conceptual and spatial definition of an estuary given by Pritchard was adopted: a semi-enclosed body of water having a free connection with the open sea and within which seawater is measurably diluted with fresh water derived from land drainage. When dividing overlay polygons into marine and estuarine systems, generally the boundary was placed across the narrowest portion of the opening between the estuary and the open sea. All polygons in the marine system were assumed to be the in the nearshore subsystem and intertidal habitat. All polygons in the estuarine system were further subdivided into coastal and tidal riverine coastal subsystems. Estuarine coastal systems were assumed to extend from the boundary with the marine system inland. Estuarine tidal riverine coastal subsystems include the most upstream regions of the estuary that can be regularly influenced by tides (to the head of tides) and/or where salinity is generally below 0.5 during the period of annual low flow. This was accomplished using national scale estuarine salinity zone data obtained from NOAA NCEI (Nelson, 2015; Bricker et al., 2007) reconciled with the extent of each polygon.

All polygons were also assigned to a Tectonic Setting per CMECS, derived from Inman and Nordstrom (1971) as and to a Physiographic Setting. Physiographic Settings describing spatially constrained landscape-level geomorphological structures into which individual shoreline segments may be grouped. Most classifications describing Physiographic Settings in the current CMECS (FGDC, 2012) are taken from Greene et al. (2007) though the definitions of various estuaries have been expanded by Madden et al. (2008). Because we are assigning a physiographic setting to linear shoreline features, we are faced with a particular challenge in that many of the existing CMECS settings are intended to describe marine features (e.g., an estuary, or continental shelf) whereas the features we are classifying are intertidal and generally form the boundaries of the conceptual entities outlined in the CMECS standard, rather than the features themselves. For these reasons, elaboration upon Physiographic Setting categories was required for the purposes of converting linear ESI shoreline data.

We refined and elaborated upon the categories to define Physiographic Settings present in CEMCS (FGDC, 2012) by including classifications modified and simplified from Shepard (1973) and Gornitz et al. (1994). We also integrated the work of Heady et al. (2014) who provide a more refined and thorough classification of the estuaries of the west coast of CONUS. In delineating boundaries between areas with different physiographic settings, we borrowed heavily from the spatial data from Gornitz and White (1992, 1994) and Gornitz et al. (1997) as described in Gornitz et al. (1994). These data were used together with polygonal data describing the boundaries of data obtained from EPA's Estuary Data Mapper (EDM) software and database - originally derived from the EPA's Environmental Monitoring & Assessment Program – to generate boundaries of overlay polygons for the purpose of assigning CMECS attributes to shoreline segments. Table 4 describes the Physiographic Setting categories adopted here. Because several of the Physiographic Setting categories are not officially present in CMECS, they are considered provisional at present. Figure 7 depicts the overlay polygons symbolized by assigned CMECS AS System and Subsystem and Physiographic Setting.

In the context of CMECS, each individual unique shoreline segment in the updated master CONUS-wide ESI shoreline dataset is considered as the smallest environmental unit. As such, the overlay polygons were used to assign attributes to all segments in the updated master CONUS-wide ESI shoreline dataset. After this, a segment specific crosswalk was used to assign Geoform Component and Substrate Component attributes to each segment based upon the ESI codes and other ESI line segment attributes via heuristic rule sets. The table in Appendix B (see accompanying MS Excel spreadsheet) describes this crosswalk in detail. See the attached generated CMECS dataset in ESRI File Geodatabase format. Note that some of Geoform types are also not officially present in CMECS, though they were required to represent linear features in a logically consistent way, so they are considered provisional at present. Figure 8 depicts shoreline segments symbolized by landward-most CMECS Geoform Component Level 1 Geoform Type and Substrate Component Class and Group.

Table 4. Description of Physiographic Setting categories adopted for classification of ESI shoreline segments compliant with CMECS.

Physiographic Setting	Setting	Primary Agent (Shepard, Gornitz)	Parent Material
Fjord	Estuarine	Glacial erosion	rock
Fjard	Estuarine	Glacial erosion	rock
Riverine estuary	Estuarine	Fluvial erosion	fluvially-deposited sediments
Coastal plain estuary	Estuarine	Fluvial erosion	fluvially-deposited sediments
Deltaic estuary	Estuarine	Fluvial deposition	fluvially-deposited sediments
Lagoonal estuary	Estuarine	Marine deposition	marine-deposited sediments
Karst estuary	Estuarine	Groundwater inflow	rock
Tectonic embayment	Estuarine	Tectonic Activity	variable
Erosional, rocky coast	Marine	Marine erosion	rock
Erosional, marine deposit coast	Marine	Marine erosion	marine-deposited sediments
Barrier, marine deposit coast	Marine	Marine deposition	marine-deposited sediments
Coastal plain, marine deposit coast	Marine	Marine deposition	marine-deposited sediments
Alluvial plain coast	Marine	Fluvial deposition	fluvially-deposited sediments
Glacial deposit coast	Marine	Glacial deposition	glacially-deposited sediments
Biogenic	Marine	Biological deposition	marine-deposited sediments
Glacial trough	Marine	Glacial erosion	rock

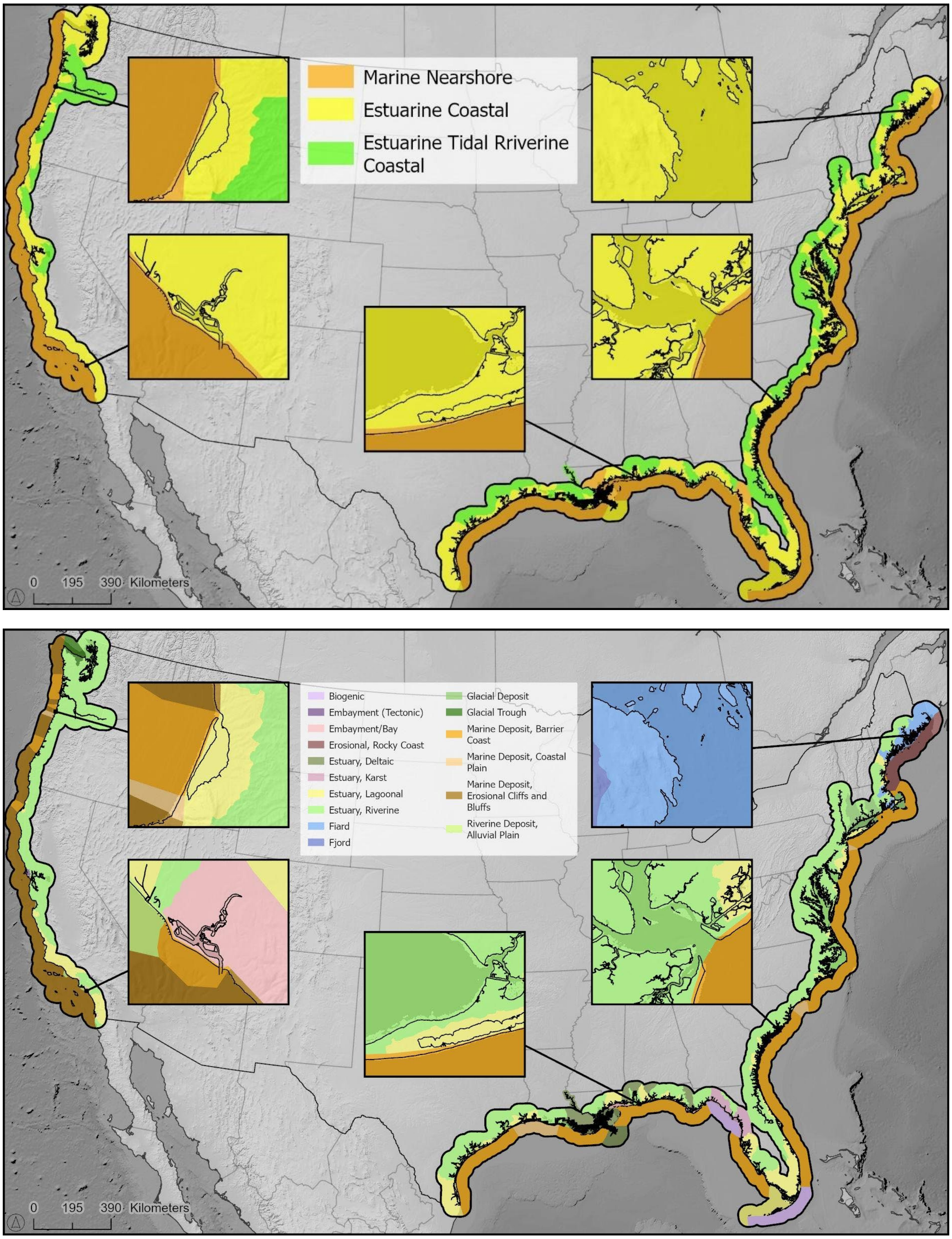


Figure 7. Overlay polygons symbolized by assigned CMECS Aquatic Setting system and subsystem (top); and CMECS Physiographic Setting subcomponent (bottom). Line segments from the updated master CONUS-wide ESI shoreline dataset are depicted as well.

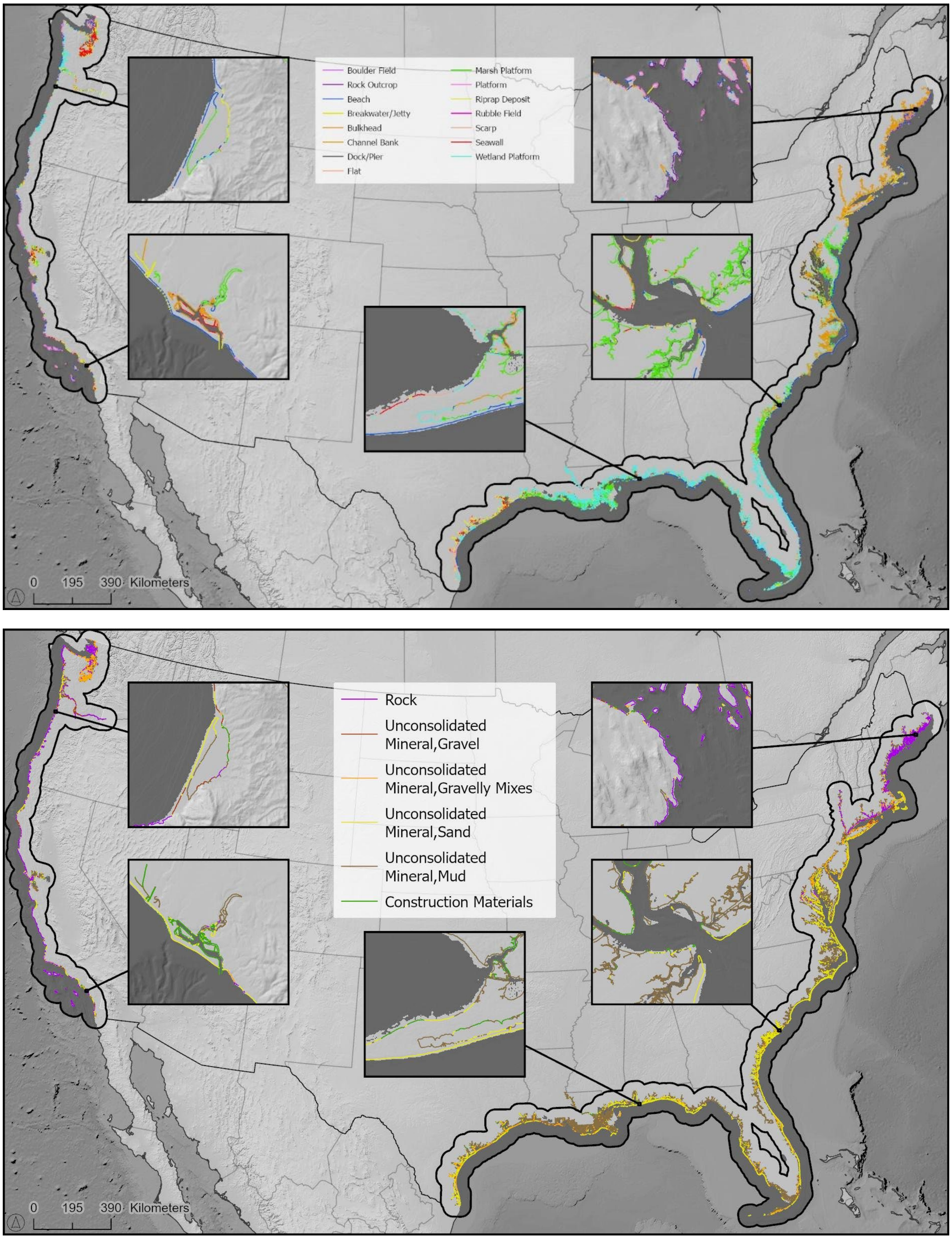


Figure 8. Individual shoreline segments symbolized by landward-most CMECS Geoform Component Level 1 Geoform Type (top); and landward-most CMECS Substrate Component Class and Group (bottom).

Method: Exposure Modeling

In many of the crosswalk systems noted above, no information is available to distinguish between sheltered or exposed shorelines and ESI codes. In the past, distinguishing between exposed and sheltered shorelines was done manually based upon map data and expert assessment of incident wave and current energy during overflights and fieldwork. More recently, simplified fetch models have been used to assign exposure modifiers to ESI shoreline segments in a more automated and defensible way. Using this method, the hydrology polygons for a given ESI atlas are used to derive a land-water grid at 30-m resolution, and overwater fetch is computed along 8 radials at 45-dgree increments using code and methods adapted from Rohwehder et al. (2012).

The advent of publicly available newly generated high resolution, nearshore wave climate modeling output from long-term hindcast models data has the potential to improve shoreline exposure classification beyond what is possible with calculation of fetch, and derivative values. Figure 9 depicts an example fetch calculation for coastal South Carolina, and a map of modeled mean significant wave height from USGS climatological wave data generated via long-term hindcast for the Atlantic and Gulf coasts (Aretxabaleta et al., 2022). Wave model output more accurately reflects the physics of wave propagation from the open ocean into estuaries and bays and is more directly related to properties of interest regarding shoreline classification. Though the USGS data do not cover the Pacific coast, other data sets may be (Yang et al., 2019) or are already publicly available (Garcia-Medina et al., 2019; Allahdadi et al.,2019) will permit complete coverage of nearshore areas across CONUS.

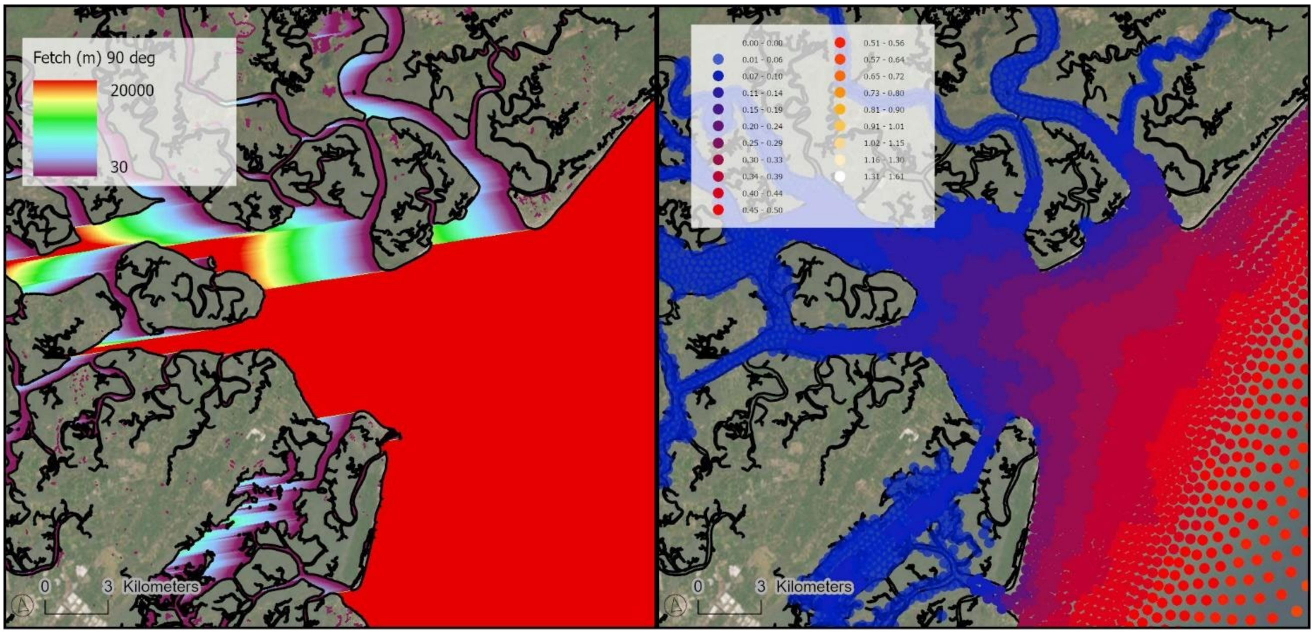


Figure 9. Example single-direction fetch calculation for coastal South Carolina using code adapted from Rohwehder et al. (2012) (left) and mean significant wave height from long-term hindcast wave climatology (Aretxabaleta et al., 2022) (right).

Method: Remotely Sensed Flat Extraction

Many of the shoreline mapping systems and classification systems described above do not explicitly map or categorize intertidal flats. In ESI data, intertidal flats are mapped as both polygonal features and as codes assigned to shoreline segments. There have been many recent advances in remotely sensed intertidal flat extraction from moderate-resolution satellite imagery time series (Fitton et al., 2021; Jia et al., 2021; Sagar et al., 2017). To investigate the potential for applying this technique for ESI shoreline classification, we conducted an experiment at six example areas, each 5 km by 5 km, distributed across the coastal and estuarine extent in CONUS. These experimental tiles were intentionally located in areas with intertidal flats present, and where ESI shoreline segments from the updated US-wide national ESI shoreline dataset described above were attributed with codes indicating intertidal flats (ESI code = 7, 9A, or 9C).

In each experimental tile, we computed inundation frequency using time series of Sentinel-2 imagery. For each tile, we used Google Earth Engine (Gorelick et al., 2017) to compile all available individual Sentinel-2 imagery scenes with less than 5% cloud cover from 2013 to the present and classify them into land and water using methods simplified from Sagar et al. (2017), Fitton et al. (2021) and Jia et al. (2021). This resulted in a stack of between 213 and 399 satellite images for each experimental tile. For each individual Sentinel-2 scene in each stack, a modified Normalized Difference Water Index (mNDWI) was computed from top-of-atmosphere reflectance after Xu (2006). The percentage of time each pixel was inundated was then computed based upon thresholding the mNDWI values for each scene at 0 and summing the resulting binary scene masks to generate an inundation frequency for each pixel. Results of this analysis are presented in Figures 10-12. Note the generally good correspondence between shoreline with codes indicating intertidal flats and visual extent of areas with extensive intertidal zones. In some locations, the ESI segments with codes indicating intertidal flats appear inconsistent. Also, note that flats are only sometimes visible in aerial imagery, depending on tidal stage, sea state, sun glint, turbidity, and other factors.

Areas with inundation frequencies between approximately 35% or 40% and 95% are likely to represent intertidal flats. Note that this range of inundation frequencies excludes areas that are intertidal but that are above the elevation range of unvegetated intertidal flats (e.g., marshes). These areas may be extracted via threshold and used for polygonal tidal flat mapping. In many areas, satellite imagery would be the only source of these data. In general, this technique holds promise for mapping the extent of intertidal flats when recent tidally controlled aerial imagery is unavailable, and in situ fieldwork at low tide stages is not feasible.

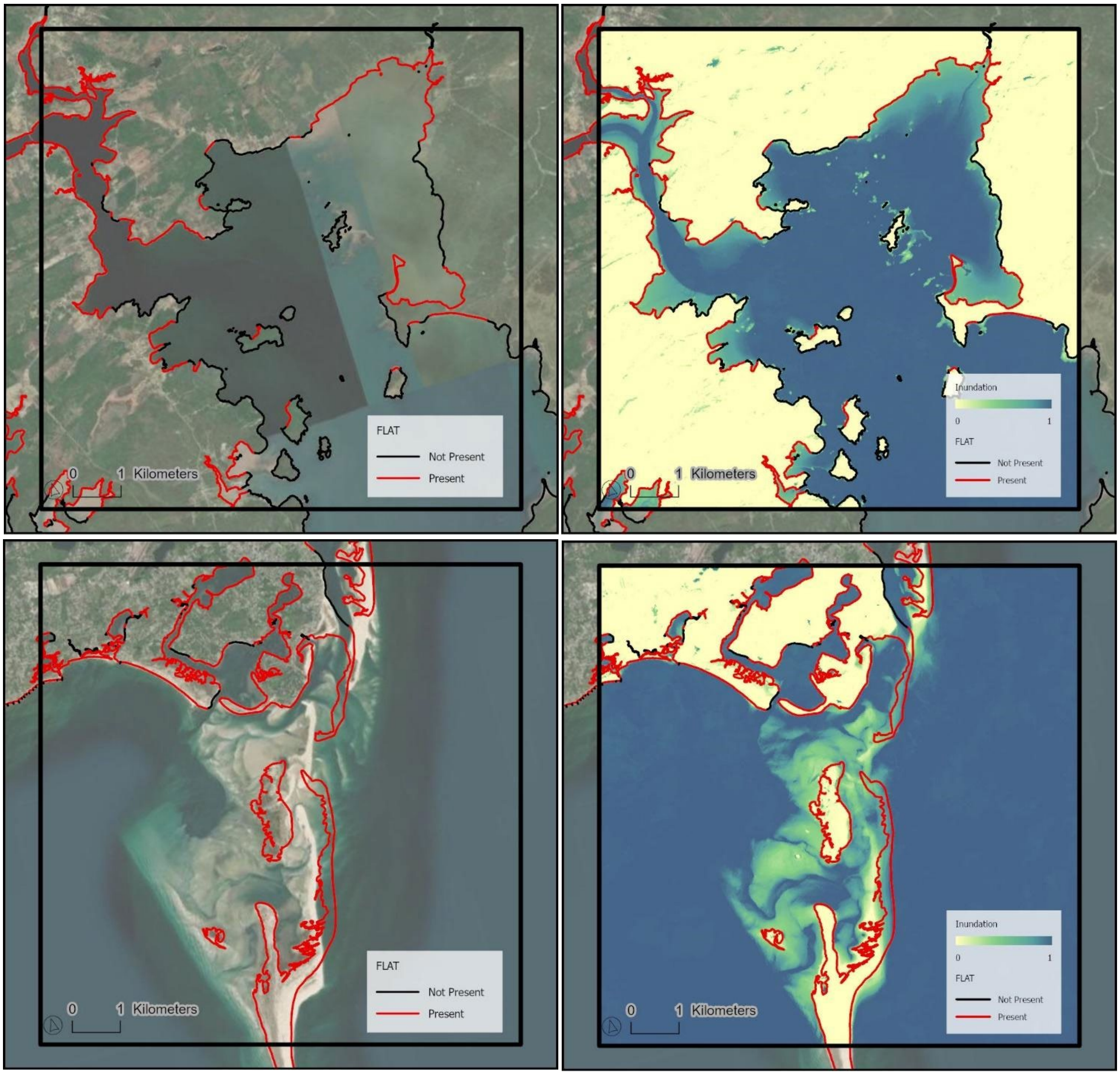


Figure 10. Satellite-derived inundation frequency and extracted intertidal flat extents from Sentinel-2 time series data for test areas in Maine (top row) and Massachusetts (bottom row). ESI shoreline is also depicted, classified by presence of code indicating intertidal flat (ESI code = 7, 9A, or 9C).

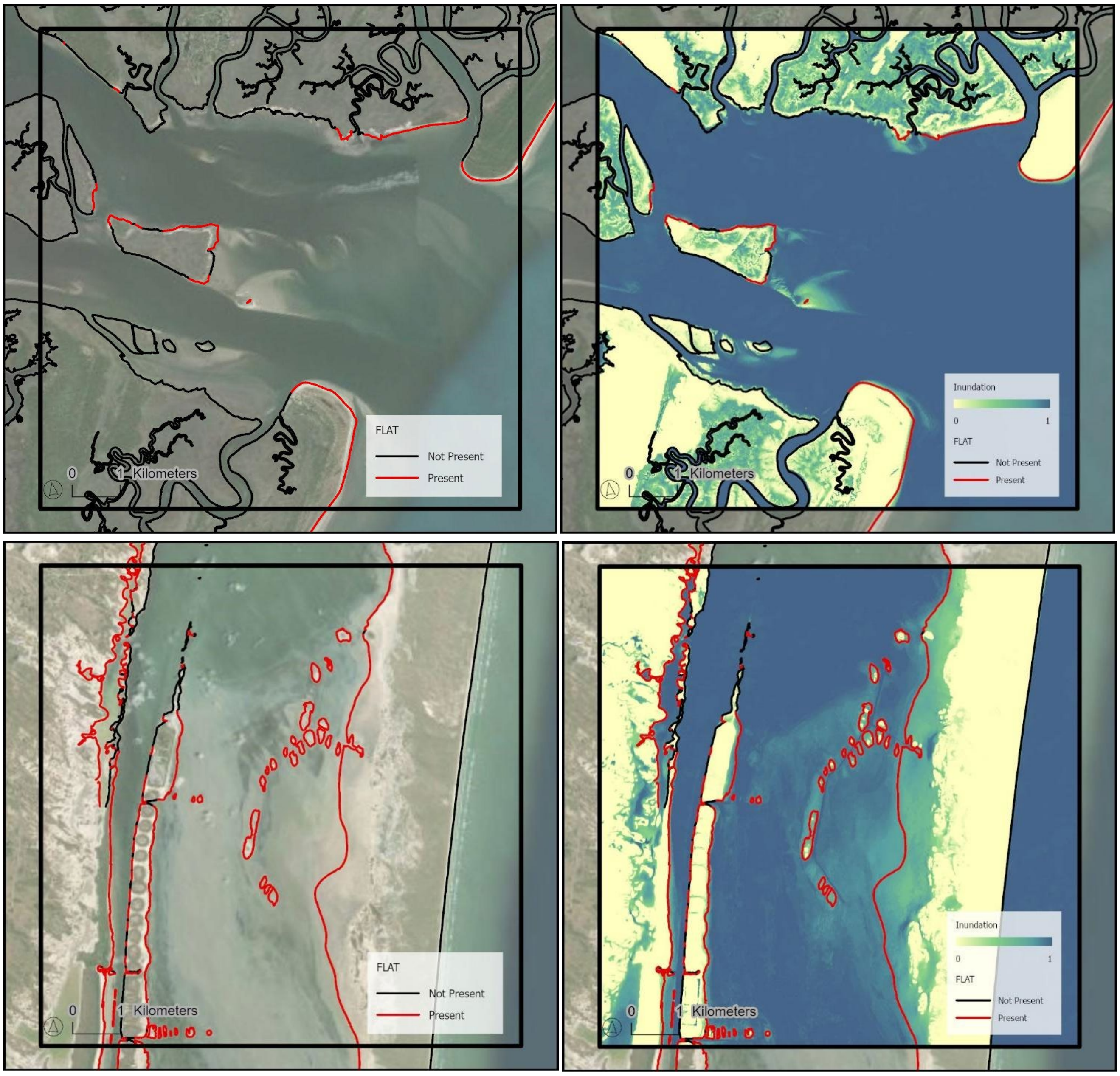


Figure 11. Satellite-derived inundation frequency and extracted intertidal flat extents from Sentinel-2 time series data for test areas in Georgia (top row) and Texas (bottom row). ESI shoreline is also depicted, classified by presence of code indicating intertidal flat (ESI code = 7, 9A, or 9C).

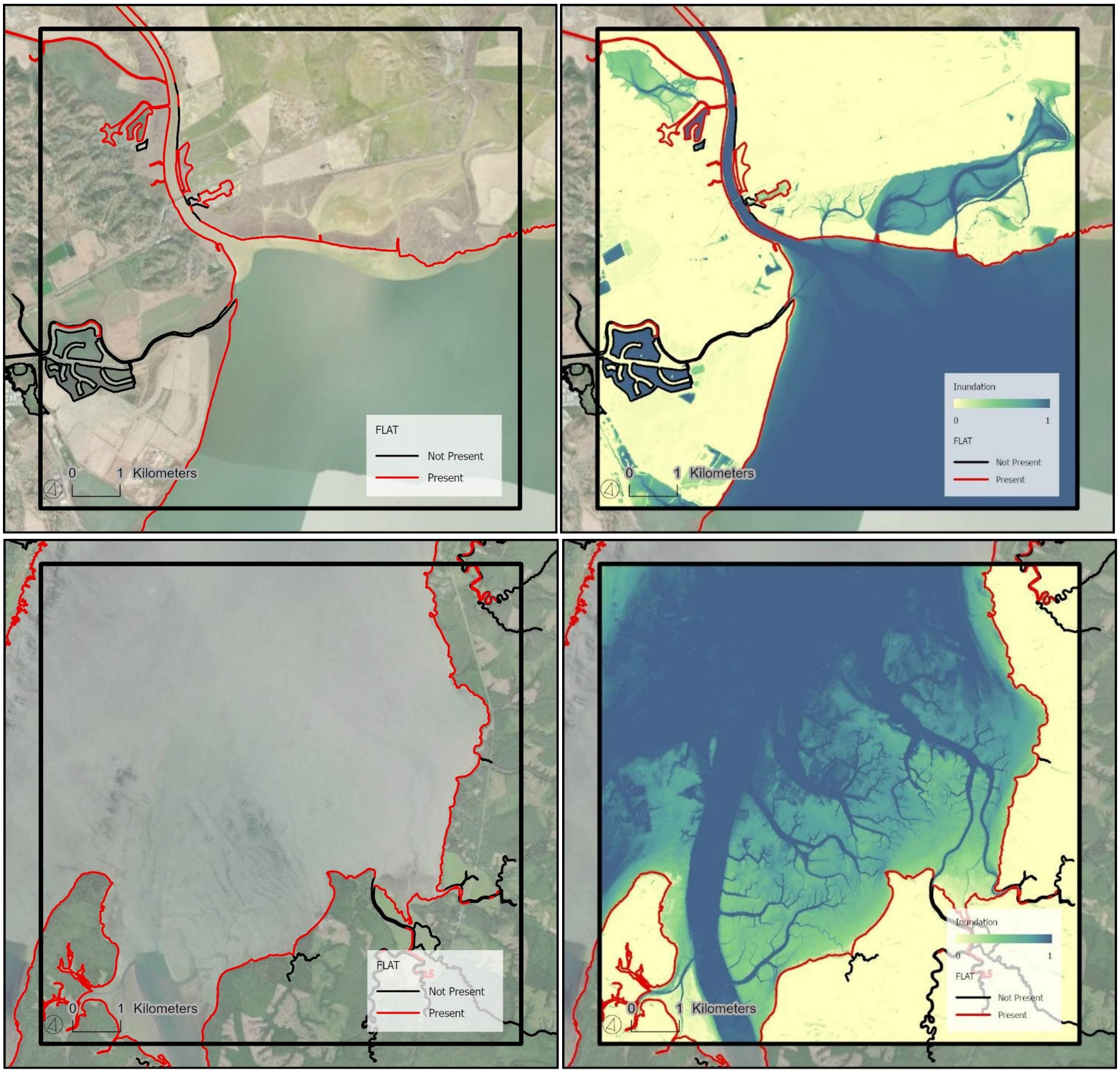


Figure 12. Satellite-derived inundation frequency and extracted intertidal flat extents from Sentinel-2 time series data for test areas in California (top row) and Washington (bottom row). ESI shoreline is also depicted, classified by presence of code indicating intertidal flat (ESI code = 7, 9A, or 9C).

Method: Shoreline Morphology Predictive Models

Other than manmade shoreline types, and wetland/non-wetland shorelines, many of the critical distinctions between ESI shoreline classes can't be made using the crosswalk systems described in the preceding sections. For example, both rocky shorelines and sand beaches are indistinguishable in CUSP. The compiled national ESI dataset, with additional attributes assembled as part of the CMECS crosswalk, represents a uniquely comprehensive body of data with which to attempt to develop a predictive shoreline morphology model that is national in scope and that may improve accuracy and efficiency of attributing shorelines, particularly for classes not included in the other crosswalk systems discussed.

To examine this possibility, we constructed a preliminary shoreline morphology classification model based upon the boosted regression tree algorithm. This model used continental-scale predictors derived from national-scale synoptic spatial data sets. Predictors included elevation derived from the NOAA 3-Arc Second Coastal Relief Models (NOAA NGDC 1999a, 1999b, 2001a, 2001b, 2001c, 2003a, 2003b, 2003c), which incorporate both topographic and bathymetric data. In addition, an elevation ruggedness index was computed as a predictor as the standard deviation of elevation within a 3-by-3 cell moving window (300 m by 300 m). Coastal Land-Use and Land Cover (LULC) was obtained from the NOAA Coastal Change Analysis Program (C-CAP) 2016 Regional Land Cover Data (NOAA OCM, 2023). The LULC data were further processed to yield a set of predictor grids computed as the proportion of area with a 5-by-5 cell moving window (150 m by 150 m) for all developed land use classes, all emergent wetlands, all scrub/shrub wetlands, all forested wetlands, all barren and unconsolidated shore areas, and all water pixels. Also included are the CMECS Aquatic and Biogeomorphic setting variables described in the CMECS section.

Finally, mean significant wave height and estimated mean great diurnal tidal range were derived for every sample location and used as predictors. For sample locations on the Atlantic and Gulf coasts, mean significant wave height was extracted from the nearest grid node in the USGS Climatological Wave data generated via long-term hindcast for the Atlantic and Gulf coasts (Aretxabaleta et al., 2022). For sample locations on the Pacific coast located in outer coast marine settings, mean significant wave height was computed for all via natural neighbor interpolation of the nearshore wave hindcast generated by EPRI (2011) for use in evaluation of wave energy generation. For sample locations on the Pacific coast located in enclosed estuarine settings, mean significant wave height was assumed to be 0.1 m. Great diurnal tidal range (MHHW to MLLW) was also computed for every sample location using the NOAA VDatum software (NOAA NGS, 2023). Sample locations with no extractable tidal range via VDatum were assigned the spring tidal range value from the closest relevant shoreline with a recorded great diurnal tidal range.

A sample of all shorelines was generated by converting all line segments in the updated master CONUS-wide ESI shoreline dataset to a grid at a 1-km resolution and generating a vector point at each grid cell in the resulting grid. These points were then snapped to the nearest location along the line segments in the updated master CONUS-wide ESI shoreline dataset. This yielded a data set of 97,669 sample locations. All attributes of the shoreline segment were extracted at that location, as well as the values of all synoptic predictors as described above (Figures 13 and 14). To more directly model actual shoreline morphology, the ESI code at all sample locations was stripped of any intertidal flat codes if present and collapsed to a single morphological indictor with no modification for exposure or detailed grain size descriptor, yielding the following pure morphological descriptors: rocky, platform, solid man-made structure, riprap, scarp, sand beach, gravel beach, vegetated banks, marsh, swamp, scrub-shrub wetland, and mangrove. See Table 5.

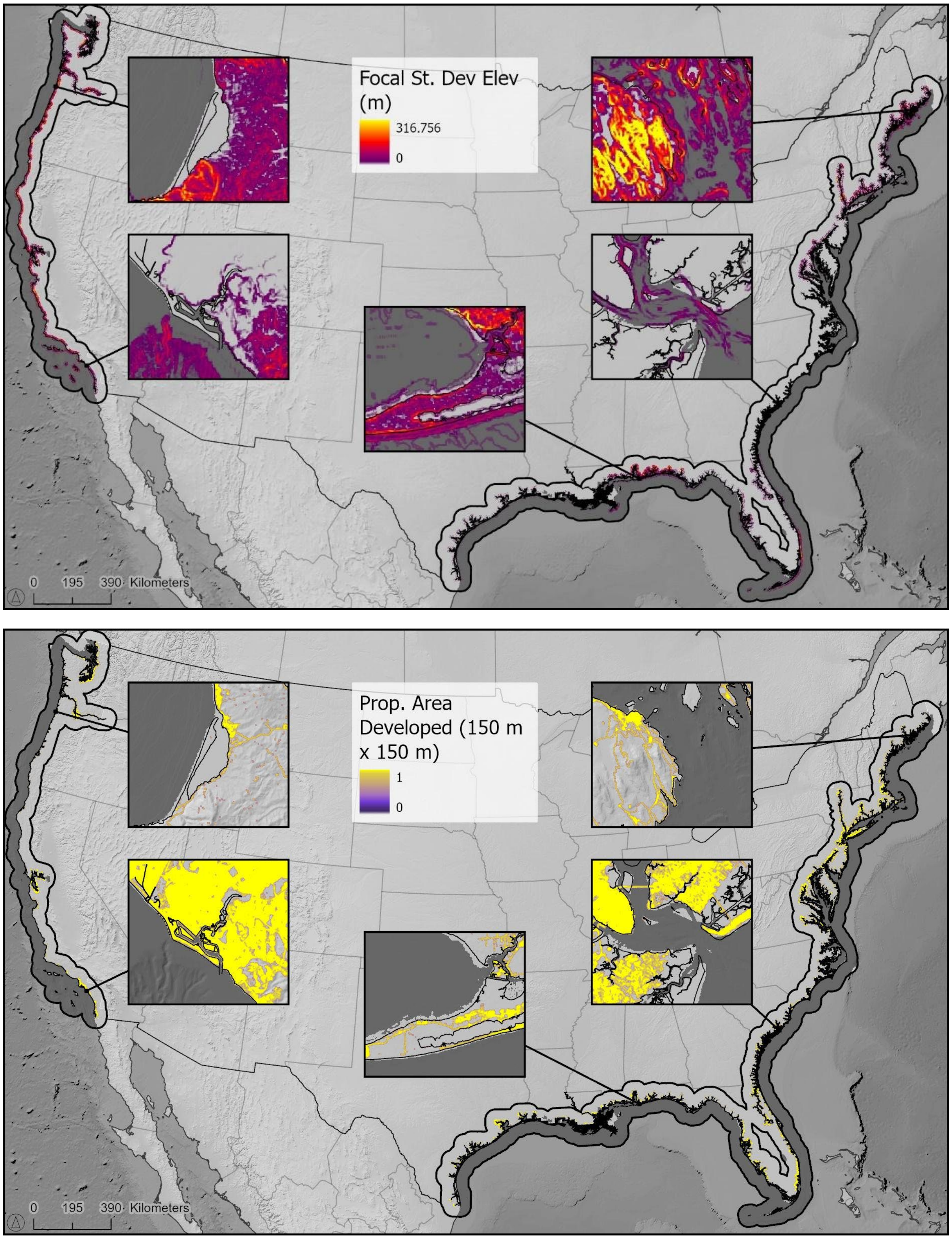


Figure 13. Selected predictor variables: ruggedness index as standard deviation of elevation within 300 m by 300 m moving window in m (top); and proportion of area within 150 m by 150 m moving window as developed land use (bottom). Line segments from the updated master CONUS-wide ESI shoreline dataset are depicted as well.

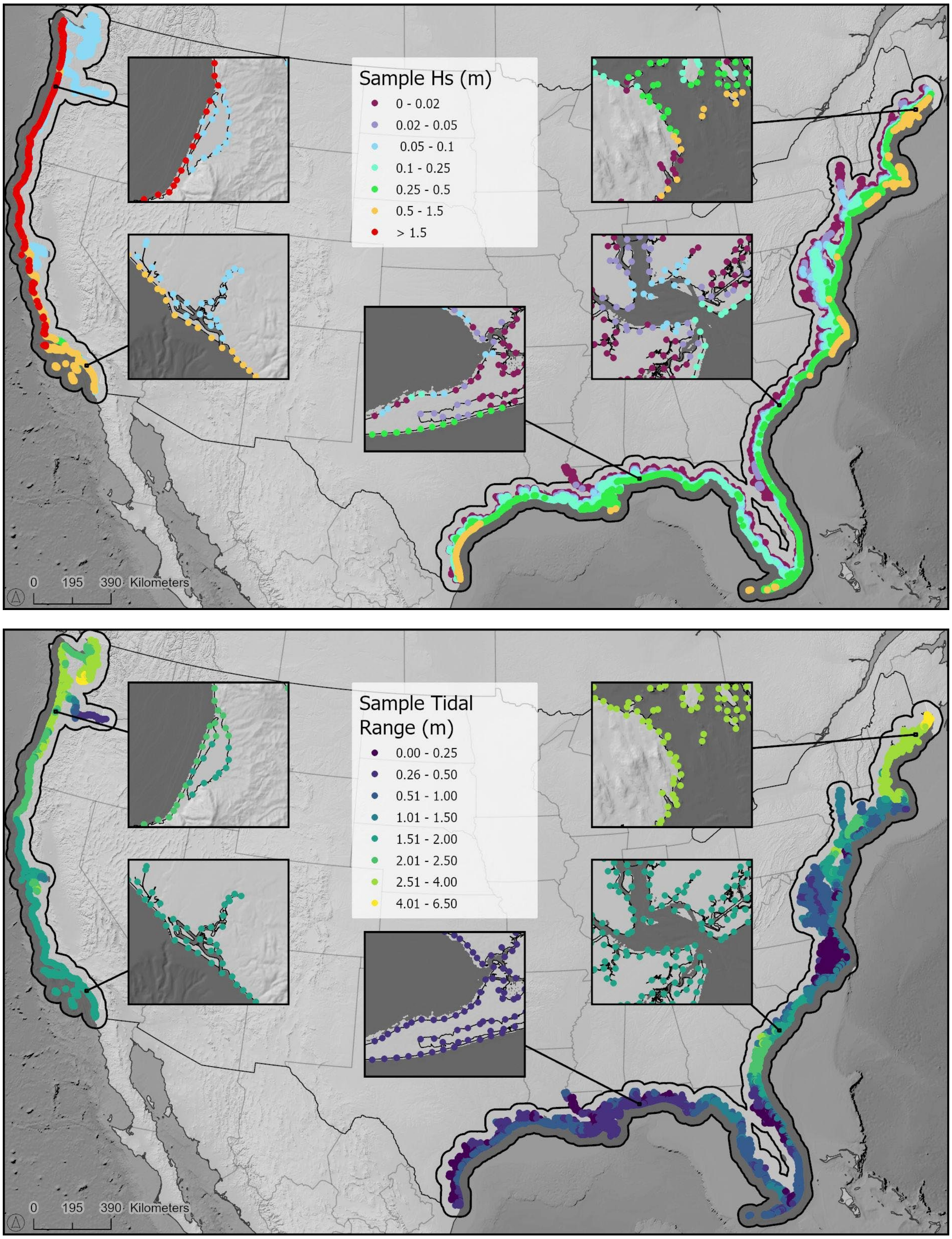


Figure 14. All shoreline sample locations symbolized by selected predictor variables: mean significant wave height in m (Hs) (top); and mean great diurnal tidal range in m (bottom). Line segments from the updated master CONUS-wide ESI shoreline dataset are depicted as well.

Table 5. Simplified morphology classes used for predictive modeling.

ESI Code	Description	Simplified Morphology Class
1A	1A: Exposed rocky shores	Rocky
1B	1B: Exposed, solid man-made structures	Man-made
1C	1C: Exposed rocky cliffs with boulder talus base	Rocky
2A	2A: Exposed, wave-cut platforms in bedrock	Platform
2B	2B: Exposed scarps and steep slopes in mud/clay	Scarp
3A	3A: Fine- to medium-grained sand beaches	Sand beach
3B	3B: Scarps and steep slopes in sand	Scarp
4	Sand beach	Sand beach
5	5: Mixed sand and gravel beaches	Gravel beach
6A	6A: Gravel beaches	Gravel beach
6B	6B: Riprap	Man-made
6D	6D: Boulder rubble	Rocky
8A	8A: Sheltered scarps (bedrock/mud/clay)	Scarp
8A	8A: Sheltered impermeable rocky shores	Rocky
8B	8B: Sheltered, solid man-made structures	Man-made
8C	8C: Sheltered riprap	Man-made
8D	8D: Sheltered rocky rubble shores	Rocky
9B	9B: Sheltered, vegetated low banks	Vegetated bank
10A	10A: Salt- and brackish-water marshes	Marsh
10B	10B: Freshwater marshes	Marsh
10C	10C: Swamps	Swamp
10D	10D: Scrub-shrub wetlands	Scrub-shrub wetland
10F	10F: Mangroves	Mangrove

Because multiple shoreline morphologies may be present at the same location along the shoreline, separate models were fitted for each of the simplified morphological descriptors, with each model predicting the probability of presence of that specific morphology. Models were fitted via random forest regression and classification (Breiman, 2001) as implemented via the ***ranger*** library (Wright and Ziegler, 2015) for the R statistical computing language (R Core Team, 2023).

Model fit and performance were evaluated by 10-fold cross validation whereby, for each of 10 folds, 10% of the total sample was withheld and the model was fit with the remaining 90% of the sample, model performance was evaluated against the hold-out sample, and performance statistics were averaged over all folds. Metrics computed for each model via this cross-validation were overall binary classification accuracy and Area Under the Receiver-Operator Characteristic Curve (AUC), and Matthews Correlation Coefficient (MCC). The AUC statistic can be thought of as the probability that the model ranks a random positive example more highly than a random negative example. This statistic ranges between 0 and 1, with a value 0.5 indicating model performance no better than random. The MCC statistic measures the correlation between actual and predicted values and ranges between -1 and 1 with a value of 0 indicating performance no better than random. These cross-validated model performance metrics are reasonable indicators of how the model would perform when predicting shoreline morphology at locations not in the sample data set. Cross-validated model performance statistics are included in Table 6.

Table 6. Individual model performance statistics including binary classification accuracy, Area Under the Receiver-Operator Characteristic Curve (AUC), and Matthews Correlation Coefficient (MCC) evaluated via 10-fold cross validation.

Morphology Model	Number of Locations in Sample	Classification Accuracy (%)	AUC (0-1)	MCC (-1 to 1)
Rocky	2,181 (2%)	98.1%	0.97	0.45
Manmade	13,648 (14%)	90.6%	0.93	0.57
Platform	5,192 (5%)	96.2%	0.97	0.56
Scarp	1,622 (2%)	98.4%	0.94	0.22
Sand beach	16,528 (17%)	91.7%	0.95	0.69
Gravel beach	7,741 (8%)	94.4%	0.95	0.55
Vegetated bank	10,177 (10%)	92.5%	0.94	0.53
Marsh	41,659 (43%)	88.8%	0.96	0.77
Swamp	9,277 (9%)	95.0%	0.96	0.68
Scrub-shrub wetland	7,099 (7%)	96.2%	0.94	0.68
Mangrove	1,226 (1%)	99.1%	0.99	0.52

These performance metrics indicate that these models all generally performed well and can be considered accurate. Binary classification accuracies ranged from 88.8% to 98.4%, though the MCC is a better indication of overall model performance given the large class size imbalances and low prevalence for some morphologies. This statistic indicates that the models for the least frequently occurring morphologies (platforms and scarps) performed the worst. The performance of these models could be improved by supplementing the sample balance prevalence of individual morphologies - intentionally including more of the less frequently occurring classes. It is also likely that the inclusion of additional predictors, including more fine-scaled elevation and derivatives, and a suite of metrics derived from the geometry of line segments in the vicinity of sample locations will also improve performance of predictive models. Additionally, the use of larger training data sets, more rigorous model hyperparameter tuning, and model stacking, or model ensemble techniques will also certainly improve performance.

We also conducted preliminary investigations into targeted use of deep Convolutional Neural Network (dCNN) models to classify small tiles extracted from aerial imagery by the shoreline morphology present, but these trials were generally less accurate that the general machine learning models summarized above and would likely be more difficult to operationalize and scale.

A remaining open question is how such models and data crosswalked from other data sets should be best integrated into a workflow for generating a classified ESI shoreline. The models described here yield probabilities of a given morphology being present at a given location. A threshold can be applied to these probabilities to yield a final ESI classification indicating the presence of one or more morphologies. However, the model provides no information about the across-shore ordering of any morphologies present. For example, a model predicted shoreline with both man-made shoreline structure and a sand beach predicted as present could be coded as a 1A/3A or a 3A/1A. Clearly, no model can perform perfectly, so manual review and correction by experienced image analysts will always be required. It is likely that crosswalking any available data for a given ESI mapping project, combined with exposure modeling, tidal flat extraction, and predictive modeling to yield a tentative pre-classification which is then verified and edited by image analysts will yield the most accurate final product in the most time-efficient and cost-effective manner.

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