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2017 Coastal Master Plan

Attachment C3-22: Integrated Compartment Model (ICM) Development

Report: Final

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Coastal Protection and Restoration Authority

This document was prepared in support of the 2017 Coastal Master Plan being prepared by the Coastal Protection and Restoration Authority (CPRA). CPRA was established by the Louisiana Legislature in response to Hurricanes Katrina and Rita through Act 8 of the First Extraordinary Session of 2005. Act 8 of the First Extraordinary Session of 2005 expanded the membership, duties, and responsibilities of CPRA and charged the new authority to develop and implement a comprehensive coastal protection plan, consisting of a master plan (revised every five years) and annual plans. CPRA's mandate is to develop, implement, and enforce a comprehensive coastal protection and restoration master plan.

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Executive Summary

The 2012 Coastal Master Plan modeling effort utilized several standalone models, which required time consuming manual data transfers and pre/post-processing. The 2017 Coastal Master Plan modeling effort improved upon the existing models by developing an integrated framework, called the Integrated Compartment Model (ICM). The ICM programmatically processes and formats all input and output data required to be passed between the master plan models, six of which are now ICM subroutines: ICM-Hydro, ICM-BIMODE, ICM-LAVegMod, ICM-Morph, ICM-HSI, and ICM-EwE. This programmatic data handling minimizes human errors in the pre/post-processing, and also allows for a more frequent feedback loop among the model subroutines. Previously, the 2012 Coastal Master Plan models allowed for a full update to the landscape (e.g., updating the landscape conditions; specifically, the land/water and elevation) only once during a 50-year simulation at year 25. The ICM, on the other hand, allows for annual updates to the landscape. Prior to each model year, the ICM updates the landscape and boundary conditions for all six ICM subroutines. In addition to these programmatic and temporal improvements, the processes (physical and ecological) modeled within each ICM subroutine have been improved from the 2012 models. These improved processes include (are described in): updated hydraulic flow calculations (Attachment C3-22.1: ICM-Hydro Flow Calculations, improved sediment distribution algorithms (Attachment C3-1: Sediment Distribution), marsh edge erosion (Attachment C3-2: Marsh Edge Erosion), a new barrier island morphology model (Attachment C3-3: Storms in the ICM Boundary Conditions), updated vegetation dynamics (Attachment C3-4: Barrier Island Model Development), updated habitat suitability indices (Attachments C3-6 – C3-19), and a fishery biomass model (Attachment C3-20: Ecopath with Ecosim). The ICM control program, ICM-LAVegMod, ICM-Morph, and ICM-HSI were written in Python 2.7. Two subroutines, ICM-Hydro and ICM-BIMODE, were programmed in Fortran; as was the Oyster Environmental Capacity Layer component of ICM-EwE. The ICM-EwE fishery biomass model was programmed in Visual Basic. The ICM is computationally efficient and can be used for a large number of 50-year, coast wide simulations in a reasonable timeframe.

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List of Abbreviations

AA	Atchafalaya/Terrebonne Region
BIMODE	Barrier Island Model
CP	Chenier Plain Region
CPRA	Coastal Protection and Restoration Authority
DEM	Digital Elevation Model
ESRI	Environmental Systems Research Institute
EwE	Ecopath with Ecosim
HSI	Habitat Suitability Index
ICM	Integrated Compartment Model
I/O	Input/Output
LaVegMod	Louisiana Vegetation Model
NAVD88	North American Vertical Datum 1988
PB	Pontchartrain/Barataria Region
TSS	Total Suspended Solids
WQ	Water Quality

1.0 Introduction

This report describes the integration of individual subroutines and modeling components that were used in the 2012 Coastal Master Plan. These individual modeling components were updated based on new field datasets and recently published literature. The updates to each of these modeling components are described in separate reports, and are listed in Table 1: Attachments to the 2017 Coastal Master Plan Appendix C Which Provide In-Depth Discussion of the Data, Processes, Algorithms, and Performance of the ICM Subroutines. The ICM, specifically, replaces four previously independent models (Ecohydrology, Wetland Morphology, Barrier Shoreline Morphology, and Vegetation) with a single model code for all regions of the coast. It also enables integrated execution of the new fish and shellfish community models (EwE). Such integration allows for coupling of processes and removes the inefficiency of manual data hand-offs and the potential human error that may occur during the transfer of information from one model to another. The ICM is computationally efficient and can be used for a large number of 50-year, coast wide simulations in a reasonable timeframe. The ICM serves as the central modeling platform for the 2017 Coastal Master Plan to analyze the landscape and ecosystem performance of individual projects and alternatives (groups of projects) under a variety of future environmental scenarios. Key outputs include hydrodynamic variables (e.g., salinity and stage), changes in the landscape (e.g., land-water interface and elevation change, including the barrier islands), and changes in vegetation.

Table 1: Attachments to the 2017 Coastal Master Plan Appendix C Which Provide In-Depth Discussion of the Data, Processes, Algorithms, and Performance of the ICM Subroutines.

Appendix C Attachment	Topic
Attachment C3-1	Sediment Distribution
Attachment C3-2	Marsh Edge Erosion
Attachment C3-4	Barrier Island Model Development (BIMODE)
Attachment C3-5	Vegetation
Attachments C3-6 through C3-19	Habitat Suitability Indices
Attachment C3-20	Ecopath with Ecosim (EwE)
Attachment C3-23	ICM Calibration, Validation, and Performance Assessment
Attachment C3-24	ICM Uncertainty Analysis
Attachment C3-26	Hydrology and Water Quality Boundary Conditions
Attachment C3-27	Landscape Data

1.1 Report Terminology

The 2012 Ecohydrology models were developed in three parts: a Fortran model for the Pontchartrain/Barataria region of the coast, and two models coded in Berkeley-Madonna; one each for the Atchafalaya/Terrebonne and Chenier Plain regions. Throughout this report, these 2012 models will be referred to as the ***PB Ecohydrology*** model and the ***AA/CP Ecohydrology*** models, respectively. If discussed together, they will be collectively referred to as the ***2012 Ecohydrology model***.

The updated Fortran code base for the coast wide hydrodynamic portion of the ICM will be referred to as the ***hydrodynamic*** subroutine or ***ICM-Hydro***. The ICM version of the 2012 Vegetation model will be referred to as ***ICM-LAVegMod***. The ICM version of the 2012 Wetland Morphology model will be referred to as ***ICM-Morph***. The ICM version of the 2012 Barrier Shoreline model will be referred to as ***ICM-BIMODE.***

Numerous spatial resolutions are used for the various ICM subroutines: **ICM-Hydro model compartment** will be used to reference the irregular polygon hydrologic compartments utilized by the hydrodynamic subroutine. The **500 m grid cell** will be used to refer to the Cartesian grid structure used by ICM-LAVegMod and several subsequent ICM subroutines. The **30 m pixel, land/water pixel,** or **pixel** will be used to refer to the 30 m raster datasets that are utilized by ICM-Morph.

2.0 2012 Coastal Master Plan Modeling Suite

During the development of the 2012 Coastal Master Plan, 397 individual projects were evaluated within a systems context using a suite of predictive models, as depicted in Figure 1. The linked models predicted change in the conditions of the Louisiana coastal system under two different types of future management strategies: a future without the implementation of additional restoration and risk reduction projects, and a future with implementation of additional projects. The following discusses those models which have been integrated as part of the ICM; storm surge and risk models are still separate.

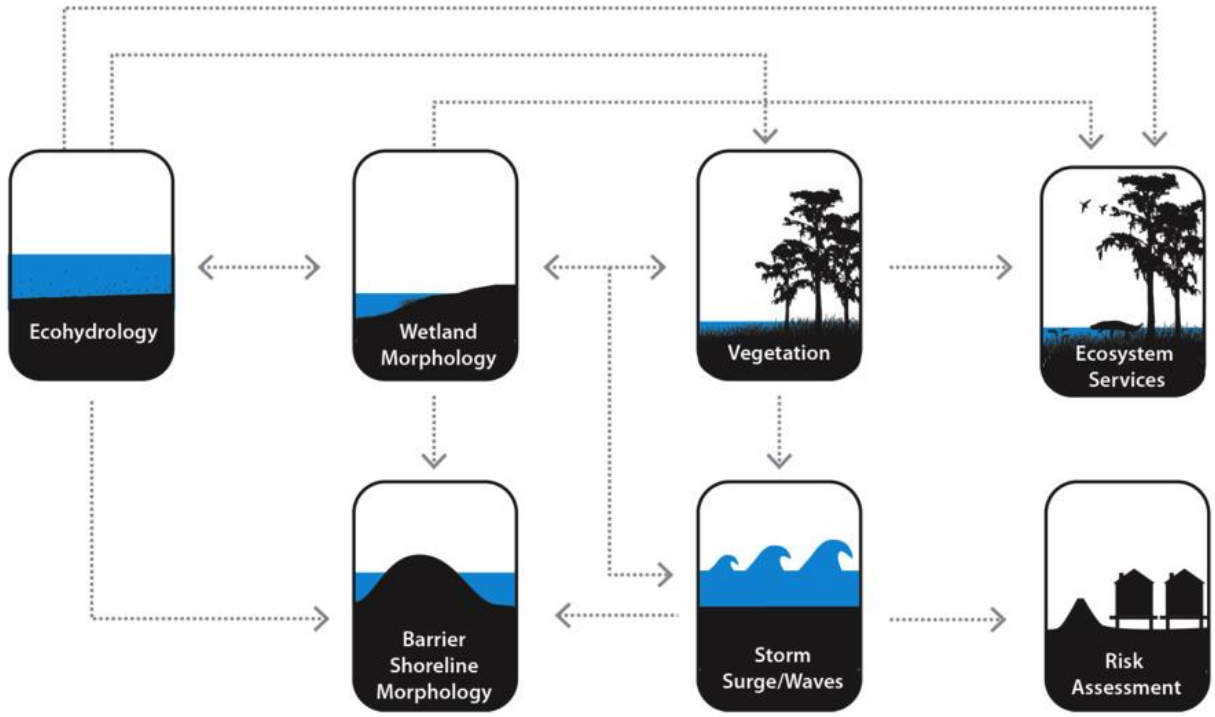
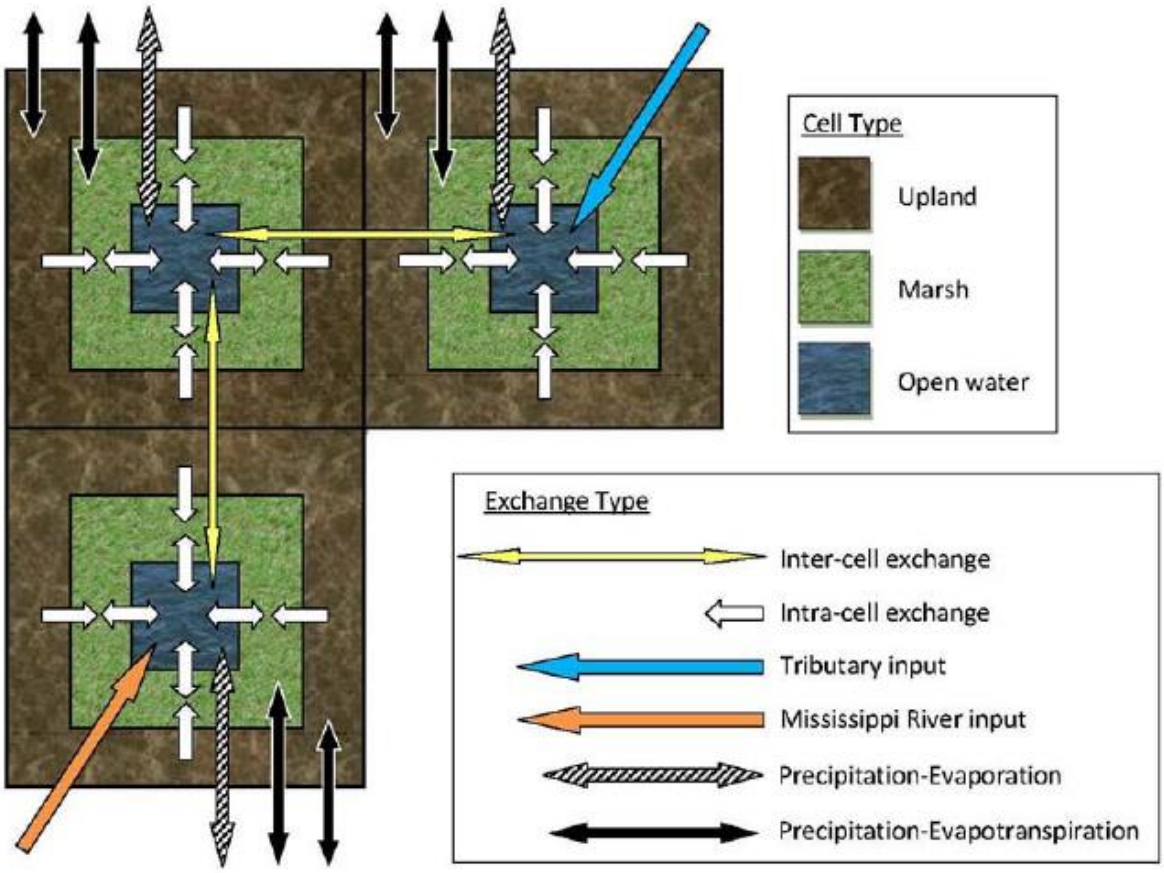


Figure 1: 2012 Coastal Master Plan Predictive Models.

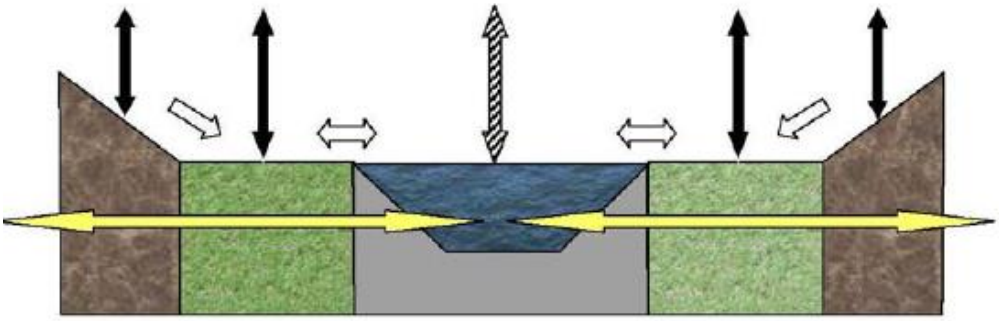
2.1 Ecohydrology Models

The 2012 Ecohydrology model consisted of three individual models (encompassing the Chenier Plain region, the Atchafalaya/Terrebonne region, and the Pontchartrain/Barataria region) the outputs of which were integrated to provide coast wide results (Meselhe et al., 2013). Each model predicted the salinity, stage, and other selected water quality constituents of the open water bodies (including channels) within estuaries using a mass balance approach to estimate the exchanges of solids and chemicals due to advection and dispersion.

While the governing equations concerning the overall mass balance of the Ecohydrology models were identical across the entire model domain, the model code was written in two different computer languages: the Pontchartrain/Barataria (PB) Ecohydrology model in the eastern portion of the domain was coded in Fortran, while the Atchafalaya/Terrebonne (AA) and Chenier Plain (CP) Ecohydrology models were coded in Berkeley-Madonna. In addition to the different computer languages, the spatial representation of the landscape differed between the two approaches. The PB Ecohydrology model required each model compartment to contain at least some open water area. In addition to the open water area, each compartment could also have marsh and/or upland areas (Figure 2). Contrary to this, the AA/CP Ecohydrology model compartments had to be classified as only one type: water, marsh, or channel. No compartment was allowed to have a mixture of these classifications (Figure 3).

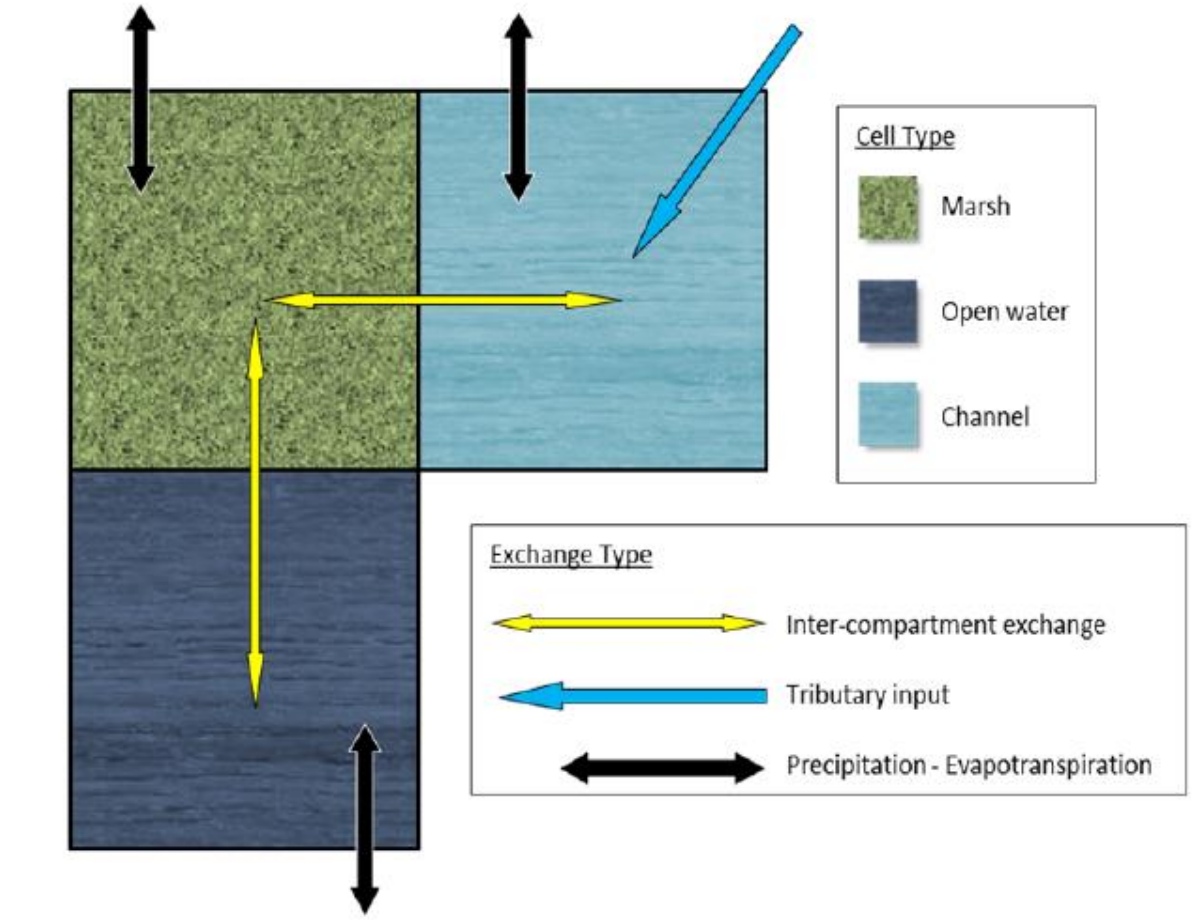


a. Plan view of PB model dynamics

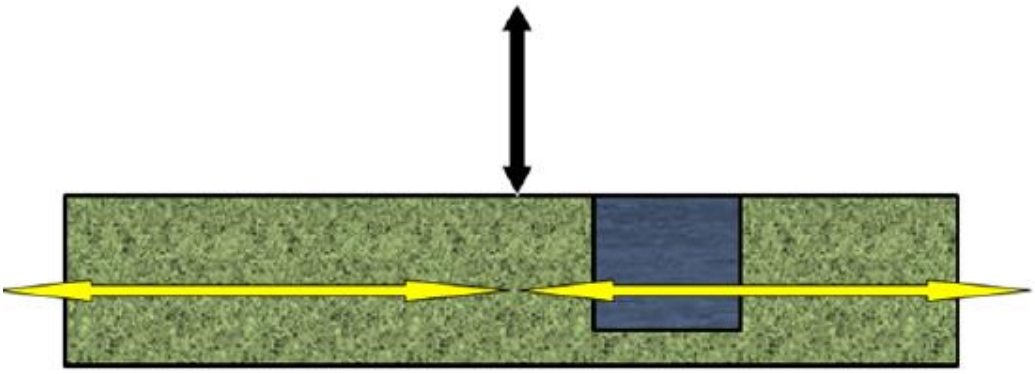


b. Cross-section view of PB model dynamics for a generalized interior cell

Figure 2: Schematic of 2012 PB Ecohydrology Compartment Geometry.



a. Plan view of AA and CP model dynamics



b. Cross-section view of AA and CP model dynamics for a generalized interior marsh compartment

Figure 3: Schematic of 2012 AA/CP Ecohydrology Compartment Geometry.

2.2 LAVegMod

The 2012 Vegetation model predicted the extent of 19 types/communities of emergent vegetation and submerged aquatic vegetation (Visser et al., 2013). It estimated spatial and temporal changes in vegetation types/communities over time based on environmental drivers such as salinity and water level change.

2.3 Barrier Shoreline Morphology

In the 2012 Coastal Master Plan modeling effort, changes in barrier shorelines and headlands were derived from a simple shoreline change model driven by analysis of historical shorelines that are a part of the Barrier Island Comprehensive Monitoring project (BICM) (Hughes et al., 2012).

2.4 Wetland Morphology

The Wetland Morphology component of the 2012 modeling effort tracked the changes in wetland-dominated landscapes over time including the loss of existing wetlands, the creation of wetlands by both natural and artificial process, and the fate of those newly created wetlands (Couvillion & Beck, 2013). Whereas previous modeling efforts simply projected past trends into the future, this model considered more characteristics (e.g., rates of subsidence, sea level rise, sediment deposition, etc.) of the landscape as predictors of change.

2.5 Ecosystem Services

Ecosystem services were evaluated using 14 Habitat Suitability Indices (HSI) and other indices including the potential for agriculture, freshwater availability, nature based tourism, nitrogen uptake, and surge/wave attenuation. For more information refer to the 2012 Coastal Master Plan Appendices D5 – D23.

3.0 Integrated Compartment Model

The modeling components that were used in the 2012 effort required manual pre/post-processing of datasets used and produced by each model. The different modeling components were also run by individual modelers, requiring manual handoffs of large datasets. The manual handoffs increased the probability of human errors and negatively affected the computational efficiency. The integration of these individual modeling components into a single framework allows for multiple improvements. First, a programmatic pre/post-processor that automatically formatted and prepared required model inputs and outputs (I/O) allows for all model components to be run on a single computer. Secondly, the automation of all formatting minimizes human errors. Thirdly, this integration of modeling components allows the landscape topography/bathymetry and vegetation cover to be updated annually, whereas this only changed at year 25 in the 2012 modeling.

Due to manual handoffs and large file transfers, each modeling component of the 2012 effort only received feedback from the other components once during a 50-year simulation at year 25. In other words, the first 25 years of the 2012 analysis, the Ecohydrology model was run on a

compartment/link network that was defined by the initial, year 1 landscape. At year 25, after the Wetland Morphology component was run for the first 25 model years, the Ecohydrology input files were updated (manually) to represent the year 25 landscape; the remaining 25 years of the 50-year simulation were run using this landscape. Within the integrated modeling framework of the ICM, this feedback loop between model components was reduced to an annual time step. A schematic overview of the physical processes and their feedbacks is depicted in Figure 4.

The overarching model architecture of the ICM that controls all processing of I/O, and calls each of the ICM subroutines was coded with Python 2.7.8 (Python, 2016). In addition to the default Python packages (*csv, os, sys,* etc.) the following additional Python packages were used across the various subroutines:

- **arcpy** – library of ESRI geoprocessing functions
- **NumPy** – array functionality for numerical calculations and input file manipulation
- **dbfpy** – file formatting functionality
- **pysftp** – SFTP connection functionality for data transfers and output backup

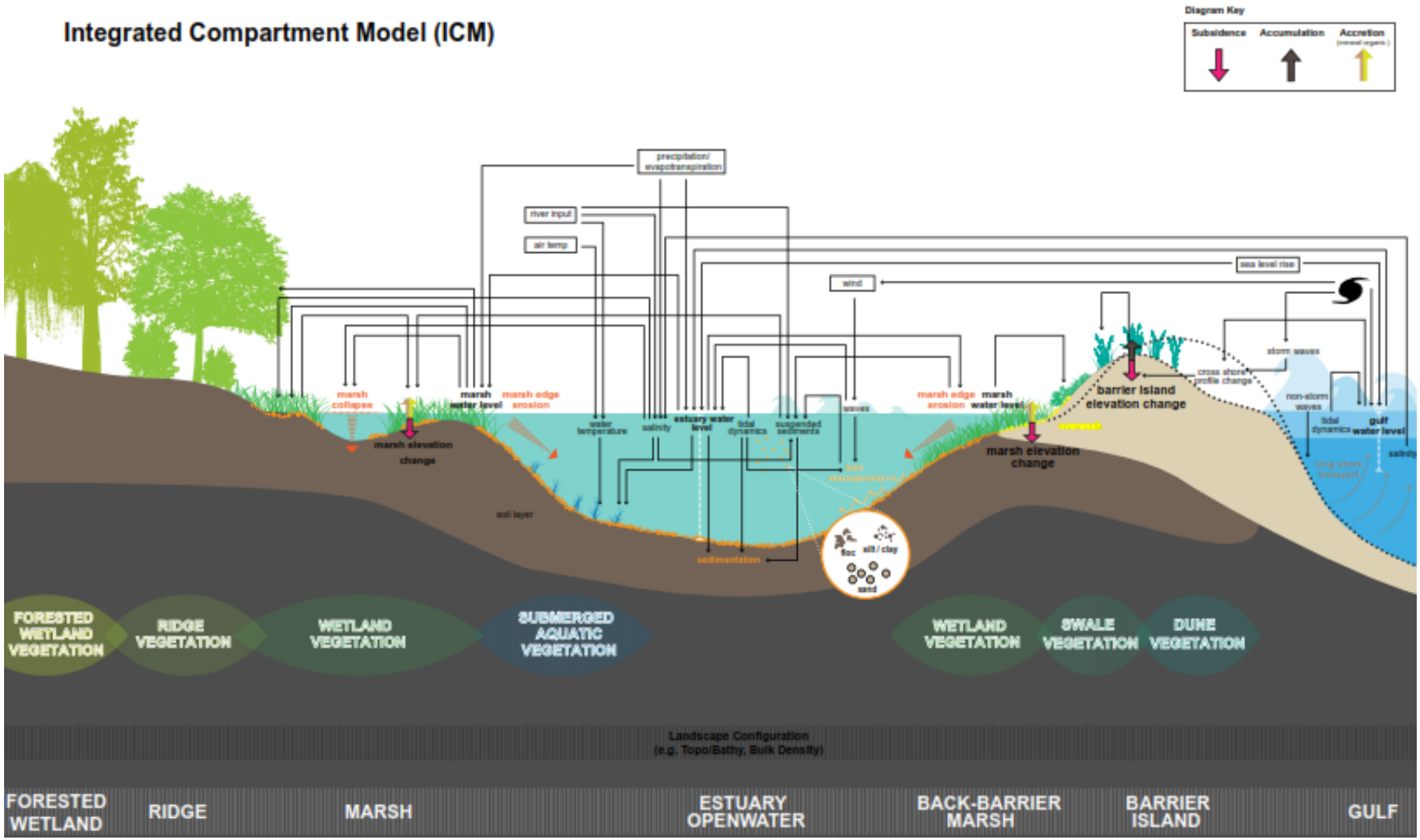


Figure 4: Coastal Components and Processes Represented by the ICM.

3.1 ICM Spatial and Temporal Resolution

Each of the model codes used in the 2012 Coastal Master Plan modeling effort utilized a different spatial representation of coastal Louisiana. During the development phase of the ICM, it was determined that it was beyond the scope and schedule of this effort to rebuild each standalone model to operate on a unified spatial representation/resolution. To that end, a significant portion of the ICM code that integrates these models is used to transform model output from one spatial resolution to a finer (or coarser) resolution used by other ICM subroutines. The model resolution of the ICM-Hydro subroutine is the coarsest of the resolutions used within the ICM. For the total model area of 106,970 km^2, there are 946 model compartments, with an average size of 113 km^2. The largest compartment is 3,187 km^2, and is located in the deep water offshore portion of the Gulf of Mexico. The smallest compartment is 0.4 km^2, and is located in a delta compartment near the Calcasieu River outlet. The ICM-LAVegMod subroutine utilizes a regular, orthogonal grid that is 500 m in size. The ICM-BIMODE subroutine is built upon individual cross-shore profile transects within the barrier island portion of the model domain. These transects are spaced at a 100 m distance in the longshore direction; elevation data are spaced at 2 m distances in the cross-shore direction. The ICM-Morph subroutine utilizes raster datasets that have a 30 m resolution. A sample of the different model resolutions can be seen in Figure 5. The ICM-HSI equations are calculated on the 500 m grid developed for ICM-LAVegMod. The ICM-EwE fisheries model is modeled using a 1 km grid. While the 30 m datasets used by ICM-Morph do not align perfectly within the 500 m ICM-LAVegMod grid, the 1 km ICM-EwE grid was developed so that the coordinates align with the 500 m ICM-LAVegMod grid.

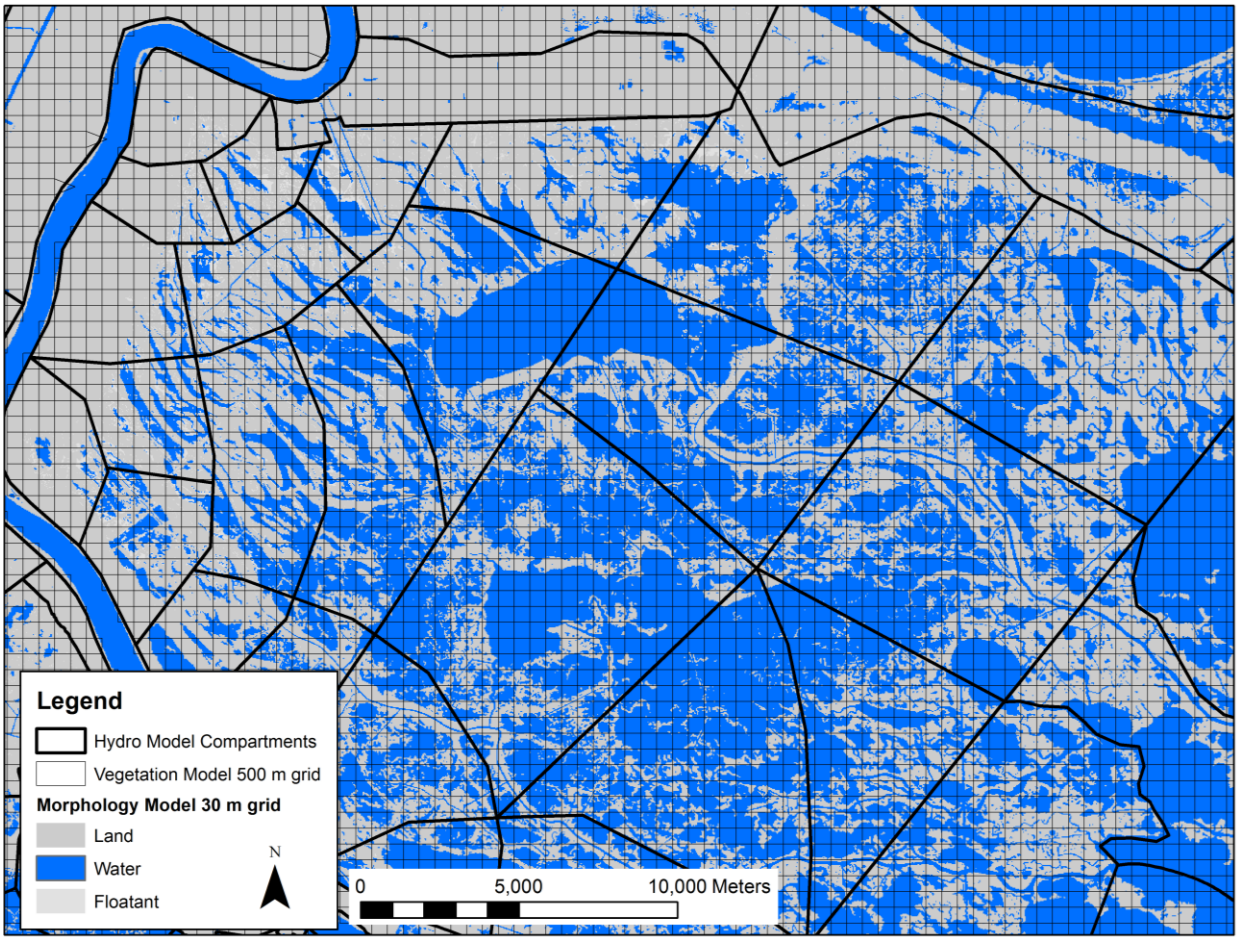


Figure 5: Spatial Resolutions of Each ICM Subroutine in the Vicinity of Upper Breton Sound. Irregular polygons are the ICM-Hydro compartments, the thin black Cartesian grid is the 500 m grid used in ICM-LAVegMod, and the blue/gray land water data are at the 30 m resolution of ICM-Morph.

In addition to various spatial resolutions, different simulation time steps are used by each model subroutine. The time step for ICM-Hydro is user defined and was chosen to be the largest possible period why still maintaining numerical stability of the the central difference solution methodology utilized. For the 2017 Coastal Master Plan modeling effort, the ICM-Hydro subroutine was modeled with a 30 second model timestep. Output data is summarized at various time steps and is discussed in Section 3.3.7. ICM-LAVegMod, ICM-Morph, and ICM-HSI are all simulated on an annual time step; however, the input data for each subroutine may be derived from only a specific portion of the year (e.g., growing season salinity). The specific input data used by each subroutine is discussed in the respective sections for each subroutine. The ICM-EwE subroutine uses a daily timestep for the OECL component, and a monthly time step for the fishery biomass calculations.

3.2 Boundary Conditions and Environmental Drivers

A full discussion of input data used to drive the various ICM subroutines can be found in: Attachment C3-26: Hydrology and Water Quality Boundary Condition, Attachment C3-27: Landscape Data, and Chapter 2 – Future Scenarios. In summary, ICM-Hydro is driven by upstream flow timeseries at numerous tributaries, downstream water surface elevation timeseries

in the Gulf of Mexico, precipitation, evapotranspiration, and wind timeseries. Each flow or water surface boundary also includes salinity, temperature, and water quality concentration timeseries. ICM-LAVegMod is driven primarily by the ICM-Hydro output, but it also requires an input vegetation species map to definie initial conditions. ICM-Morph has an initial condition defined by the vegetation species map, a land/water interface map, and a topobathymetric digital elevation model (DEM).

3.3 ICM-Hydro – Hydrology Model

3.3.1 Model Compartment Delineation

In addition to the re-delineation of the AA/CP Ecohydrology models into the new ICM-Hydro model compartment configuration, the spatial resolution of the compartments in the PB portion of the model was also refined. Large compartments were maintained in the deep water, offshore portions of the Gulf and finer scale compartments were developed in the estuarine zone. Higher resolution compartments were also incorporated in to the model domain in regions where potential master plan projects could potentially be placed, in anticipation for more complex hydrologic features in a potential future with action (e.g., river diversions).

Due to the simplified geometries of the ICM-Hydro model domain, sediment deposition patterns were highly sensitive to model compartment size. Therefore, to improve the representation of shoaling and land building in active and proposed sediment deposition zones, ICM-Hydro model compartments near river outlets and active deltas (Mississippi River, Wax Lake Outlet, Calcasieu River, Sabine River, etc.) were delineated using a delta compartment stencil. Locations of potential diversion outfalls were also delineated with this delta stencil. Each delta compartment was connected with two hydraulic links: one conventional open channel hydraulic link, and one Lacey Regime channel link. To prevent ICM-Hydro from completely filling in an entire compartment with deposited material over the 50-year run, a minimum hydraulic connectivity was maintained via the Lacey Regime channel links. A full description of the Lacey Regime channels, as well as the delta stencil used in compartment delineation, is provided in Attachment C3-1.

For each model time step, the code must iterate through all hydraulic links within each of the model compartments to determine the exchange flows that are needed to compute the changes in the state variables in each compartment. Due to this iterative solution technique (which is required for all numerical models), increasing the spatial resolution of ICM-Hydro would result in a significant increase in model runtime due to an increase in the raw number of items iterated across during each model time step. Additionally, the smaller the compartment size, the smaller the model time step would be required to ensure that the solution is numerically stable. The final ICM-Hydro resolution was set during the compartment delineation effort and was chosen so that a 30 second model time step would suffice for ICM-Hydro. Increasing the spatial resolution beyond this level would not only increase the raw number of calculations required, but it would have also required using a smaller model time step to ensure stable numerical solutions.

3.3.2 Hydraulic Link Network Improvements

New hydraulic link types were required to be added to the ICM-Hydro Fortran code to account for hydraulic connections in the 2012 AA/CP Ecohydrology Berkeley-Madonna models. A

secondary flow network of overland flowpaths was also added to ICM-Hydro to better simulate high water events such as are seen during hurricane and storm surge events.

3.3.2.1 Main Channel Network

Each ICM-Hydro model compartment must be connected to the surrounding compartments via a primary flow path. Link types, and the various attributes required for each type, are provided in Table 2. The default flow connection was a rectangular open channel. In addition to the default open channel, flow could be controlled between two compartments via: a weir, an orifice or culvert (frictional losses on all four sides), a one-way tide gate, a pump, or a hydraulic control structure. Hydraulic control structures in ICM-Hydro activated flow control rules based on any of the following control mechanisms: differential stage, hour of the day, downstream water surface, downstream salinity, or a combination of both downstream water surface *and* downstream salinity. The control rule logic for these links was set at the start of the model run, and was assumed to remain unchanged throughout the simulation unless project implementation during the course of the run resulted in changes.

The hydraulic equations and further detail on the main channel network hydraulic connections are provided in Attachment C3-22.1.

3.3.2.2 Secondary Flow Network, Overland Flow

During high water periods, flow may occur between adjacent compartments outside of the traditional channel network. This overland flow mechanism was not included in the 2012 Ecohydrology models and was subsequently added to ICM-Hydro by the inclusion of a secondary flow network across the marsh surface. Depending upon the topography/hydrography of an ICM-Hydro compartment, the overland flow path was defined as either a marsh surface link or a ridge link. Marsh surface links were modeled as a wide, shallow open channel with high roughness. Ridge links were modeled as a wide weir. Link lengths were determined from the landscape data: if a compartment was predominantly marsh, the length of the overland marsh link was the distance from the centroid of the marsh in the upstream compartment to the centroid of the marsh in the downstream compartment. If the compartment was not predominantly marsh, the length of the marsh surface link was the distance from the centroid of the marsh to the edge of the marsh.

The majority of ICM-Hydro compartments had both primary and secondary flow path connections. For these compartments, the main channel was always active in the flow calculations; therefore, the width of the overland flow links was calculated to exclude the channel width from the overall marsh surface link width.

The hydraulic equations and further detail on the overland flow network are provided in Attachment C3-22.1.

Table 2: Attributes of Each Link Type Modeled in ICM-Hydro.

Link Type	Type	Link Attributes									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Channel with defined geometries	1	Invert elevation	Channel bank elevation	Channel length	Channel width	Manning's roughness	$K_{entrance}$ ~0.5	K_{exit} =1	$K_{structure}$	-	-
Weir	2	Crest elevation	Upstream ground elevation	Downstream ground elevation	Crest length	-	-	999	C_{weir}	Initial Q =0	-
Channel with hydraulic control structure (e.g., locks)	3	Invert elevation	Control threshold value 2: if attribute 9 = 5 , downstream salinity (ppt)	Channel length	Channel width	Manning's roughness	Channel $K_{entrance}$	Channel K_{exit}	K_{lock}	Lock control:	Lock control threshold value:
										1 = differential stage	diff stage (m)
										2 = hour of day	-9999
										3 = downstream WSEL	d/s WSEL (m)
										4 = downstream salinity	d/s salinty (ppt)
										5 = downstream WSEL & salinity	d/s WSEL (m)

Link Type	**Type**	**Link Attributes**									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
										6 = control structure has observed operations	Column in observed operation data file corresponding to this control structure
Tide Gate- flow is uni-directional	4	Invert elevation	Crown elevation	Upstream ground elevation	Mean width	Downstream ground elevation	-	-	$C_{orifice}$	-	-
Orifice - flow is bi-directional	5	Invert elevation	Crown elevation	Upstream ground elevation	Mean width	Downstream ground elevation	-	-	$C_{orifice}$	-	-
Culvert/Bridge	6	Invert elevation	Crown elevation	Channel length	Mean width	Manning's roughness	$K_{entrance}$ ~0.5	K_{exit} =1	$K_{structure}$	-	-
Pump	7	Upstream Stage threshold for turning pump on	Upstream Stage threshold for turning pump off	-	-	-	-	-	-	Q capacity of pump	-
Marsh overland flow	8	Marsh elevation	Upstream marsh elevation	Channel length	Channel width	Manning's roughness	$K_{entrance}$ ~0.5	K_{exit} =1	$K_{structure}$	-	downstream marsh elevation
Ridge/Levee overland flow	9	Crest elevation	Upstream ground elevation	Channel length	Crest length	Manning's roughness	$K_{entrance}$ ~0.5	K_{exit} =1	$K_{structure}$	-	downstream ground elevation

Link Type	**Type**	**Link Attributes**									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Regime channel in delta compartments	10	Invert elevation	Link number of corresponding non-regime channel link	Length of corresponding non-regime channel link	Channel width	Manning's roughness	$K_{entrance}$ ~0.5	K_{exit} =1	$K_{structure}$	Regime Q	D50 mm
Channel without defined geometries (used for marsh areas without channelized flow)	11	Invert elevation	Channel bank elevation	Channel length	Channel width	Manning's roughness	$K_{entrance}$ ~0.5	K_{exit} =1	$K_{structure}$	-	
Maintained Channel	12	Same as type 1; however, the channel dimensions will never be updated by ICM – all dimensions will be assumed to be maintained.									
Inactive links	All link attributes can be assigned based on the original link type, but if a link should be set to inactive, assign the type number attribute to be negative. ICM-Hydro will set flowrates for all links with a negative type value to 0.0 cms for every time step.										

3.3.2.3 Barrier Island Breaching

For each ICM-Hydro compartment which bordered a barrier island, an additional, inactive link was added to represent a potential flow path through the center of a barrier island if an island breaching event would occur during a simulation. A lookup table mapping these inactive ICM-Hydro 'breach' links to a respective ICM-BIMODE profile number was manually developed by the modeling team. During each model year, the ICM code examines the ICM-BIMODE breached profile output data to determine if an inactive link should be activated within ICM-Hydro to better simulate an increase in exchange flows due to a barrier island breach. The hydraulic properties of these 'breach' links (e.g., roughness, width, depth, etc.) were all assumed to be identical and set to default values of 500 m long with a roughness coefficient of 0.025. The bottom invert was set equal to the bottom elevation of the deep water, offshore Gulf compartments. Each island represented within ICM-BIMODE was initialized with one hydraulic link in ICM-Hydro. Once an island was breached, the respective link was activated in ICM-Hydro. Subsequent breaching at that location would not result in any further breach link activation, nor would the breach link's default geometry be adjusted.

3.3.3 Water Quality

Due to the separate Fortran and Berkeley-Madonna code bases for the 2012 Ecohydrology model, two different water quality routines were used in the 2012 Coastal Master Plan modeling suite. Significant effort went into the development of the AA/CP Ecohydrolgy models in order to incorporate equations for source and sink terms for each water quality constituent. These more complex source/sinks were not included in the same manner in the 2012 PB Ecohydrology model. Therefore, as part of the ICM development, the source/sink terms were updated in ICM-Hydro to include the same equations previously used in the Berkeley-Madonna code base. The equations and calibration coefficients provided in the 2012 Coastal Master Plan Appendix D-1 Ecohydrology were chosen as a starting point for this effort. Further calibration of these water quality equations was conducted on the final ICM version during the model calibration and validation exercise described in Attachment C3-23.

3.3.4 Sediment Distribution

One of the primary updates to the physics modeled within ICM-Hydro from the 2012 Ecohydrology model was the addition of a more physically accurate sediment distribution algorithm. The algorithm and equations utilized are described in detail in Attachment C3-1 while this section outlines specific implementation aspects of ICM-Hydro.

3.3.4.1 Sediment Deposition Zones

Sediment deposition was calculated as a mass of inorganic sediment deposited per unit area of each deposition zone. The open water area was set equal to the area of open water in each ICM-Hydro compartment at the start of the simulation year. The marsh interior and edge areas were calculated by assuming that the marsh area was an idealized square shape, surrounded by the open water zone. The marsh edge length was then equal to the perimeter of this marsh area. The width of this edge zone was assumed to be equal to one 30 m pixel of the land/water dataset used by ICM-Morph, as prescribed during the sediment distribution algorithm development process (Attachment C3-1).

The ICM-Morph subroutine accurately calculates the total edge area within each ICM-Hydro model compartment; however, the method described above was implemented so that the ICM-Hydro simplified geometry assumed for all hydrologic calculations remained consistent for this routine as well.

3.3.4.2 Erodible Bed Depth

During the model calibration effort (Attachment C3-23), it was determined that the initial depth of sediment available for resuspension from the bed of open water areas was a highly sensitive parameter when calibrating for total suspended sediments. To accommodate this sensitivity, an additional parameter was added to each ICM-Hydro model compartment, which defined the initial depth of the bed sediments available for sediment resuspension. This initial erodible bed depth was permitted to gain depth as sediments were deposited within ICM-Hydro; however, if the entire initial depth was eroded during any given model year, resuspension from the respective ICM-Hydro model compartment was deactivated. Sediment deposition was still permitted to occur in these resuspension-deactivated compartments, and as soon as any amount of sediment was deposited, resuspension was re-activated.

3.3.5 Spatial Interpolation of Output

Due to the coarse resolution of the ICM-Hydro compartments, a spatial interpolation routine was added to ICM-Hydro which, using an Inverse Distance Weighting approach, mapped the salinity values for compartments and links to the 500 m ICM-LAVegMod grid cells. Each 500 m grid cell was associated with the compartment in which it was located and all hydraulic connection links into and out of the respective compartment. The distance from the centroid of the 500 m grid cell and the centroid of the ICM-Hydro model compartment was computed (green dot in Figure 6). Similarly, the distance from the grid cell centroid and the location at which each hydraulic link crossed the compartment boundary was also calculated (red dots in Figure 6). These distances were used, in conjunction with the salinity at each compartment as well as in each connected hydraulic link, to determine an inverse distance weighted salinity value. The hydraulic links were used in this exercise instead of the surrounding compartments in order to better capture the impact of hydraulic control structures on salinity patterns. For instance, if two compartments were separated by a flap gate, the salinity interpolation would only take into account the time steps in which flow was moving through the flap gate. If the surrounding model compartment were used instead of the link to interpolate salinity, the impact of this neighboring salinity would be over represented in the interpolated output.

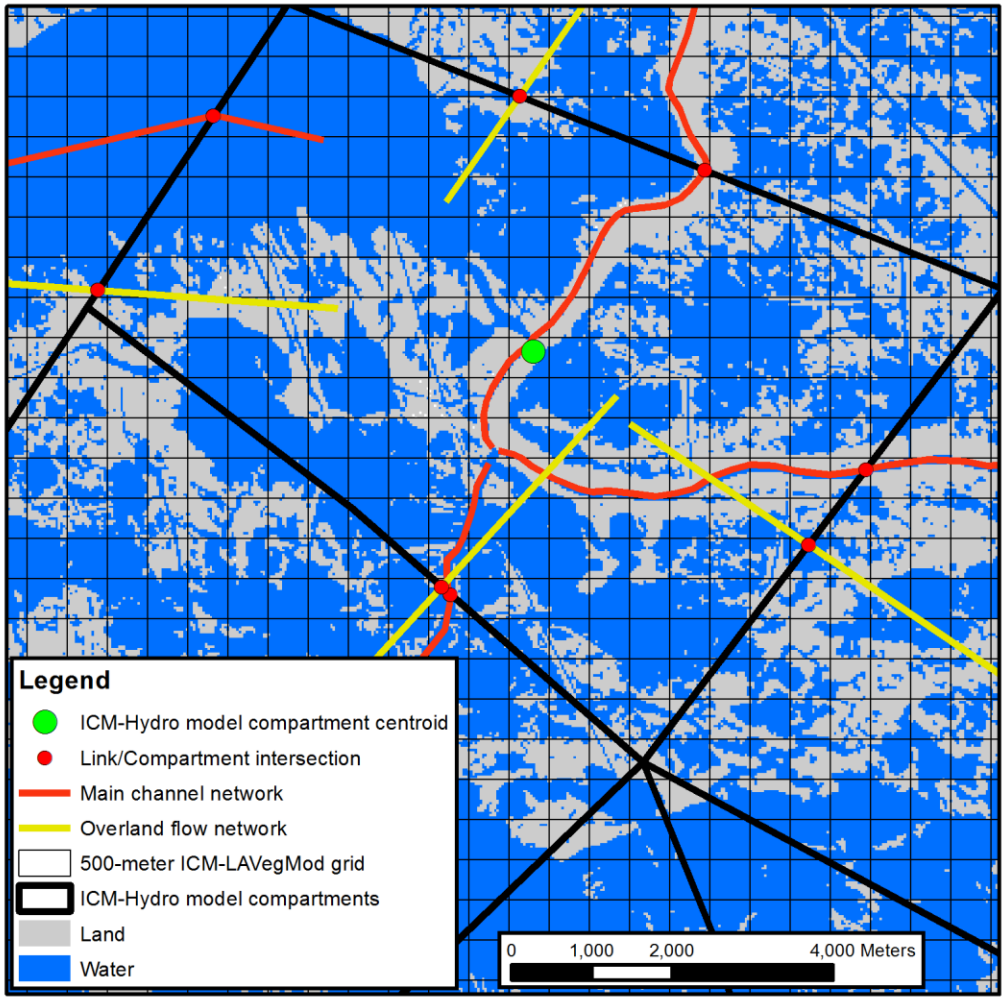


Figure 6: Schematic of Spatial Interpolation Methodology.

3.3.6 End-of-Year Output File Used Internally by ICM-Hydro

The 2012 Ecohydrology model was originally run for 25 consecutive years, with a spin-up period at the start of each 25-year simulation period. The annual feedback between subroutines within the 2017 ICM would then require a spin-up period for every simulation year. To improve model efficiency, hotstart functionality was added to ICM-Hydro which removed the need for a spin-up period. At the end of a model year's final simulation time step, all state variables within ICM-Hydro (water level, salinity, water temperature, total suspended solids (TSS) concentration, water quality (WQ) constituent concentrations, etc.) were saved to an output text file. This text file was then read in at the start of the next simulated year after all other ICM subroutines were run. All state variables within ICM-Hydro were reset to the values from the previous simulation year's final time step that had been written to file. External text files were utilized, as opposed to storing the data in computer memory, so that the ICM-Hydro executable was allowed to exit and free up memory for other ICM subroutines. A separate hotstart output text file was required, as opposed to the output files utilized by other ICM subroutines, due to the disparity between the 30 second model time-step utilized by ICM-Hydro and the summary time steps used for other ICM-Hydro output files (e.g., mean daily, monthly, or annual values).

3.3.7 ICM-Hydro Output Files

3.3.7.1 Mean Daily Output Time Series

For each ICM-Hydro model compartment, the daily mean value for many state variables are written to output text files. To minimize memory requirements internal to ICM-Hydro, only two values for each state variable are saved to internal memory, the current model time step value and the value from the previous time step. Each state variable is also saved to an array that stores the mean value. This mean value is updated at each time step, and after the final time step for each simulated day, the mean value is written to an output text file. Each column in the output text file corresponds to the ICM-Hydro model compartment, while each row is a simulated day. These output files are written in Fortran 'append' mode, which allows for a single file to be generated for each output variable for the entire 50-year ICM simulation. Daily mean output values for each ICM-Hydro model compartment are prepared for stage (m relative to NAVD88) in open water and marsh areas, tidal range (m), salinity (ppt), total suspended inorganic solids (mg/L), water temperature (C), and numerous water quality constituents (mg/L): dissolved oxygen, dissolved organic nitrogen, dissolved inorganic nitrogen, ammonium-nitrogen, nitrate-nitrogen, total Kjeldahl nitrogen, soluble phosphorus, total phosphorus, and total organic carbon.

3.3.7.2 Mean Annual Output

The time series of mean daily output are useful in understanding the dynamics of the ICM-Hydro output; however, the other ICM subroutines generally required hydrologic data that are averaged over a longer time frame than a day. The ICM-LAVegMod model, for instance, uses input data prepared from either mean annual values or the mean for the growing season. The various input files prepared for ICM-LAVegMod are described in Section 3.4.1.

The ICM-Morph subroutine, like ICM-LAVegMod, generally uses mean annual output data. As discussed in Section 3.6.2, geospatial representations of these output data must be generated within ICM-Morph. To accommodate the need to programmatically prepare raster datasets, the various output data required by ICM-Morph are saved, by ICM-Hydro, to a standardized text file output table that can be joined to blank geospatial data templates. Two output files are generated at the end of each simulation year in ICM-Hydro, one with mean annual output summarized by ICM-Hydro model compartment, and one with mean annual output summarized by the 500 m ICM-LAVegMod grid.

Mean annual data summarized by ICM-Hydro model compartment included: mean annual stage (m relative to NAVD88), maximum annual stage (m relative to NAVD88), mean annual salinity (ppt), maximum two week mean salinity (ppt), sediment deposited per unit area of open water bed (g/m^2), sediment deposited per unit area of marsh edge (g/m^2), sediment deposited per unit of marsh interior (g/m^2), mean annual water temperature (C), and tidal prism volume (m^3).

In addition to the ICM-Hydro model compartment level data described above, the same output data was also mapped to the 500 m ICM-LAVegMod grid and written to a separate output text file. These data were supplemented with the following mean annual output data that were only available at 500 m ICM-LAVegMod grid cell resolution: spatially interpolated mean annual salinity (ppt), spatially interpolated maximum two week mean salinity (ppt), spatially interpolated mean annual temperature (C), as well as mean annual water depth (m). The mean depth was calculated for each grid cell by subtracting the mean bed elevation within each 500 m ICM-

LAVegMod grid cell from the mean water level in the overlying ICM-Hydro model compartment. The methodology for calculating the mean bed elevation for each 500 m ICM-LAVegMod grid cell is provided in Section 3.6.3.4.

3.3.7.3 Mean Monthly Output

Some algorithms in ICM-HSI, as well as the ICM-EwE subroutine, utilize hydrologic data that are summarized by month. Therefore, the following data were mapped to each 500 m ICM-LAVegMod grid cell and a separate file was saved for each month of the year: monthly mean salinity (ppt) interpolated to each 500 m ICM-LAVegMod grid cell, monthly mean temperature (degrees Celsius) interpolated to each 500 m ICM-LAVegMod grid cell, monthly mean total suspended inorganic sediment (milligrams per liter), and monthly mean total Kjeldahl nitrogen (milligrams per liter). Due to the size of gridded monthly output data, these monthly output files are overwritten by each subsequent model year.

3.3.7.4 Model Output at Specific Time Intervals

Some of the algorithms included in ICM-LAVegMod and ICM-HSI require hydrologic data for specific time periods (e.g., growing season for plants or different animal species). Therefore, the compartment output tables containing annual mean values (Section 3.3.7.2) also have an array of other mean output values reported. These specific output data include mean stage (m relative to North American Vertical Datum of 1988 [NAVD88]) for the following time intervals: summer months from May through August, non-summer months January through March and September through December, and non-summer months January through April and October through December. The other specific time interval output data included: standard deviation (m) of the water surface during summer from May through August, mean salinity (ppt) during summer from May through August and mean temperature (degrees Celsius) during summer from May through August.

3.4 ICM-LAVegMod – Vegetation Dynamics Model

The LAVegMod algorithms and application underwent an extensive update procedure prior to integration into the ICM. Refer to Attachment C3-5 for a full discussion of the model improvements that were made.

3.4.1 Input Files Generated by ICM-Hydro

ICM-LAVegMod required several input files to run each year; the input Excel spreadsheets containing the probability of establishment and mortality of each vegetation species as a function of water level variability and salinity, the initial vegetation conditions at the start of the model run, and numerous environmental condition files representing the hydrodynamics and landscape of the model domain each year. The environmental conditions required by ICM-LAVegMod were calculated by various ICM subroutines and the input files representing each condition were formatted for ICM-LAVegMod by the ICM-Hydro subroutine. All environmental condition input files were formatted identically into a variant of the Environmental Systems Research Institute (ESRI) ASCII raster grid format (ESRI, 2013). The conditions included in the file (e.g., salinity) were mapped to an ESRI ASCII grid, and all grids for each model year were appended into a single ICM-LAVegMod input file. The standard ESRI ASCII raster grid format header was adjusted in these input files to include the model year represented by each subsequent data grid.

3.4.1.1 Mean Summer Hydrologic Data

For salinity, water level variability, and water temperature data, ICM-LAVegMod required mean summer values (as described in Section 3.3.7.4). Both mean summer salinity and temperature data were interpolated to the 500 m ICM-LAVegMod grid (see Section 3.2.5); water level variability data were not interpolated.

3.4.1.2 Mean Annual Salinity

In addition to the summer salinity, ICM-LAVegMod also required the mean annual salinity data (as described in Section 3.3.7.2). The mean annual salinity was interpolated to the 500 m ICM-LAVegMod grid (see Section 3.3.5).

3.4.1.3 Mean Summer Water Depth

The mean depth of water during summer months (May through August) within each 500 m grid cell was determined within ICM-Hydro by subtracting the mean bed elevation of each 500 m grid cell's water portion from the mean summer water surface elevation of the overlying ICM-Hydro model compartment. The mean bed elevation of each 500 m grid cell was calculated each year within the morphology subroutine from the 30 m topobathymetric DEM. If a 500 m grid cell did not have a calculated bed elevation (e.g., no water was present), the average bed elevation of the hydrology compartment was used instead.

3.4.1.4 Mean Height above Water

The height above the mean annual water surface within each 500 m grid cell was determined within the ICM-Hydro subroutine by subtracting the annual mean water surface elevation from the mean elevation of the land portion within each 500 m grid cell. The mean land elevation of each 500 m grid cell was calculated within the morphology subroutine from the 30 m topobathymetric DEM. If a 500 m grid cell did not have a calculated land elevation (e.g., all water), the average elevation of the marsh portion of the ICM-Hydro model compartment was used instead.

3.4.1.5 Tree Establishment Conditions

Hydrologic conditions are considered appropriate for tree establishment if a 500 m grid cell experiences at least two weeks of dry conditions followed by a two week period where the water depth does not exceed 10 cm. A 500 m grid cell was considered dry if the water surface elevation was at least 30 cm below the mean elevation of the land portion of the 500 m grid cell. The water surface and mean land elevations were determined in the ICM-Hydro and ICM-Morph subroutines, respectively.

3.4.1.6 Percent Land

The percentage of land and water within each 500 m grid cell was calculated by the ICM-Morph subroutine based on the 30 m land/water dataset. The portion of land and water within each 500 m grid cell was passed into the ICM-Hydro subroutine and subsequently mapped to the ESRI ASCII grid format each model year.

3.4.2 Output Files Used by Other ICM Components

ICM-LAVegMod prepares two specific output files that are utilized by other ICM subroutines: vegetative cover by species and the amount of floating marsh that was lost and converted to open water area.

3.4.2.1 Vegetative Species Coverage

For every model year, ICM-LAVegMod reports the percent of each 500 m grid cell that is covered by each species included in the model. The format of these files is a modified ESRI ASCII raster grid file. The header of each annual file is a standard ESRI ASCII grid where the grid values are an identification number. Beneath the grid of identifying values, there is a standard comma-separated portion of the file where each row corresponds to one of the grid cells with a unique identifier provided in the ESRI ASCII grid portion. Each row has data pertaining to the portion of each 500 m grid cell (values ranging from 0 to 1.0) that is covered by each modeled vegetation species.

3.4.2.2 Dead Floating Marsh Coverage

The floating marsh portion of ICM-LAVegMod is built on a slightly different modeling framework (see Section 6 in Attachment C3-5), and the floating marsh output data are therefore able to be summarized on a different time step than the other vegetation species. A summary time step is provided in the ICM-LAVegMod configuration input file, and the percentage of floating marsh that dies during this time step is reported out in the standard ESRI ASCII grid format.

3.5 ICM-BIMODE – Barrier Island Model

The BIMODE model was conceptualized and developed prior to integration into the ICM. Refer to Attachment C3-4 for a full discussion of BIMODE development.

3.5.1 Input Files Generated by ICM

The vast majority of input data required to run ICM-BIMODE for each of the six island regions were contained in ICM-BIMODE specific data that did not have any feedback with other ICM subroutines. The two input files that did require updating by the ICM were files that defined annual mean sea levels and the annual tidal prism volume at each island.

3.5.1.1 Annual Mean Sea Level

Each of the six island regions modeled in ICM-BIMODE required a water level to be used in defining shoreline locations. Each island region was mapped to a corresponding ICM-Hydro compartment, and the annual mean water level for each respective compartment is extracted by the ICM code and written directly to an input text file within the ICM-BIMODE input folder. This file is prepared every model year and overwrites the previous model year's data.

3.5.1.2 Annual Tidal Prism

Each of the six island regions modeled in ICM-BIMODE required a tidal prism volume as an input parameter. ICM-Hydro model compartments on the bayside (interior) of each island region were identified and the tidal prism from all associated compartments were summed for each island region by the ICM code and written directly to an input text file within the ICM-BIMODE input folder. The tidal prism was defined as the annual mean of the daily tidal range, which was calculated within ICM-Hydro as the difference between the daily maximum water level and the daily minimum water level for each model compartment.

3.5.2 Output Files Used by ICM

Only two ICM-BIMODE output files were used by other ICM subroutines: the profile elevation data and the breach locations.

3.5.2.1 Profile XYZ

Each island region modeled in ICM-BIMODE returned an individual XYZ file which contained the coordinates (in UTM meters) of each cross-shore profile point modeled by ICM-BIMODE. These points were set at a distance of 2 m in the cross-shore direction along each profile line. The profiles were spaced at 100 m in the long-shore direction. Each coordinate also contained a profile ID number and an elevation in meters, relative to NAVD88. Since each island region prepared an individual XYZ file, the ICM control code needed to combine these into a single text file that was passed into ICM-Morph every model year. This single text file was formatted to match the required ASCI XYZ file format used by ESRI's geoprocessing functions (ESRI, 2016a).

3.5.2.2 Breached Profiles

If a profile was breached in ICM-BIMODE, the corresponding profile was deactivated, and kept inactive for the remaining model years. A list of all breached profiles was recorded every model year for use by the ICM in activating any ICM-Hydro model links that were initialized to represent breached profiles on any of the modeled islands. The list of ICM-Hydro links that represented a potential island breach was manually prepared by the modeling team during the ICM-Hydro compartment delineation procedure, as previously discussed.

3.6 ICM-Morph – Wetland Morphology Model

The Wetland Morphology model used for the 2012 Coastal Master Plan was a standard set of operations and algorithms implemented within the ESRI ArcMap environment. The first step towards integrating this component into the ICM was the removal of any manual interactions with the ESRI function calls. This was accomplished by having the ICM code write all necessary input parameters to a configuration text file that was passed directly into the ICM-Morph Python code. Additional parameters and datasets generated by other ICM subroutines that were manually prepared during the 2012 modeling effort (e.g., mean water level and salinity geospatial data) were incorporated into a pre-processing step within ICM-Morph.

In addition to the programmatic pre-processing of ICM-Morph input data, many post-processing functions were added to ICM-Morph as well. All elevation and land/water data required to update the ICM-Hydro and ICM-LAVegMod subroutines for the next simulation year were

placed as separate functions within the ICM-Morph subroutine. Furthermore, various water depth summations required for the habitat suitability indices were also prepared in ICM-Morph.

3.6.1 Changes to Wetland Morphology Model

In addition to the I/O processing functions added to ICM-Morph, several changes were made to the underlying logic of the land change algorithms developed for the 2012 Wetland Morphology model (Couvillion et al., 2013). The improved land change algorithms better accommodated improvements within other ICM subroutines (e.g., sediment distribution improvements), new model processes (e.g., floating marsh in ICM-LAVegMod), and improved model feedback time steps (e.g., annual mean water level calculations). The improved algorithms also addressed suggestions from the reviewers of the 2012 modeling effort (e.g., using the maximum two week mean salinity for collapse thresholds).

3.6.1.1 Mean Water Level/Sea Level Rise

During the 2012 modeling effort, the Wetland Morphology model was run on a five year time step, which required a mean water level representation for every five year time step. This input dataset was manually prepared from daily output values from the 2012 Ecohydrology models and captured the assumed sea level rise rates at this five year time step. The use of an annual time step in the 2017 ICM modeling effort, therefore, resulted in a much finer temporal resolution of mean water levels used within ICM-Morph than in 2012. By averaging over a smaller timescale, the mean water levels used within ICM-Morph to define the land/water interface were more sensitive to extreme events such as storm surge from tropical storm events and flood or drought years in the riverine inputs to the estuary. Similarly, during later years, the rate of change in sea level rise rates increases substantially from one year to the next resulting in annual change that would not be captured at a five year time step (see Chapter 2 and Attachment C2-1 for a discussion of sea level rise rates modeled). However, while the increase in time step allows for a more dynamic response to mean water levels, it could potentially lead to an over sensitivity to extreme events. During the model calibration effort, it was determined that model representation of wetland collapse and land gain was best captured if the mean water level conditions from two consecutive years were used instead of a single annual value (see Table 6 in Attachment C3-23).

3.6.1.2 Maximum Two Week Salinity

Fresh marsh and fresh forested vegetation types are susceptible to collapse if exposed to periods of high salinity. To account for short periods of high salinity that may result in fresh wetland collapse, a two week moving window average was performed on the daily mean salinity values calculated in ICM-Hydro. The maximum of these two week mean salinities in a model year was used in ICM-Morph to determine what areas of fresh forest or fresh marsh should be converted to open water due to a salinity spike. This salinity-threshold collapse routine within ICM-Morph was only applied to fresh areas that were inundated at some point during the previous year. In order for a fresh forest or fresh marsh 30 m pixel to collapse it must 1) be classified as fresh, 2) have an elevation below the maximum daily mean water level of the year, and 3) have a two week maximum salinity above the collapse salinity threshold (see Table 6 in Attachment C3-23).

The Wetland Morphology component of the 2012 Coastal Master Plan modeling suite used the mean salinity during an eight week growing season to determine salinity-driven collapse of fresh

areas. Utilizing a two week moving window will result in an increase in fresh marsh collapse, relative to the eight week mean previously used.

3.6.1.3 Sediment Deposition Zones

To accommodate the improvements to the sediment distribution calculations within ICM-Hydro (Attachment C3-1), the sedimentation surface (Steyer et al., 2012) derived for the 2012 modeling effort was removed from ICM-Morph. In its place, the three zones for which sediment was deposited in ICM-Hydro (open water, marsh edge, and marsh interior) were determined from the geospatial land/water dataset used by ICM-Morph. The open water zone was defined as any 30 m pixel classified as *water*. The pixels classified as *land*, were then classified as either edge or interior pixels. To identify the edge pixels, ESRI's geospatial "expand" function (ESRI, 2016b) was applied to the water pixels in the land/water dataset (Figure 7a). This function identifies all land pixels that border a water pixel, and expands the water pixels by reclassifying the border land pixels to be water (Figure 7b). The original land/water dataset was subtracted from the dataset containing the expanded water, isolating the edge pixels. (Figure 7c). Any pixel in the expanded water dataset that remained as land was classified as interior.

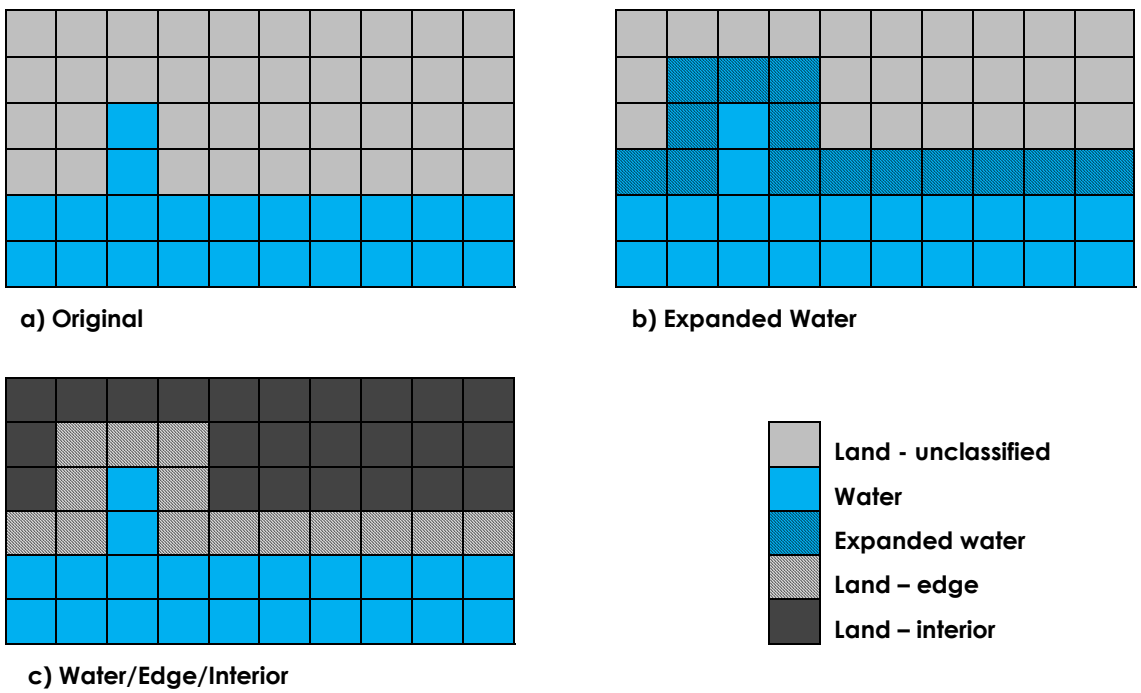


Figure 7: Schematic of Methodology Used to Determine Marsh Zones for Sediment Deposition.

The sediment deposition data for each ICM-Hydro model compartment were passed into ICM-Morph via the standard ICM-Hydro annual compartment output text files, with three values representing sediment deposition, in g/m^2, in the open water, on the marsh edge, and on the marsh interior. The area used to normalize this mass loading rate was the total area of each of these zones within ICM-Hydro. Within ICM-Morph, it was assumed that the entire open water and marsh edge zones would receive this mass per unit area sediment load. However, to accurately determine the deposition areas within the marsh interior, the extent of inundation from the maximum water level was calculated. Any interior marsh pixel with an elevation at or below this

water level was assumed to be inundated, and therefore would receive sediment deposition. The mass balance on the sediment deposition rate within ICM-Hydro was closed by assuming the entire non-edge marsh surface within a compartment received deposition. Therefore, to conserve sediment masses between the ICM-Hydro and ICM-Morph subroutines, the sediment loading rate calculated in ICM-Hydro was adjusted, via equation 1, to account for the change from total marsh interior area to inundated marsh interior area.

$$\frac{Sediment\ Deposition\ [g]}{Area\ iundated\ [m^2]} = \frac{Sediment\ Deposition\ [g]}{Area\ interior\ [m^2]} \times \frac{Area\ interior\ [\ m^2]}{Area\ inundated\ [m^2]} \tag{1}$$

From this point forward, the sediment deposition rates were used in the same manner that they were used in the 2012 modeling effort; the sediment deposition rates were assigned bulk density and organic matter values based upon the vegetation type present, and an annual vertical accretion rate was calculated and used to update the marsh elevation, along with the subsidence and marsh collapse algorithms (Steyer et al., 2012).

3.6.1.4 Marsh Edge Erosion

In addition to removing the sedimentation surface from the 2012 Wetland Morphology model, the loss-gain zones were also removed. These zones were predetermined rates of land loss and land gain that were estimated to account for the morphologic process that were not captured in the 2012 Wetland Morphology model (Steyer, et al., 2012). Due to the improved sediment distribution process in the 2017 ICM, the land gain component of this removed process was assumed to be accounted for. The land loss component was addressed by the inclusion of marsh edge erosion as a specific physical process (Attachment C3-2). In addition to including the edge erosion as a source term in the overall sediment mass balance within ICM-Hydro (Section 3.3.4.1), the marsh edge erosion was added to ICM-Morph landscape update algorithm.

The implementation of marsh edge erosion within the ICM required two distinct calculations. First, a 30 m land pixel needed to be identified as marsh edge; otherwise, it would not be subjected to the marsh edge erosion algorithm. The methodology described in Section 3.6.1.3 was also used here to identify marsh edge pixels. The second calculation required, was to determine whether during any given model simulation year, a pixel classified as marsh edge should be eroded or not. If an edge pixel was determined to have a historic retreat rate (as described in Section 7 of Attachment C3-2), the frequency at which an edge pixel should be eroded (e.g., converted from land to water) was determined by dividing the retreat rate into the pixel resolution (30 m). For instance, if a region of the model domain was determined to have an historic marsh edge erosion rate of 10 m/yr, one 30 m pixel of marsh edge would be eroded every three simulation years. As discussed in Attachment C3-2, the historic marsh edge erosion data were interpolated to a 500 m resolution raster. This allowed for any edge pixel (throughout the entire simulation period) within 500 m of the initial edge location to be subjected to the historic marsh edge erosion rates.

3.6.1.5 Floating Marsh

The dead floating marsh output files were generated by ICM-LAVegMod every five years and reported the amount of floating marsh located within each 500 m grid cell that had died during those five years. ICM-LAVegMod does not contain a spatial component; therefore, ICM-Morph did not receive any information regarding exactly which 30 m floating marsh pixels within the 500 m grid cell should be converted to water. Therefore, a threshold was applied that would not

remove any floating marsh from the 30 m ICM-Morph dataset until at least 50% of the floating marsh within a 500 m ICM-LAVegMod grid cell had died. Once this threshold was met, all 30 m floating marsh pixels underlying the respective 500 m grid cell were assumed to have died and converted to open water. ICM-LAVegMod accounted for the tally of living versus dead floating marsh within each pixel internally, so the only information needed to be passed to other ICM subroutines was the subsequent increase in open water area due to this loss of floating marsh.

Updates were made to this floating marsh algorithm for some model runs conducted for the 2017 Coastal Master Plan modeling effort; these are discussed in Section 4.2 of this report.

3.6.2 Input Data Processed from Other ICM Component Outputs

As the final subroutine in the chain of ICM components that provide feedback to one another, ICM-Morph contained a substantial library of data pre-processing functions. The majority of the model integration effort was to ensure that the model output from other ICM subroutines was adequately converted to geospatial datasets for use within ICM-Morph each simulation year. The built-in ESRI functions that can join text files to geospatial datasets were heavily relied upon to complete this integration effort.

3.6.2.1 ICM-Hydro Output Data

For each simulation year, several raster datasets were developed which represented a variety of hydrologic conditions calculated by ICM-Hydro. The standard ICM-Hydro annual compartment output text file was joined to a template polygon representing the spatial footprint of each ICM-Hydro compartment. Once joined, each data type required by ICM-Morph was exported to a separate raster dataset with a 30 m resolution that was projected identically to all other 30 m raster datasets used by ICM-Morph.

Compartment-level data that were converted into raster datasets for use in ICM-Morph included:

- annual mean water level
- annual maximum water level
- sediment deposition in open water area
- sediment deposition in marsh edge area
- sediment deposition in marsh interior area

The sediment deposition mass per unit area values calculated by ICM-Hydro were updated, as described in Section 3.5.1.3, to account for deposition occurring only in areas that would have been inundated at some point during the model year.

In addition to the compartment-level data described above, a parallel process was followed to develop raster datasets of ICM-Hydro output data that had been interpolated to the 500 m ICM-LAVegMod grid (see Section 3.3.5).

The standard ICM-Hydro grid-level output text file was joined to a template polygon representing the spatial footprint of each 500 m ICM-LAVegMod grid cells. Once joined, each data type required by ICM-Morph was exported to a separate raster dataset, with a 30 m resolution that was projected identically to all other 30 m raster datasets used by ICM-Morph.

ICM-Hydro output data interpolated to the 500 m ICM-LAVegMod grid-level that were converted into raster datasets for use in ICM-Morph included:

- annual mean salinity
- maximum two week mean salinity

3.6.2.2 Vegetation Type

For each simulation year, the ICM-LAVegMod species output file is read into ICM-Morph and used to assign a predominant vegetation type to each 30 m land/water pixel. The ICM-LAVegMod data are modeled as a percent cover for each modeled species within each 500 m grid cell. ICM-Morph iterates through each 500 m grid cell and reclassifies each individual species' coverage to a vegetation type (Table 3). The percentage of each 500 m grid cell that is covered by each vegetation type (fresh forest, fresh marsh, intermediate marsh, brackish marsh, saline marsh, or upland) is then tabulated. The vegetation type that is the most prevalent is then used to assign a predominant vegetation type to each 500 m grid cell. This algorithm *does not* require a majority of land cover; rather, if a plurality of the 500 m grid cell is one vegetation type, then the entire 500 m grid cell will be classified as that vegetation type. For example, a 500 m grid cell may be covered by 40% of species that are fresh marsh, 41% of species that are classified as intermediate marsh, and 19% of species that are brackish marsh; the entire 500 m grid cell will be classified within ICM-Morph as predominantly intermediate marsh.

Once the ICM-LAVegMod output data are used to derive predominant vegetation types for each 500 m grid cell, the data are resampled to a resolution and alignment that matches the rest of the 30 m pixel data utilized by ICM-Morph. After this, the pre-existing land/water dataset maintained by ICM-Morph is used to overlay 30 m resolution land/water data onto the 500 m ICM-LAVegMod vegetation type data.

In addition to vegetation species, ICM-LAVegMod also reports the portion of each 500 m grid cell that is not populated with any modeled species; it is considered bare ground. Unless the bare ground portion covers more than 99% of a 500 m grid cell, the portion of a 500 m grid cell that is considered bare ground is excluded from the predominant vegetation type analysis. For instance, a 500 m grid cell could be 70% bare ground, 20% fresh marsh, and 10% fresh forest; the entire 500 m grid cell will be classified as predominantly fresh marsh. However, once a 500 m grid cell has more than 99% bare ground, the entire grid cell will be classified as predominantly bare ground.

Table 3: Reclassification Table Used to Convert Vegetation Species to Vegetation Type.

Species Code	Species Common Name	Species Scientific Name	ICM-Morph Vegetation Type
NYAQ2	Tupelo	Nyssa aquatica L.	Fresh forested
QULA3	Laurel Oak	Quercus laurifolia Michx.	Fresh forested
QULE	Hybrid Oak	*Quercus xleana Nutt. (pro sp.) [imbricara x velutina]*	Fresh forested
QUNI	Water Oak	*Quercus nigra L.*	Fresh forested
QUTE	Texas Red Oak	*Quercus texana Buckley*	Fresh forested
QUVI	Live oak	*Quercus virginiana Mill.*	Fresh forested
SANI	Black Willow	*Salix nigra Marsh.*	Fresh forested
TADI2	Cypress	*Taxodium distichum (L.) Rich.*	Fresh forested
ULAM	American Elm	*Ulmus Americana L.*	Fresh forested
CLMA10	Sawgrass	*Cladium mariscus (L.) Pohl*	Fresh herbaceous
ELBA2	Spikerush	*Eleocharis baldwinii (Torr.) Chapm.*	Fresh herbaceous
HYUM	Pennywort	*Hydrocotyle umbellata L.*	Fresh herbaceous
MOCE2	Wax myrtle	*Morella cerifera (L.) Small*	Fresh herbaceous
PAHE2	Maidencane	*Panicum hemitomon Schult.*	Fresh herbaceous
SALA2	Arrowhead	*Sagittaria latifolia Willd.*	Fresh herbaceous
SCCA11	Bullwhip	*Schoenoplectus californicus (C.A. Mey.) Palla*	Fresh herbaceous
TYDO	Cattail	*Typha domingensis Pers.*	Fresh herbaceous
ZIMI	Cutgrass	*Zizaniopsis miliacea (Michx.) Döll & Asch.*	Fresh herbaceous
ELBA2_Flt	Spikerush - floating	*Eleocharis baldwinii (Torr.) Chapm.*	Floating marsh
HYUM_Flt	Pennywort - floating	*Hydrocotyle umbellata L.*	Floating marsh
PAHE2_Flt	Maidencane -	*Panicum hemitomon Schult.*	Floating marsh

Species Code	Species Common Name	Species Scientific Name	ICM-Morph Vegetation Type
	floating		
BAHA	Baccharis	*Baccharis halimifolia L.*	Intermediate herbaceous
IVFR	Marsh-elder	*Iva frutescens L.*	Intermediate herbaceous
PHAU7	Roseau Cane	*Phragmites australis (Cav.) Trin. ex Steud.*	Intermediate herbaceous
SALA	Bulltongue	*Sagittaria lancifolia L.*	Intermediate herbaceous
PAVA	Paspalum	*Paspalum vaginatum Sw.*	Brackish herbaceous
SPPA	Wiregrass	*Spartina patens (Aiton) Muhl.*	Brackish herbaceous
SPPABI	Wiregrass – Barrier Island	*Spartina patens (Aiton) Muhl.*	Brackish herbaceous
AVGE	Mangrove	*Avicennia germinans (L.) L.*	Salt herbaceous
BAHABI	Baccharis - Barrier Island	*Baccharis halimifolia L.*	Salt herbaceous
DISP	Saltgrass	*Distichlis spicata (L.) Greene*	Salt herbaceous
DISPBI	Saltgrass - Barrier Island	*Distichlis spicata (L.) Greene*	Salt herbaceous
JURO	Needlegrass	*Juncus roemerianus Scheele*	Salt herbaceous
PAAM2	Beachgrass – Barrier Island	*Panicum amarum Elliott*	Salt herbaceous
SOSE	Seaside goldenrod	*Solidago sempervirens L.*	Salt herbaceous
SPAL	Oystergrass	*Spartina alterniflora Loisel.*	Salt herbaceous
SPVI3	Seashore dropseed	*Sporobolus virginicus (L.) Kunth*	Salt herbaceous
STHE9	Amberique	*Strophostyles helvola (L.) Elliott*	Salt herbaceous

Species Code	Species Common Name	Species Scientific Name	ICM-Morph Vegetation Type
	bean		
UNPA	Seaoats – Barrier Island	*Uniola paniculata L.*	Salt herbaceous
BAREGRND	Bare Ground	*n/a*	Upland/ BareGround/ NotModeled
NOTMOD	Not Modeled	*n/a*	Upland/ BareGround/ NotModeled
WATER	Water	n/a	Water
SAV	Sub Aquatic Vegetation	n/a	Water

3.6.3 Output Files Used by Other ICM Components

The ICM-Morph subroutine, is the primary set of algorithms that 'updates' the modeled landscape every model year. New land is built due to sediment deposition; marsh is lost to open water due to inundation and salinity thresholds, marsh edge erosion; and the elevation changes due to spatially varied subsidence and accretion. Due to the many geospatial functions included in ICM-Morph, many of the geospatial summary data required by other ICM subroutines are determined by ICM-Morph. These model I/O files used solely by other ICM-subroutines and are deemed 'internal'; they are not intended to be used as summary output files for manual analysis. However, many of these same datasets are summarized in deliverable files, which are formatted for a human end-user; these deliverable files are discussed in the next section.

The internal model files are generally used to aggregate and summarize various landscape characteristics at either the 500 m ICM-LAVegMod grid scale or to the ICM-Hydro model compartment scale. These data files are formatted text files that maintain an identifying attribute (e.g., grid or compartment number) and the data value associated with it (e.g., percent land area within each grid cell). A list of the many internal data files generated by the ICM (and the formats used) is provided in Attachment C3-22.3.

3.6.3.1 Compartment Averaged Elevation Data

For each ICM-Hydro model compartment, the following information is reported: average marsh surface elevation (m relative to NAVD88) and average open water bed elevation (m relative to NAVD88). This file also reports the total area, in m^2, of marsh area that is classified as edge. This dataset represents the elevation and edge areas at the end of each ICM-Morph model time step. If any compartment does not have a value for one of the data types (e.g., no land

elevation because compartment is 100% water), the value is set to the default No Data value of -9999.

3.6.3.2 Portion of Land in Compartment

The portion land output file contains the amount of land within each ICM-Hydro model compartment (based on the pixels in the land/water/floating marsh raster) that was classified as either land or floating marsh at the end of the model year. The amount of land is reported as the portion of the compartment that is land, ranging from 0 (all water) to 1 (all land). This dataset represents the amount of land at the end of each ICM cycle after all subroutines are complete.

3.6.3.3 Portion of Water in Compartment

The portion water output file contains the percentage of each ICM-Hydro model compartment that was classified as water at the end of the model year (based on the pixels in the land/water/floating marsh raster). The amount of water is reported as the portion of the compartment that is water, ranging from 0 (all water) to 1 (all land). This dataset represents the amount of water at the end of each simulation period after all subroutines are complete.

3.6.3.4 500 Meter Grid Averaged Data

The landscape information calculated by ICM-Morph is summarized by 500 m ICM-LAVegMod grid cell. The data included in this file are: average elevation of the open water portion of the grid cell, average elevation of the land surface within the grid cell, percentage of the grid cell that is any type of land, percentage of the grid cell that is water, and percentage of grid cell that is land and is classified as either forested wetland or marsh. All grid elevation data are reported in meters, relative to NAVD88. All percentages are reported from 0 to 100. If any grid cell does not have a value for one of the data types (e.g., no land elevation because grid cell is 100% water), the value is set to the default No Data value of -9999.

3.6.3.5 500 Meter Grid Data – HSI Specific

In addition to the general elevation and percent land/water data averaged by 500 m ICM-LAVegMod grid cell, several HSI equations required specific geospatial data compiled per grid cell. Each of the waterfowl equations (Gadwall, Green-Winged Teal, Mottled Duck) required tabulated areas for a variety of water depth classifications (e.g., portion of grid cell less than 2 cm deep, portion of grid cell with depths between 2 and 4 cm, etc.). Several other HSI equations required average water depth within each grid cell, which required a calculation from mean water level and elevation data. Additionally, the Brown Pelican HSI required the calculation of numerous geospatial variables: size of islands with salt marsh habitat and distance from large islands or the mainland. The exact datasets required for each HSI can be found in the individual HSI reports (Attachments C3-6 to C3-19).

3.6.4 Output/Deliverable Files

At the completion of each annual ICM-Morph simulation, several geospatial datasets are prepared and exported as standalone raster files. Summary tables were also prepared which provided output values tabulated for each of the 2017 Coastal Master Plan ecoregions. The ecoregions (Figure 8) are unique zones across coastal Louisiana that were chosen by CPRA as the spatial unit for assessment of many ICM outputs. Rather than focusing on individual pixels of

land or water, or an individual ICM-Hydro model compartment's change in water level throughout the model run, output is aggregated to the ecoregion scale. The 12 ecoregions used for summarizing ICM output are provided in Table 4.

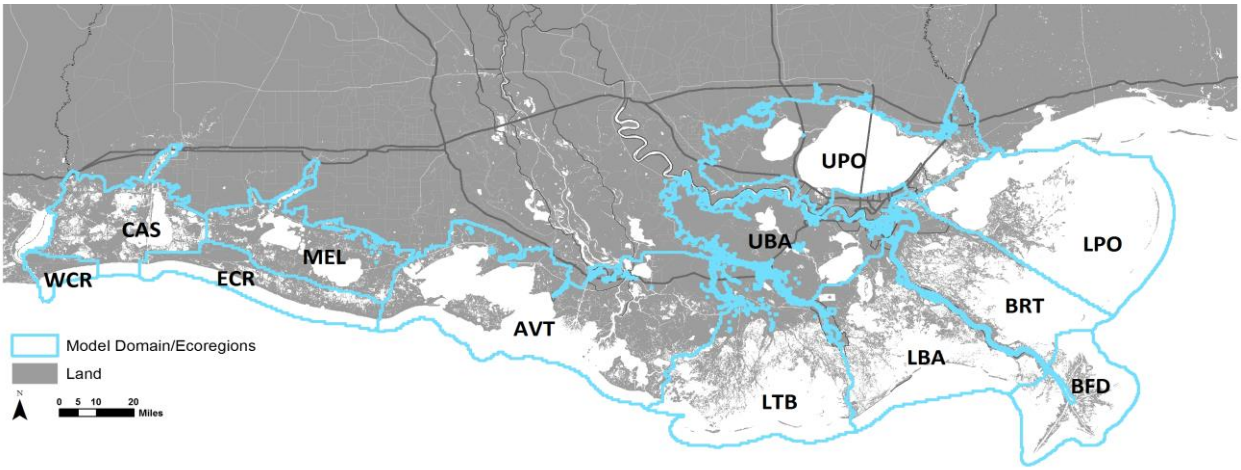


Figure 8: 2017 Coastal Master Plan Ecoregions.

Table 4: 2017 Coastal Master Plan Ecoregions Used for Summarizing Model Output.

Ecoregion Code	Ecoregion
UPO	Upper Pontchartrain
LPO	Lower Pontchartrain
BRT	Breton
UBA	Upper Barataria
LBA	Lower Barataria
BFD	Bird's Foot Delta
LTB	Lower Terrebonne
AVT	Atchafalaya/Teche/Vermillion
MEL	Mermentau/Lakes
CAS	Calcasieu/Sabine
ECR	Eastern Chenier Ridges
WCR	Western Chenier Ridges

Data exported from ICM-Morph to an IMG format raster with a 30 m resolution are:

- annual mean water level (m NAVD88)
- spatially interpolated annual mean salinity (ppt)
- spatially interpolated annual maximum two week mean salinity (ppt)
- vertical accretion spatial dataset (compiled from sediment deposition, organic matter, and bulk density datasets)
- the vegetation type dataset that is classified based upon predominant vegetation species
- the land/water/floating marsh dataset

The spatial extent of each of these datasets is clipped to exclude any model data outside of the 2017 Coastal Master Plan ecoregions. For the vegetation type, the values within the raster are integer values which correspond to the predominant vegetation type as provided in Table 5. For the land/water/floating marsh datasets, the values in the raster are integer values which correspond to the land/water/floating marsh classification as provided in Table 6.

Table 5: Vegetation Type Raster Values.

Raster Value	Predominant Vegetation Type
1	Fresh Forest
2	Fresh Herbaceous Marsh
3	Intermediate Herbaceous Marsh
4	Brackish Herbaceous Marsh
5	Saline Herbaceous Marsh
6	Water
7	Upland/Bare Ground/Not Modeled
8	Floating Marsh

Table 6: Land/Water/Floating Marsh Raster Values.

Raster Value	Predominant Vegetation Type
1	Land
2	Water
5	Floating Marsh

In addition, within each 2017 Coastal Master Plan ecoregion, the total amount of land, water, and floating marsh are individually tabulated and written to an output text file. The total amount

of land that is classified as each of the eight vegetation types (listed in Table 5), water, and floating marsh within each ecoregion are also individually tabulated and written to an output text file.

3.7 Non-Landscape ICM Components

The subroutines discussed above (ICM-Hydro, ICM-BIMODE, ICM-LAVegMod, and ICM-Morph) are the four subroutines that provide feedback amongst the ICM. In addition to these dynamic subroutines, there are two additional subroutines (ICM-HSI and ICM-EwE) that receive output from the other subroutines, but do not have an active feedback loop with the rest of the ICM.

3.7.1 ICM-HSI – Habitat Suitability Indices

The habitat suitability equations modeled in ICM-HSI were all coded into a standalone Python function. The ICM control code passed several input variables into the ICM-HSI function (e.g., salinity, temperature, and water level data). Other input data required by ICM-HSI were written to text files by other subroutines, which were subsequently read into ICM-HSI during execution of the model code as the last step of the ICM algorithm for each model year.

3.7.1.1 ICM-HSI Input Files

The input files used by the ICM-HSI routine were generated either by the ICM-Morph routine (summaries of land/water, depth, elevation, etc.) or by the ICM-Hydro subroutine (mean monthly salinity, water temperature, etc.). Due to the size of data I/O, gridded monthly mean salinities required by ICM-HSI were generated for each model year and subsequently over-written during the following year. The spatially interpolated mean monthly salinity data were written to text file, and were subsequently read into a Python dictionary for each HSI to utilize during calculation. Several ICM-HSI input files for the pelican island size and water depth classifications for water fowl HSI are saved for every model year. All ICM-HSI equations use the ICM-LAVegMod grid cell as the calculation unit; therefore, all ICM-HSI input files have the input data tabulated for each grid cell.

3.7.1.2 ICM-HSI Output Files

The ICM-HSI subroutine prepares two output files for each species habitat modeled. The first file is formatted in the standard ESRI ASCII grid format that is used by other ICM subroutines. Each value mapped to the ASCII grid is the HSI value (ranging from 0 to 1) of the species habitat that is mapped. An individual ASCII file is prepared for each of the HSI equations (Attachments C3-6 through C3-19). The second file that is prepared for each species habitat is a formatted text file that contains each of the terms used to calculate each HSI for every 500 m ICM-LAVegMod grid cell. These text output files are saved for analysis purposes in order to determine which input variable(s) to the HSI were responsible for the HSI value of any specific grid cell.

3.7.2 ICM-Ecopath with Ecosim

After the completion of all simulation years for all ICM subroutines, a standalone model ICM-EwE (Attachment C3-20) was run to model fisheries biomass dynamics over space and time. The input files required for ICM-EwE were produced by the ICM control program.

3.7.2.1 ICM-EwE Input Files

The ICM-EwE subroutine is modeled on a separate model spatial resolution: a 1 km grid that is aligned with the 500 m ICM-LAVegMod grid used by other subroutines. Therefore, to map the required input data to the ICM-EwE grid, the ICM output already formatted for the 500 m grid cells are read in and aggregated to develop the ICM-EwE input. However, the 500 m grid cell data have a maximum spatial extent that is set to the 2017 Coastal Master Plan Ecoregions boundary. ICM-EwE requires data for the offshore portion of the ICM-Hydro domain, which is outside of the Ecoregions. The initial ICM-EwE data are then amended to include the offshore data that is outside of the extent of the other 500 m gridded datasets. This step was completed by the ICM control program which reads in the full daily time series output data from ICM-Hydro, separately calculates the required monthly average values for the offshore locations, and generates the required ASCII grid data files of the ICM-EwE input data.

All ICM-EwE input data are provided in the standard ESRI ASCII grid raster formatted text file. The data prepared for ICM-EwE are calculated for each 1 km grid cell and include:

- monthly mean salinity (ppt)
- monthly mean water temperature (degrees Celsius)
- monthly mean total Kjedahl nitrogen concentration (mg/L)
- annual mean water depth (m)
- annual percent wetland

3.7.2.2 Oyster Environmental Capacity Layer (OECL)

ICM-EwE was packaged with a standalone oyster model called the Oyster Environmental Capacity Layer (OECL). This subroutine utilizes daily mean hydrologic data (e.g., salinity) to model oyster population dynamics, which rely upon a finer temporal resolution than the monthly data utilized by the rest of ICM-EwE. The raw time series output files produced by ICM-Hydro are passed into OECL, which in turn generates monthly gridded data input files used by ICM-EwE.

4.0 Model Updates for Alternative and Plan Level Analyses

After completing several multi-decadal model runs under a variety of environmental scenarios, it became clear that several aspects of the ICM required adjustment to ensure appropriate response to changing environmental conditions. The changes described in this section were implemented in the ICM upon the completion of the project-level runs. All model runs of alternative plans, the draft plan and the final 2017 Coastal Master Plan were completed with the following updates included in the ICM.

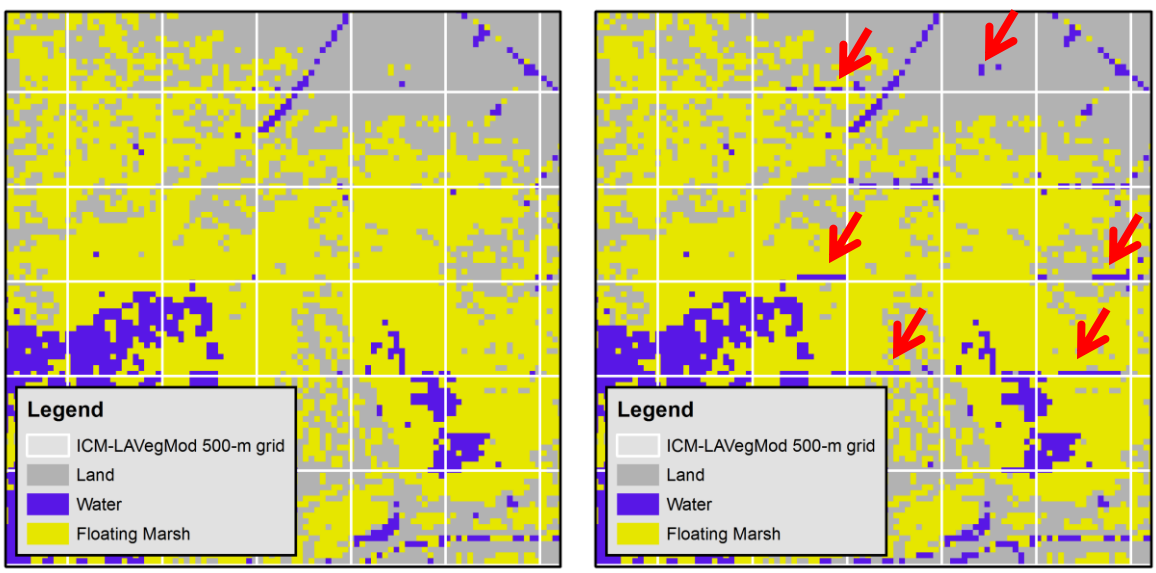
4.1 Further Calibration of ICM-Hydro for Salinity Stability

Due to changing hydraulic conditions during later decades, some ICM-Hydro compartments that performed well during the calibration period were subject to some instabilities in salinity calculations. A re-calibration effort was undertaken to improve salinity calculation stability during later decades. The adjustments made to the salinity mass balance and re-calibration effort, as well as the updated model performance statistics, are provided in Attachment C3-23.

4.2 Floating Marsh

Upon completion of a multi-decade simulation, it became apparent that the threshold approach for dead floating marsh in ICM-Morph was not adequately capturing the floating marsh dynamics, as modeled by ICM-LAVegMod. A new methodology was developed that did not rely on meeting a threshold of dead floating marsh, but instead used an approach to progressively remove dead 30 m floating marsh pixels within each 500 m grid cell.

At the start of the model run, all 30 m floating marsh pixels contained within a single 500 m grid cell were counted and assigned a number. The floating marsh pixels were scanned and numbered starting in the northwest corner of each 500 m grid cell. The scanning/numbering system progressed across each 500 m grid cell in a west-to-east direction, starting at the northernmost row. As the ICM-LAVegMod dead floating marsh output files were generated, ICM-Morph would follow this same scanning pattern, scanning each 30 m floating marsh pixel until enough floating marsh was registered that equaled the amount of floating marsh that was calculated by ICM-LAVegMod to be remaining within the 500 m grid cell. Any pixels previously classified as floating marsh to the east and south of this last registered floating marsh pixel would be converted to open water (see Figure 9).



a) Initial Land/Water/Floating Marsh **b) Dead Floating Marsh Converted to Water**

Figure 9: Sample 500 m Grid Cells With 30 m Floating Marsh Before (a) and After (b) the West-to-East, North-to-South Scanning Approach Used for Converting Dead Floating Marsh to Open Water. Floating marsh converted to open water is indicated by the red arrows.

4.3 Bare Ground Collapse

Due to rapidly increasing salinity in later years of the 50-year model simulation, the vegetation dynamics occasionally predict large areas of bare ground; hydrologic conditions are not appropriate for any modeled vegetation species within the dispersal distance, but inundation or salinity collapse thresholds had not yet been crossed in ICM-Morph. Due to a lack of vegetation type in bare ground areas, ICM-Morph would not apply collapse criteria to this land. To correct for this, a new collapse threshold was added to the ICM-Morph algorithms, which examined bare ground areas for inundation. If a 30 m pixel remained bare ground and was inundated for

two consecutive years, the bare ground would collapse into open water. The criterion of two consecutive years was chosen to allow for a brief period of time for the dispersal routine in ICM-LAVegMod to allow for vegetation to establish in bare ground. However, if after two years, no vegetation species were established and the bare ground had been inundated for both of those years, the land was converted to water. Unlike the analysis that was conducted to determine appropriate inundation thresholds for marsh collapse (Couvillion & Beck, 2013), no such analysis had been performed for bare ground areas. Therefore, an inundation depth of 20 cm was chosen to remain consistent with the water-to-marsh elevation difference required for land building to occur within ICM-Morph (see Table 6 in Attachment C3-23).

5.0 File Formats and Naming Convention

The files generated and used by the model, as described in the previous sections, are named and organized programmatically by the ICM code. A file naming convention was put into place to differentiate between the scenarios and projects modeled throughout the 2017 Coastal Master Plan process. The file naming convention used is provided in Attachment C3-22.2. A compiled list of all files and the formats used is provided in Attachment C3-22.3.

6.0 References

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Additional Information

Attachment C3-22.1 – ICM-Hydro Flow Calculations
Attachment C3-22.2 – File Naming Convention