2023 COASTAL MASTER PLAN

MODELING WETLAND VEGETATION AND MORPHOLOGY: ICM-LAVEGMOD AND ICM-MORPH

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COASTAL PROTECTION AND RESTORATION AUTHORITY

This document was developed in support of the 2023 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 six 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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CPRA	COASTAL PROTECTION AND RESTORATION AUTHORITY
CRMS	COASTWIDE REFERENCE MONITORING SYSTEM
CSV	COMMA SEPARATED VALUES
DEM	DIGITAL ELEVATION MODEL
FFIBS	FORESTED, FRESH, INTERMEDIATE, BRACKISH, SALINE
FWA	FUTURE WITH ACTION
FWOA	FUTURE WITHOUT ACTION
GIWW	GULF INTRACOASTAL WATERWAY
HPC	HIGH PERFORMANCE COMPUTING
HSI	HABITAT SUITABILITY INDEX
ICM	INTEGRATED COMPARTMENT MODEL
LAVEGMOD	LOUISIANA VEGETATION MODEL
LULC	LAND USE/LAND COVER
MORPH	MORPHOLOGY MODEL
OMAR	ORGANIC MATTER ACCUMULATION RATE
PM-TAC	PREDICTIVE MODEL TECHNICAL ADVISORY COMMITTEE
SAV	SUBMERGED AQUATIC VEGETATION
USGS	UNITED STATES GEOLOGICAL SURVEY

1.0 INTRODUCTION

This report describes the vegetation and morphology subroutines of the Integrated Compartment Model (ICM), ICM-LAVegMod and ICM-Morph respectively. The subroutines are described here as they were used to support modeling for the 2023 Coastal Master Plan. They were built upon versions previously applied to support the 2012 and 2017 Coastal Master Plans and incorporate new updates recommended by the ICM-Wetlands, Vegetation, and Soils Model Improvement Team. While this report includes some description of the reasoning behind specific improvements, the focus is to describe the final version applied for 2023 Coastal Master Plan model runs. Details on previous versions of the models are available in appendices to the 2012 and 2017 Coastal Master Plans (e.g., White et al., 2017). Appendix D of the 2023 Coastal Master Plan summarizes improvements made from the version used for the 2017 Coastal Master Plan, as well as discuss additional information on the development of these improvements.

The ICM-LAVegMod and ICM-Morph subroutines are the main components of the ICM responsible for tracking land change, elevation change, and vegetation change over time for ICM predictions, based on input from the ICM-Hydro subroutine. These subroutines were fully integrated into the ICM as part of model improvements for the 2017 Coastal Master Plan, and they work together in the current ICM – with information passed back and forth among them – to determine related outputs. More specifically, ICM-Hydro tracks water levels, salinities, and other related variables that serve as inputs for ICM-Morph and ICM-LAVegMod; ICM-Morph tracks surface elevations and land change, and ICM-LAVegMod tracks the coverage of vegetation on areas determined by ICM-Morph to be land (Figure 1) and the extent of flotant marsh (i.e., floating marsh). Unvegetated land, or bareground, transitions (Figure 1) are tracked by ICM-LAVegMod. ICM-LAVegMod determines each year how much land is left bare due to mortality of existing species and lack of establishment of new species. Predictions of submerged aquatic vegetation (SAV), which depend on outputs from ICM-Hydro and ICM-Morph, were removed from the current version of ICM-LAVegMod, and an updated model, informed by newly available data, is included separately in the ICM (see Attachment D3: ICM-Wetlands – Submerged Aquatic Vegetation (SAV) Updates).

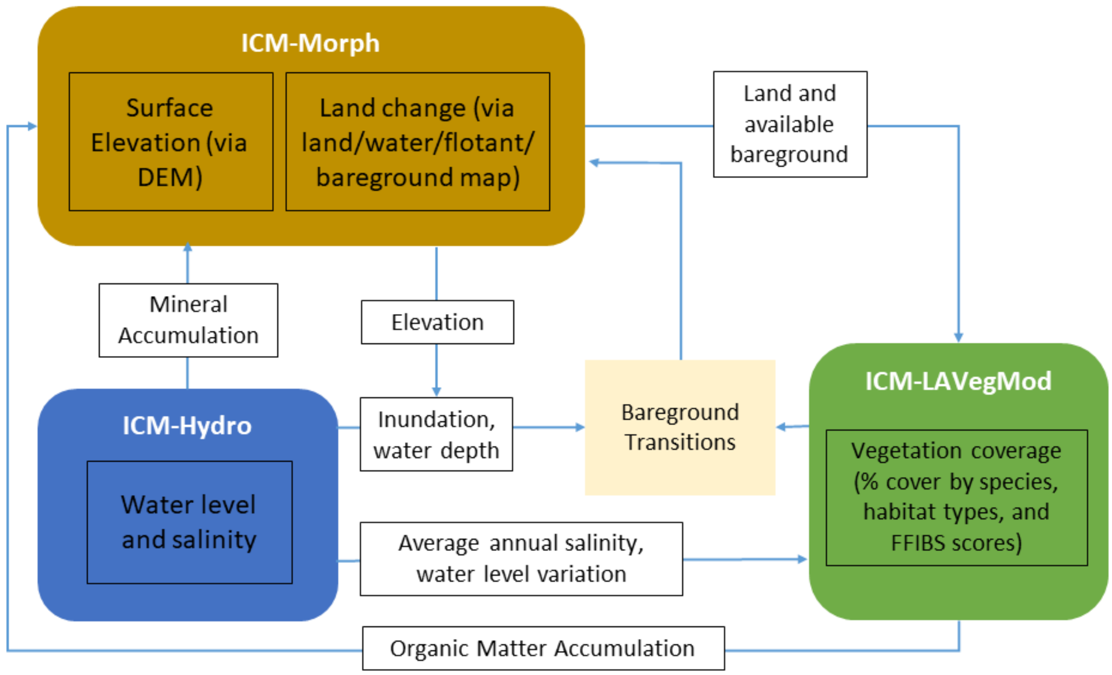


Figure 1. Flow of information and the main outputs generated by the subroutines in the ICM.

To understand interactions among ICM subroutines, it is important to recognize that the different subroutines act on separate, overlapping grids with different resolutions (Figure 2). ICM-Hydro **compartments** are the largest (i.e., the lowest resolution) and are irregularly shaped to account for landscape features. These compartments were refined for 2023 Coastal Master Plan to more closely align with expected flows due to known hydrologic features (e.g., natural ridges, control structures, etc.). ICM-Morph **pixels** are the smallest (i.e., highest resolution) at 30 m x 30 m and make up a regular grid. Elevation and land cover type is calculated and tracked, with the existing conditions digital elevation model (DEM) as the starting point, at this finer scale and then aggregated up as needed to inform calculations for other subroutines. ICM-LAVegMod **grid cells** are sized in between at 480 m x 480 m and are aligned with the ICM-Morph pixels such that 256 are captured in each ICM-LAVegMod grid cell.

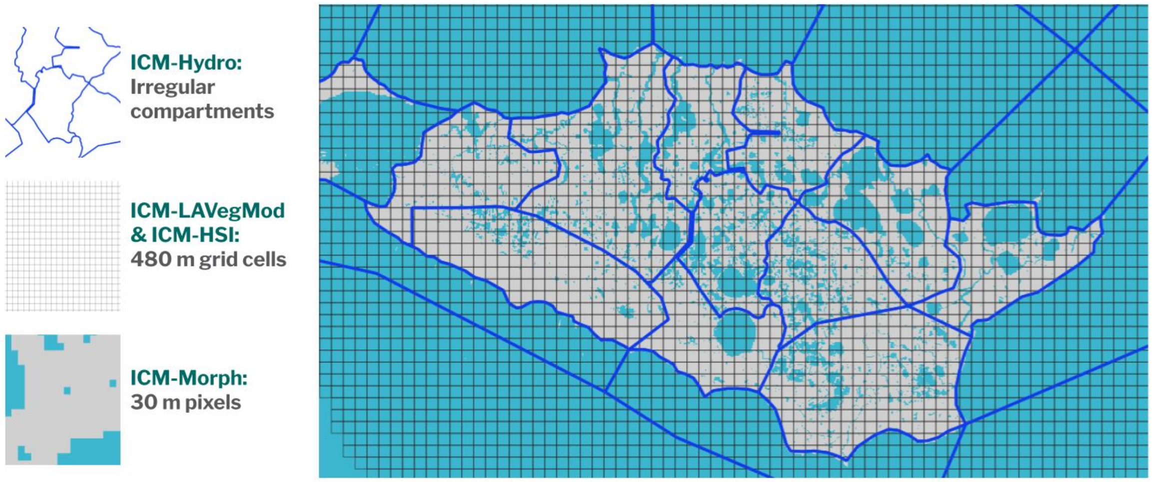


Figure 2. Spatial Resolution for ICM subroutine separate, overlapping grids in the area around Marsh Island in Vermilion Bay.

In later sections of this report, ICM-LAVegMod and ICM-Morph are described in more detail, including description of the inputs from and outputs to other ICM subroutines. Additional information regarding these subroutines are provided in Appendix C and Appendix D to the 2023 Master Plan. Attachment D2 (Baustian et al., 2020) provides a summary of the main model improvements to ICM-LAVegMod and ICM-Morph incorporated for the 2023 Coastal Master Plan. That attachment contains results of test runs to help inform model improvements, specifically those that were conducted after completion of recommendations from the ICM-Wetlands, Vegetation, and Soils Team. It also discusses additional background to support the use of variable values for organic matter accumulation rate (OMAR) across vegetation types and regions of coastal Louisiana, which is part of the updated approach to calculating OMAR incorporated in the current ICM.

2.0 LOUISIANA VEGETATION SUBROUTINE (ICM-LAVEGMOD)

2.1 INTRODUCTION

Wetland vegetation is a critical driver of coastal processes. Vegetation impacts hydrodynamics, altering flow paths and where sediment deposition occurs; accretes organic matter, increasing the elevation of the wetlands; and creates niche habitat, supporting fauna. Vegetation species shift as environmental conditions change, and ICM-LAVegMod predicts these vegetation shifts on an annual basis based on predictions of changing conditions from other ICM subroutines (e.g., ICM-Hydro and ICM-Morph). ICM-LAVegMod models the species distribution of 41 vegetation species that cover the full range of habitat types along the Louisiana coast, from bottomland hardwood and swamp forest to saline marsh. This report describes the rules and processes that govern how species coverage expands and contracts in each model year in more detail.

ICM-LAVegMod requires several input files to run, including: spreadsheets containing the probability of establishment and mortality of each vegetation species, attributes describing each vegetation species, the initial vegetation conditions at the start of the model run, and numerous environmental condition files representing the hydrodynamics and landscape character across the model domain. There are four main processes that occur each model year. First, the percentage of water and land available for wetland vegetation establishment is updated based on input from ICM-Morph. Second, the vegetation coverages are updated based on the environmental conditions from ICM-Hydro. This process occurs in two steps: vegetation mortality is assessed, removing vegetation coverage and creating bareground for new vegetation establishment; then vegetation establishment is assessed. For a vegetation species to establish in a grid cell, it must have suitable environmental conditions and be present in the dispersal zone of the cell. The size of the dispersal zone depends on the vegetation species. Third, acute salinity stress is applied, if it occurred in the cell during the model year. Fourth, the coverages within each cell are assessed and prepared for output.

ICM-LAVegMod outputs are used by ICM-Habitat Suitability Index (ICM-HSI) to determine changes in availability and quality of habitat for wildlife, fish, and shellfish species; by ICM-Morph to determine the amount of organic accretion and to track the change in coverage type (i.e., flotant, unvegetated, vegetated); and by ADCIRC+SWAN to determine drag coefficient across the model domain. ICM-LAVegMod interacts particularly closely with ICM-Morph. Within each ICM-LAVegMod grid cell, ICM-Morph tracks the location and amount of land and open water, while ICM-LAVegMod tracks the distribution (i.e., percent coverage) of each vegetation species on the land portion of the cell.

The current ICM-LAVegMod subroutine is the product of interactive development over many years. ICM-LAVegMod was part of the suite of predictive models used to support the 2012 Coastal Master Plan (e.g., Visser et al., 2013) and was fully integrated into the ICM for the 2017 Coastal Master Plan (e.g., Visser & Duke-Sylvester, 2017). For each master plan iteration, revisions and updates have been tested and incorporated into the model. For comparison of the current subroutine described here to previous models, refer to documentation from the appropriate plans. For example, similar information for the version of ICM-LAVegMod used for the 2017 Coastal Master Plan is provided in Section 3.4.1 of Attachment C3-22 to the 2017 Coastal Master Plan).

2.2 ICM-LAVEGMOD GRID AND COVERAGE TYPES

The ICM-LAVegMod grid contains 480 m x 480 m orthogonal cells. The size was set to align with the ICM-Morph grid, which has 30 m x 30 m orthogonal pixels (Figure 2). The ICM-LAVegMod domain extends across all ecoregions[1] south of Interstate-10 (Figure 3) and contains 173,898 grid cells.

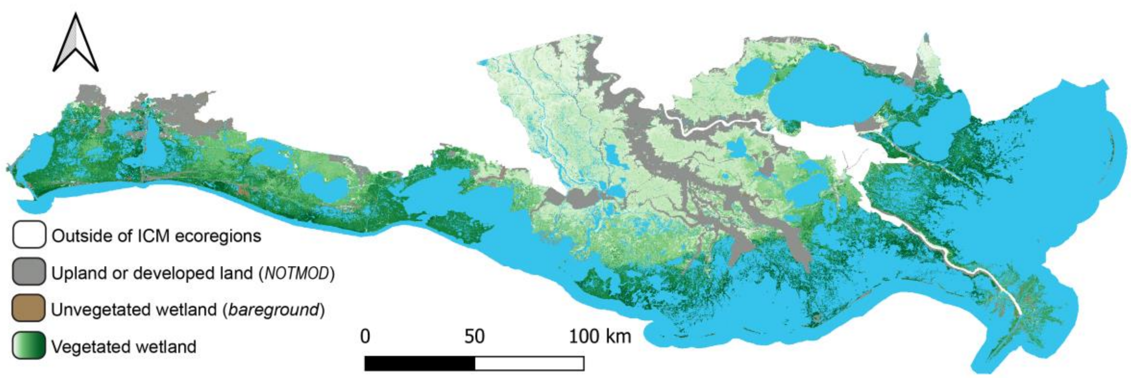


Figure 3. ICM-LAVegMod grid domain. White areas are outside of the ICM ecoregions. Gray areas are NOTMOD. Shades of green are vegetation, and blue is water.

Each grid cell can contain 46 different coverage types: 41 vegetation species; water; unvegetated wetland that was created this model year, called *new bareground*; unvegetated wetland that was

[1] For a description and map of ecoregions used for the 2023 Coastal Master Plan, please refer to the Ecoregion and Regional Boundaries section of **Attachment C2: 50-Year FWOA Model Output, Regional Summaries – ICM.**

created the previous model year, called *old bareground*; dead thick-mat flotant, called *flotant bareground*; and upland or developed land, which is not modeled and therefore called *NOTMOD*. The percent of each coverage type within each grid cell is tracked over time at an annual timestep. Since *NOTMOD* portions of each cell do not change over the course of the model runs, if a grid cell is more than 95% *NOTMOD*, it is removed from the grid and not assigned a grid cell ID value (example shown in Figure 2). Exceptions to this rule are described in Special Areas below.

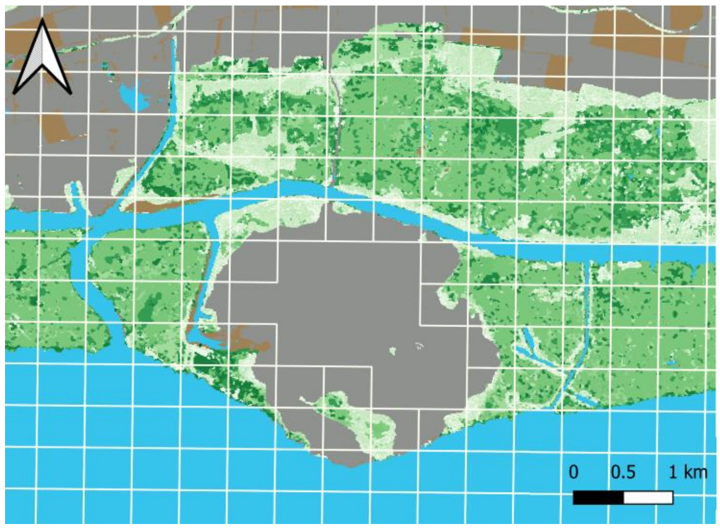


Figure 4. ICM-LAVegMod grid in the area surrounding Cote Blanche. Color legend is the same as in Figure 3. All grid cells (shown by white lines) containing 95% or more of upland or developed land (NOTMOD) are removed from the grid.

2.3 INITIAL CONDITIONS

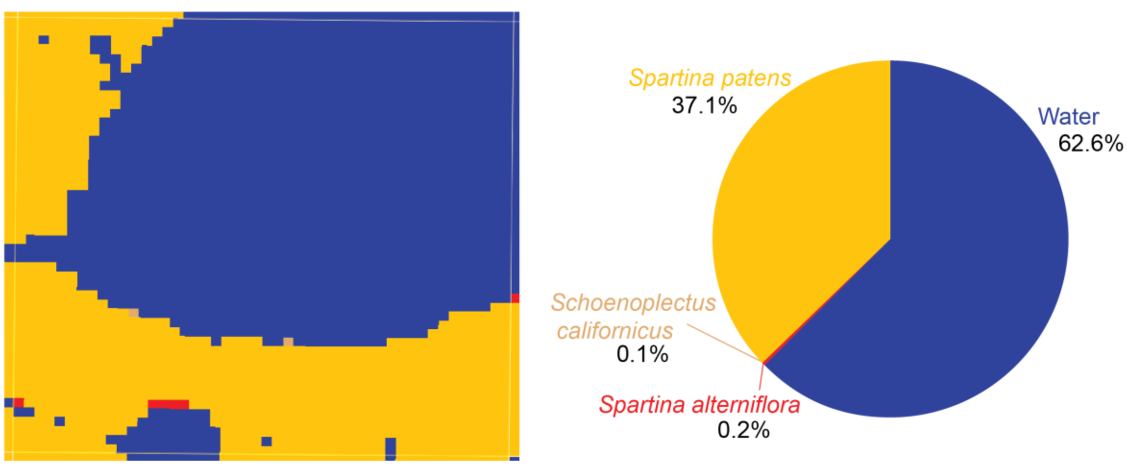
Every cell within ICM-LAVegMod grid has initial coverage values of vegetation and land types that are derived from the coastal Louisiana landscape. The initial conditions for the 2023 Coastal Master Plan come from the 2018 land use land cover (LULC) data collected by USGS (Baustian et al., 2020). This data is processed satellite imagery and has a 10 m resolution, which is higher resolution than the ICM-LAVegMod grid with 480 m x 480 m cells. The USGS dataset contains more coverage types than the 46 used in ICM-LAVegMod. The sections below outline the standard method applied to produce the ICM-LAVegMod initial conditions from the LULC dataset and special areas for which exceptions to this method were applied. The full ICM-LAVegMod domain was evaluated, producing an asc+ file of initial conditions. The format for this file is a comma-separated table where each row is the cell ID and every column is a coverage type. The initial conditions are generated once and then used to initiate the model for all subsequent runs, including both future with action (FWA) and future without action (FWOA).

STANDARD PROCESSING METHOD

The following steps outline the standard processing method for generating the ICM-LAVegMod initial conditions from the USGS LULC dataset.

1. *Reclassify the USGS LULC dataset to ICM-LAVegMod coverages:* The USGS LULC dataset contains more categories than are used in ICM-LAVegMod. The 10 m LULC cells were classified according to the conversions shown in Table S1 (in Supplemental Materials). For example, cells classified as water, palustrine aquatic bed, and estuarine aquatic bed in the USGS LULC dataset are all reclassified as water in the ICM-LAVegMod initial conditions. As shown under *NOTMOD* Table S1. ICM-LAVegMod does not model upland or developed land types. There are also 11 coverage types used by ICM-LAVegMod that are not included in the USGS LULC dataset (e.g., *new bareground* and *Sagittaria latifolia*). These coverages are set to zero in the initial conditions and are then allowed to increase based on modeled conditions as simulations run.

Tabulate the coverages within each ICM-LAVegMod cell: The area of each ICM-LAVegMod coverage type within a cell was summed and tabulated, and then the total area for each coverage type was converted to a decimal percentage. For example, the ICM-LAVegMod cell shown in Figure 5.



2. Figure 5 contains 1,443 LULC cells of water (144,300 m^2), 854 LULC cells of *Spartina patens* (85,400 m^2), 5 LULC cells of *Spartina alterniflora* (500 m^2), and 2 LULC cells of *Schoenoplectus californicus* (200 m^2). The initial conditions for this cell in ICM-LAVegMod are therefore 0.626 water, 0.371 *Spartina patens*, 0.002 *Spartina alterniflora*, 0.001 *Schoenoplectus californicus*, and 0 for all other coverage types.

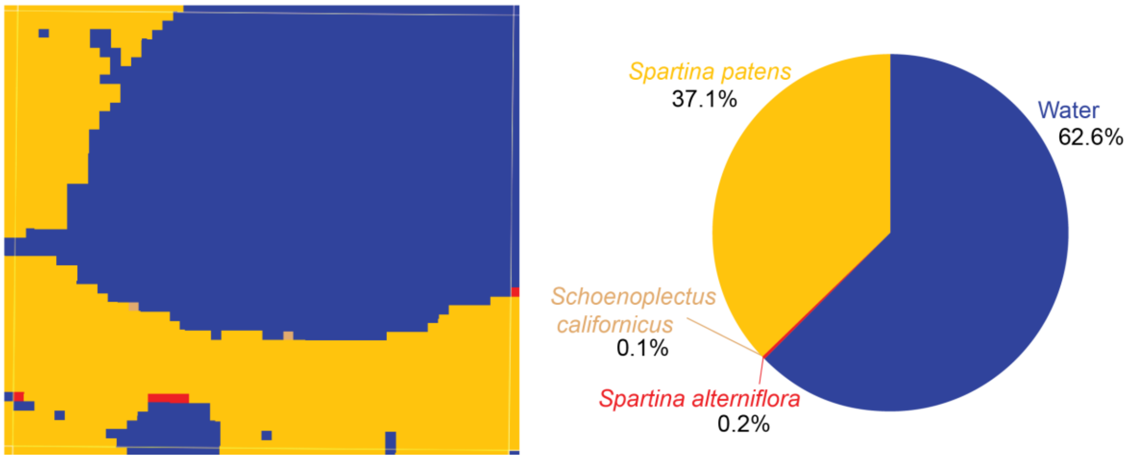


Figure 5. Left: Example of an ICM-LAVegMod grid cell and the USGS LULC dataset (colored squares). Right: Result of tabulating the coverage types within the ICM-LAVegMod cell shown on the right. The percentages shown in the pie chart are tabulated and used as the initial conditions.

3. *Determine cells to remove:* If an ICM-LAVegMod cell contained more than 95% of NOTMOD, meaning coverage categories that are not modeled in ICM-LAVegMod, then that cell was not included in model runs. The NOTMOD coverages in each cell do not change over the course of the simulation; therefore, removing these cells reduces memory requirements without altering the model results (see example shown in Figure 4).

4. *Adjust for compatibility with ICM-Morph*: ICM-Morph operates on a 30 m raster structure, and each pixel is initially assigned one of five coverage types: water, vegetated land, flotant, bareground, or NOTMOD. This assignment is done by resampling the 10 m USGS LULC dataset using a nearest neighbor algorithm in ArcGIS. Since the methods for creating the initial coverages differ between ICM-LAVegMod and ICM-Morph, the results also differ. To ensure compatibility, the percent coverages for ICM-LAVegMod are adjusted to match those of ICM-Morph. For example, the coverage of vegetated wetland in the ICM-Morph pixels within one ICM-LAVedMod cell matches the sum of all vegetated land in ICM-LAVegMod. These adjustments were minor (< 5% within the cell). When vegetated land needed to be reduced, all species were reduced by the same proportion.

SPECIAL AREAS

The following areas are special categories that require additional or alternative processing steps to create the initial conditions. The underlying data is the same USGS LULC dataset described above.

CANAL SPOIL BANKS

When access canals were historically dredged through wetlands, the dredged materials or "spoils" were commonly piled on the sides of the canal, creating low linear levees or "banks." Louisiana wetlands contain an estimated 33,000 km of these dredged material levees (Turner & McClenachan, 2018). Since these areas are elevated relative to surrounding wetlands, they often contain upland vegetation species, but over time these areas subside to elevations that can support wetland species. Within the USGS LULC dataset, dredged material levees are often classified as upland species that are not modeled in ICM-LAVegMod. Classifying these areas as NOTMOD removes them from the ICM-LAVegMod grid for modeling, even in future years when elevations could become suitable for wetland species. To enable their inclusion, a different classification conversion was used within the dredged material levee areas. Pate (2014) identified and created polygons containing dredged material levees along the Louisiana coast. Within these polygons, all LULC coverages first assigned as *NOTMOD* (Table S1 in Supplemental Materials, below) were reclassified to *old bareground* for the initial conditions. This reclassification allows surrounding vegetation to establish in these areas if conditions are right during model simulations.

FORCED DRAINAGE POLDERS

Many communities and agricultural areas across the Louisiana coast are drained with pumps and surrounded by low-lying levees that prevent tidal flooding. These 'polders' were identified during the development of input files for ICM-Morph (described below) and were subsequently removed from the ICM-LAVegMod domain. These areas are cutoff from natural hydrologic forcing and thus the processes driving vegetation and morphology dynamics are not expected to align with patterns observed in surrounding wetland areas. All coverages from the UGSS LULC dataset within these areas were converted to *NOTMOD*.

DEVELOPED AND AGRICULTURAL LAND

Agricultural land, open fields, and other predominantly developed areas in the upper-basins of the domain were often classified as bareland in the USGS LULC dataset. In the standard method, these areas would become *old bareground* in ICM-LAVegMod and thus be available for wetland vegetation establishment in model simulations. While it is possible that subsidence and sea-level rise might bring them under tidal influence, and thus eligible for consideration in the ICM, it is likely that such inundation in the future will be prevented by drainage or small levees (i.e., they will become like polders). Thus, the decision was made to not consider them in ICM-LAVegMod, and bareland LULC cells were reclassified as *NOTMOD* in the areas listed below. This conversion left a lot of grid cells with only *NOTMOD* and small coverages of water. Cells with greater than 90% NOTMOD and greater than 95% of total *NOTMOD* plus water were removed from the ICM-LAVegMod grid. This classification and cell removal criteria was only applied to cells meeting the conditions in the following areas: the entire

Verret Ecoregion, the entire Upper Verret Ecoregion, the entire Upper Barataria Ecoregion, the portion of the Eastern Terrebonne Ecoregion that is north of the Gulf Intracoastal Waterway (GIWW), the portion of the Western Terrebonne Ecoregion that is north of the GIWW, and the portion of the Maurepas Ecoregion south of Interstate-10[2].

2.4 INPUT VEGETATION ATTRIBUTES

ICM-LAVegMod models the change in distribution for 41 vegetation species in response to changing environmental conditions. Each species has attributes used in the model that do not change over the course of the simulation. These attributes are probability of mortality and establishment tables, dispersal class, habitat class, and FFIBS score, which are each described in the sections below. Table S2 (in Supplemental Materials, below) contains the assigned attributes for each species.

PROBABILITY OF MORTALITY AND ESTABLISHMENT

Each vegetation species has a relationship between environmental conditions and the probability of mortality and establishment. These relationships are given in input tables and were derived from vegetation data from the Louisiana Coastwide Reference Monitoring System (CRMS). These tables were updated for the 2023 Coastal Master Plan and can be found in Baustian et al. (2020). If the given environmental condition from ICM-Hydro falls between values in the table, the mortality and establishment probabilities are linearly interpolated.

DISPERSAL CLASS

The dispersal class defines how far from its location a species can establish. In the version of ICM-LAVegMod used to support the 2017 Coastal Master Plan modeling, species could establish within a cell if they were present in one of the eight surrounding cells (i.e., Moore's neighborhood). For the 2023 Coastal Master Plan, ICM-LAVegMod has been updated such that there are now three classes of dispersal: low, medium, and high (Baustian et al., 2020). Low dispersal class species have the same restrictions as for the 2017 Coastal Master Plan modeling and can establish from the eight surrounding cells (light blue bounding box in Figure 6). Medium dispersal class species can establish from two away (darker blue bounding box in Figure 6). High dispersal class species do not have to be

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[2] An ecoregion map is available in Figure 3 of **Attachment C2: 50-Year FWOA Model Output, Regional Summaries – ICM**

present in the surrounding area to establish. These species are considered to be “weedy” due to their high dispersal rates.

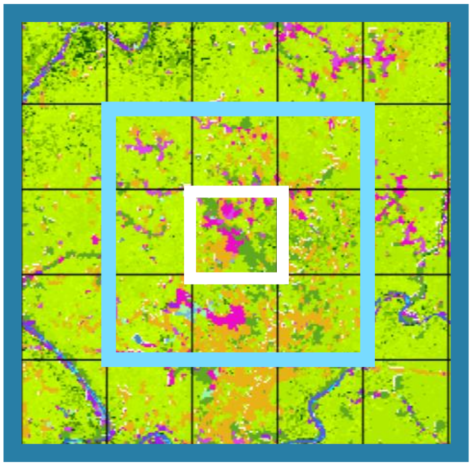

Figure 6. The extent of different dispersal classes: Low dispersal class species can establish in the white cell from the cells bound by the light blue border, and medium dispersal class species can establish in the white cell from the cells bound by the darker blue border. Background image is from the USGS LULC dataset. Black lines show the ICM-LAVegMod grid.

HABITAT CLASS

Habitat classes are used to group vegetation species that are often found in areas with similar environmental conditions and with similar behaviors within the code. There are five habitat classes within the ICM-LAVegMod code that correspond to generalized habitat types: bottomland hardwood forest, swamp forest, emergent wetland, flotant, and barrier island. The emergent wetland class includes species from freshwater, intermediate, brackish, and saline marshes (often referred to as FIBS or habitat type). The functions of the different habitat classes are described in Section 2.5.

FFIBS SCORE

The FFIBS score is a numeric value that indicates the salinity regime of the vegetation species. FFIBS stands for **F**orested, **F**resh, **I**ntermediate, **B**rackish, and **S**aline. The values range from 0 for forested to 24 for saline. Species that exist in environments not strictly in one category have scores that are between the different cutoffs. For example, *Sagittaria lancifolia* and *Schoenoplectus californicus* are both intermediate species, but *Schoenoplectus californicus* has a FFIBS score of 2.75 because it can tolerate higher salinity than *Sagittaria lancifolia,* which has a FFIBS score of 1.5. Additional information on FFIBS score can be found in Baustian et al. (2020) and Visser et al. (2002). Coverages that do not have a FFIBS score are assigned a value of -9999. Calculation of FFIBS score for a grid cell in ICM-LAVegMod is described in Section 2.6. The FFIBS score of each cell is an input for ICM-Morph and is used to calculate the organic matter accumulation rate (OMAR), which is described in ICM-Morph Model Subroutines: Organic Matter Accumulation, below. Flotant species do not have a FFIBS score and do not influence the OMAR on land.

2.5 HABITAT CLASS FUNCTIONS

There are five habitat classes within the ICM-LAVegMod code that correspond to generalized habitat types: bottomland hardwood forest, swamp forest, emergent wetland, flotant, and barrier island. The emergent wetland class includes species from freshwater, intermediate, brackish, and saline marshes. Each species and their assigned habitat class are listed in Table 1. Using classes within Python allows for more flexibility in the code. One function can be called multiple times but will perform a different action depending on the class. The following sections describe the two functions key to ICM-LAVegMod, mortality probability and expansion likelihood, and how they differ for different habitat classes.

Table 1. Vegetation species included in ICM-LAVegMod, along with corresponding habitat classification

Habitat Class	Scientific Name
Bottomland Hardwood Forest	*Quercus laurifolia, Quercus lyrate, Quercus nigra, Quercus texana, Quercus virginiana, Ulmus americana*
Swamp Forest	*Nyssa aquatica, Salix nigra, Taxodium distichum*
Flotant	*Eleocharis baldwinii, Panicum hemitomon*
Emergent Wetland	*Colocasia esculenta, Morella cerifera, Panicum hemitomon, Sagitttaria latifolia, Zizaniopsis miliacea, Cladium mariscus, Eleocharis cellulose, Iva frutescens, Typha domingensis, Paspalum vaginatum, Phragmites australis, Polygonum punctatum, Sagittaria lancifolia, Schoenoplectus californicus, Schoenoplectus americanus, Juncus roemerianus, Spartina alterniflora, Distichlis spicata, Avicennia germinans, Spartina patens, Spartina cynusuroides, Schoenoplectus robustus*
Barrier Island	*Uniola paniculate, Strophostyles helvola, Sporobolus virginicus, Spartina patens, Solidago sempervirens, Panicum amarum, Distichlis spicata, Baccharis halimifolia*

There are three species that are in both the emergent wetland and barrier island habitat classes: *Baccharis halimifolia*, *Distichlis spicata*, and *Spartina patens*. These are kept distinct within the code and follow the rules of the habitat class depending on location (i.e., when in a barrier island area, they follow the barrier island class). Note, the results from the barrier island class have limited utility due to the large grid size. The functions of this class depend on the elevation of the grid cell, and the complex topography of the barrier islands is smoothed out at this scale. A possible future improvement would be to apply the barrier island class to the more finely resolved grid used within the ICM-Barrier Island subroutine. While the barrier island class species are included in ICM-LAVegMod following the functions described below, the results are not used by other ICM subroutines due to this limited utility.

MORTALITY PROBABILITY

The mortality probability determines the decrease in coverage of each species. A value of 100% completely removes the species coverage from an ICM-LAVegMod cell, and conversely, a value of 0% leaves the species coverage unchanged. The mortality probability is a function of one or more variables depending on the habitat class. The relationships between environmental variable(s) and the mortality probability are given in the mortality tables, an input to ICM-LAVegMod. The specific criteria for calculating the mortality probability is given below for each habitat class.

BOTTOMLAND HARDWOOD FOREST CLASS

If the mean annual salinity is greater than 1.0 ppt, the mortality probability is set to 100%. If the annual salinity is less than 1.0 ppt, the mortality probability is a function of the elevation of the cell (i.e., the height above mean annual water level).

SWAMP FOREST, EMERGENT WETLAND, FLOTANT CLASSES

The mortality probability is a function of both mean annual salinity and water level variability.

BARRIER ISLAND CLASS

The mortality probability is a function of the elevation of the cell. Barrier island species can only exist in the designated barrier island area. If the ICM-LAVegMod cell being evaluated is not in the barrier island area, the mortality probability is set to 100%.

EXPANSION LIKELIHOOD

The expansion likelihood determines how the coverage of each species expands. A value of 100% indicates the species has a high likelihood of expansion, whereas a value of 0% means the species cannot expand. The expansion likelihood is dependent upon the establishment probability, which is a function of one or more environmental variables depending on the habitat class. The relationships between environmental variable(s) and the establishment probability are given in the establishment tables.

For most habitat classes, the expansion likelihood is also dependent on the coverage of the species in the surrounding area, called the dispersal coverage. The dispersal coverage is calculated as:

$$D_i = \frac{C_{T,i}}{A_{surrounding}} \quad \text{Eq. 1}$$

Where D_i is the dispersal coverage for the i^{th} vegetation species; $C_{T,i}$ is the total coverage for the i^{th} vegetation species in $A_{surrounding}$; and $A_{surrounding}$ is the total area of the surrounding cells. If the species is in the low dispersal class, $A_{surrounding}$ is the area of nine cells, and if the species is in the medium or high dispersal classes, $A_{surrounding}$ is the area of 25 cells. The specific criteria for how establishment probability is calculated for each habitat class described below.

BOTTOMLAND HARDWOOD FOREST CLASS

For expansion to occur, the tree establishment condition must have been met, meaning there must have been a 14 day period with no inundation followed by a 14 day period with water depth less than 14 cm in the current model year and the mean annual salinity must be less than 1.0 ppt. ICM-Hydro determines if these criteria are met for each ICM-LAVegMod cell (from compartment-level water surface elevation and grid-level average land surface elevation), and this information is passed to ICM-LAVegMod each simulation year. If these criteria are not met, then the establishment probability is set to 0% for bottomland hardwood species. If these criteria are met in the cell being evaluated, then expansion can occur, and the establishment probability is determined. The establishment probability is a function of elevation of the cell (i.e., the height above water). The establishment probability is then multiplied by the dispersal coverage of the species to produce the expansion likelihood.

SWAMP FOREST, EMERGENT WETLAND, FLOTANT CLASSES

The establishment probability is a function of both mean annual salinity and water level variability. The expansion likelihood is the product of the establishment probability and the dispersal coverage.

BARRIER ISLAND CLASS

The establishment probability is a function of the elevation of the cell. The dispersal coverage is not considered, meaning the establishment probability is the same as the expansion likelihood. If the cell is not in a set barrier area, the expansion likelihood is set to 0%.

2.6 ICM-LAVEGMOD ANNUAL PROCESSES

ICM-LAVegMod updates vegetation coverages each year of the model simulation. The following sections describe each processing step for this update in the order it occurs. Each process applies to every ICM-LAVegMod cell, but the processes are explained on an individual cell basis. Inputs from ICM-Hydro and ICM-Morph are required. From ICM-Hydro, there are five inputs: the annual mean salinity, water level variability, height above annual mean water level, acute salinity stress, and tree establishment condition. The annual mean salinity is the annual average of the daily mean salinities calculated within the open water area of each respective ICM-Hydro compartment. The water level variability is the standard deviation of the hourly water level[3]. The acute salinity stress input indicates which ICM-LAVegMod cells experienced salinity of greater than or equal to 5.5 ppt for consecutive 2 weeks[4]. Similarly, the tree establishment condition indicates which ICM-LAVegMod cells met the conditions required for tree establishment, described in Section 2.5. All of these inputs are at the scale of the ICM-Hydro compartments. There is one input from ICM-Morph, the percent water coverage in each ICM-LAVegMod cell. Due to the order the subroutines of the ICM are run, the ICM-Hydro inputs are for the same model year, and the ICM-Morph input is from the previous model year. These annual inputs are in addition to the inputs attributes that do not change throughout the simulation, described in Input Vegetation Attributes section 2.4, above. The annual processes described here are shown in the left side of Figure 7; the right side of Figure 7 shows an example of how these processes govern the coverage changes of one cell.

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[3] ICM-LAVegMod statistical relationships rely on standard deviation of hourly water level during the year; however, due to memory limitations, hourly water levels are not saved for every ICM-Hydro compartment for the entire year, however daily tidal range is saved. Using observed CRMS water level data, a linear correlation was fit to predict standard deviation of hourly water level from daily tidal range values. See code on Github for relationship used.

[4] This acute salinity threshold value is set in ICM.py – a value of 5.5 was used for 2023 modeling.

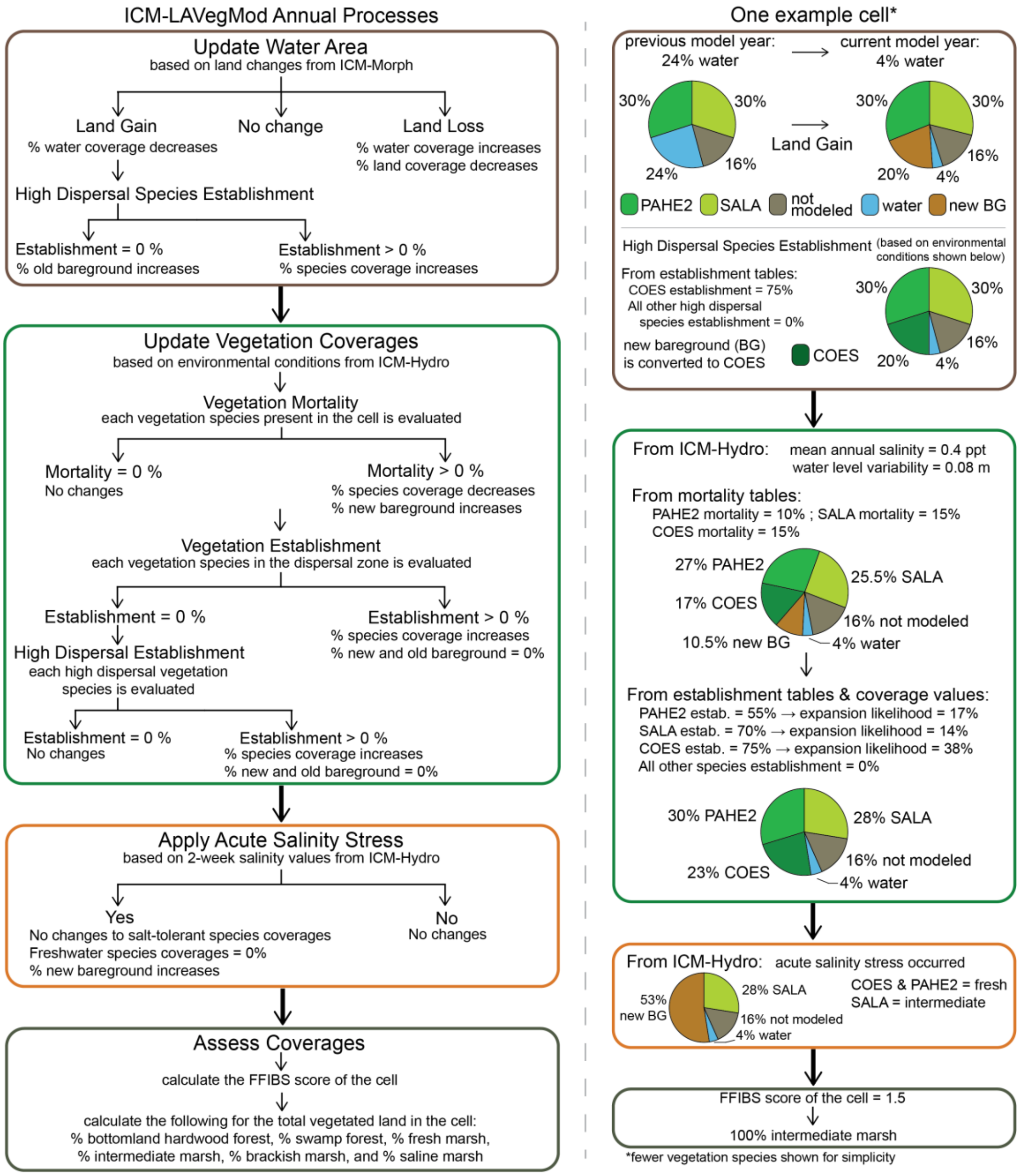

Figure 7. Left: The four main processes performed each model year in ICM-LAVegMod with details on how each process is governed. Right: An example scenario in one grid cell. Vegetation abbreviations are as follows: COES = Colocasia esculenta; SALA = Sagittaria lancifolia; PAHE2 = Panicum hemitomon.

UPDATE WATER AREA

Changes in water area that occurred in ICM-Morph are assessed and incorporated into the ICM-LAVegMod coverages. ICM-Morph governs all elevation changes and determines what area is eligible for vegetation establishment, referred to as land, and what is open water. The percentage of water in each ICM-LAVegMod cell is compared to the percentage water in ICM-Morph, calculated at the end of the previous model year. If the percentage is the same, land was not lost or gained, and no further action is needed. If the percentage has increased or decreased, land has been lost or gained, respectively.

LAND GAIN

If the percentage of water from ICM-Morph is less than the prior model year, land was gained. The difference between the two percentage values, $\Delta water$, is subtracted from the water coverage and added to the *new bareground* coverage.

VEGETATION ESTABLISHMENT ON LAND GAINED

Vegetation species with high rates of dispersal are often the first to establish on newly formed land. This step mimics that process by allowing vegetation in the high dispersal class (i.e., “weedy” species) to establish before other species on new land created during the previous model year in ICM-Morph.

If new land was gained, vegetation species in the high dispersal class (i.e., “weedy” species) are allowed to establish first. Establishment probability is based on the mean annual salinity and water level variability in the ICM-LAVegMod cell. If no species can establish due to unfavorable conditions, then the area of the new land gained is added to *old bareground*. This *old bareground* will be available for vegetation establishment from all species during the Vegetation Establishment step.

LAND LOSS

If the percentage of water from ICM-Morph is greater than the year prior, land was lost. The difference between the two percentage values, $\Delta water$, is added to the *water* coverage. If any *old bareground* exists in the ICM-LAVegMod cell, that coverage is lost first. If there was no *old bareground* coverage or if it was less than the amount of land lost, the vegetation coverages are all proportionately decreased following Eq. 2. Flotant and *NOTMOD* coverages, which are not altered by ICM-Morph, are not decreased and remain the same.

$$C_{1,i} = C_{0,i}\left(\frac{A_{land,\ ICM-LAVegMod}}{A_{land,\ ICM-Morph}}\right) \quad \text{Eq. 2}$$

C is the coverage for the i^{th} vegetation species; a subscript of 1 indicates the resulting value at the end of the step; a subscript of 0 indicates the value at start of the step; $A_{land,\ ICM-LAVegMod}$ is the total vegetated land within the cell from ICM-LAVegMod in the previous model year; and $A_{land,\ ICM-Morph}$ is the total vegetated land within the cell after updates from ICM-Morph in the previous model year.

UPDATE VEGETATION COVERAGES

VEGETATION MORTALITY

This step assesses the amount of vegetation mortality that occurred within each cell due to the environmental conditions in the current model year. The mortality probability of each vegetation species is calculated with the exception of flotant species, which are handled separately (see Flotant Updates). The reduction in coverage of each species is calculated based on the mortality tables, and the specific criteria for each class is described in Section 2.5. The mortality probability is directly applied to each species coverage. For example, if the mortality probability is 20% based on the conditions associated with an ICM-LAVegMod cell, the coverage of that species is reduced by 20% in that cell (Eq. 3). If a species coverage is reduced, the area it no longer occupies is added to *new bareground* coverage (Eq. 4)

$$C_{1,i} = C_{0,i} * (1 - M_i) \quad \text{Eq. 3}$$

$$BG_{new} = \sum_{i=1}^{n} C_{0,i} * M_i \quad \text{Eq. 4}$$

Where C_i is the coverage for the i^{th} vegetation species, M_i is the mortality probability for the i^{th} vegetation type; BG_{new} is *new bareground*; n is the total number of vegetation species; a subscript of 1 indicates the resulting value at the end of the step; and a subscript of 0 indicates the value at start of the step. At the end of this step, the new and *old bareground* coverages are summed, and this area becomes the total area of unoccupied land, which is available for vegetation establishment.

VEGETATION ESTABLISHMENT

The total amount of unoccupied land (i.e., the sum of *new* and *old bareground*) updated in the previous step is available for vegetation establishment. In coastal wetlands, species must compete to establish on the unoccupied land. Here, the establishment probability and the dispersal coverage of the species in the surrounding ICM-LAVegMod cells are used to calculate an expansion likelihood. Species with a higher establishment probability and/or a greater coverage in the surrounding areas have a larger expansion likelihood. The expansion likelihoods of all species are then normalized to model the process of natural competition. Two species with equal expansion likelihoods will occupy equal portions of the available land.

In this step, the expansion likelihood of each vegetation species is calculated as follows:

$$L_i = E_i * D_i \qquad \text{Eq. 5}$$

Where L_i is the expansion likelihood for the i^{th} vegetation species; E_i is the establishment probability for the i^{th} vegetation type; and D_i is dispersal coverage for the i^{th} vegetation species. The establishment probability is calculated based on the environmental conditions and comes from the establishment tables (Baustian et al., 2020). The specific criteria of how expansion likelihoods are calculated for each class is described in Section 2.5. The resulting expansion likelihoods are normalized to divide the unoccupied land accordingly, and the change in coverage for each species follows:

$$C_{1,i} = C_{0,i} + \left(\frac{L_i}{\sum_{i=1}^{n} L_i}\right) A_{unoccupied} \qquad \text{Eq. 6}$$

Where C_i is the coverage for the i^{th} vegetation species, L_i is the expansion likelihood for the i^{th} vegetation species; $A_{unoccupied}$ is the total unoccupied area; n is the total number of vegetation species; a subscript of 1 indicates the resulting value at the end of the step; and a subscript of 0 indicates the value at start of the step.

If only one species has a non-zero expansion likelihood, it will occupy all of the unoccupied land, and *old* and *new bareground* are reset to 0%. This step differs from the Vegetation Establishment on Land Gained step in two ways: both *old* and *new bareground* are available for vegetation establishment, as opposed to only *new bareground*, and all vegetation species, as opposed to only the high dispersal class species, have the opportunity to establish.

If all species have expansion likelihoods of zero, high dispersal species are given the opportunity to establish without the restriction of having dispersal coverage in the area. This modified form of expansion likelihood is called spread likelihood and is equal to the establishment probability (i.e., $E_i = S_i$). If there are more than one non-zero spread likelihoods, the values are normalized to determine the apportionment of the unoccupied area:

$$C_{1,i} = C_{0,i} + \left(\frac{S_i}{\sum_{i=1}^{m} S_i}\right) A_{unoccupied} \qquad \text{Eq. 7}$$

Where C_i is the coverage for the i^{th} vegetation species, S_i is the spread likelihood for the i^{th} vegetation species; $A_{unoccupied}$ is the total unoccupied area; m is the total number of vegetation species in the high dispersal class; a subscript of 1 indicates the resulting value at the end of the step; and a subscript of 0 indicates the value at start of the step.

If both the expansion and spread likelihoods for all species are zero, the unoccupied land remains unoccupied, and the coverage of *new bareground* and *old bareground* are unchanged.

FLOTANT UPDATES

Flotant, or floating marsh, are marshes that are permanently underlain by an open water layer. The vegetation and soil below flotant marsh moves up and down as water levels change. The process for updating flotant coverage was improved from the version of ICM-LAVegMod used for modeling to support the 2017 Coastal Master Plan. There are now two types of flotant considered by ICM-LAVegMod: thick-mat flotant, *Panicum hemitomon*, and thin-mat flotant, *Eleocharis baldwinii*. An intermediate step was also added for the mortality of thick-mat flotant, which reflects that it does not immediately convert to open water when it dies (Baustian et al., 2020).

FLOTANT MORTALITY

This step assesses the amount of flotant mortality that occurred within each ICM-LAVegMod cell due to the environmental conditions in the current model year. The mortality probability, or the percent reduction in coverage, is calculated based on the mortality tables, which are a function of annual mean salinity and water level variability. The coverage lost by each species is tracked separately but is summed to produce unoccupied flotant area.

FLOTANT ESTABLISHMENT

Flotant establishment can occur on any of the unoccupied flotant area created in the previous step, in addition to *bareground flotant* created in the previous model year. *Bareground flotant* is the area occupied by thick-mat flotant that died in the previous model year. The expansion likelihood for each species is calculated in the same way as described in the Vegetation Establishment step above. If one or both of the flotant species has a non-zero expansion likelihood, then all of the unoccupied flotant and *bareground flotant* become established with flotant vegetation.

If both flotant species have expansion likelihoods of zero, then the following occurs: the *bareground flotant* and area of dead thin-mat flotant are summed to become *dead flotant* coverage, and the area of dead thick-mat flotant becomes the *bareground flotant* for the next model year. The *dead flotant* coverage in each cell is passed to ICM-Morph at the end of the ICM-LAVegMod run, where it is converted to open water with a depth of 1 m. Within ICM-LAVegMod, the *dead flotant* coverage is added to the *water* coverage. The *dead flotant* coverage is reset to 0% at the start of every model year.

APPLY ACUTE SALINITY STRESS

Freshwater wetland and flotant vegetation can experience mortality if exposed to elevated salinities for a short period of time (i.e., on the order of weeks). This impact of salinity may not be captured in the annual mean salinity values. Since the previous vegetation mortality steps depend on mean annual salinity, this acute salinity stress must be assessed separately.

If the two-week average salinity in the ICM-LAVegMod cell exceeded 5.5 ppt at any time over the course of the ICM-Hydro model year, the cell is flagged for acute salinity stress. The coverage of all freshwater marsh species within the cell is converted to *new bareground*. The coverage of thin-mat flotant is added to the *dead flotant* coverage and converted to open *water*, and the coverage of thick-mat flotant is added to the *bareground flotant*. Acute salinity stress is not applied to bottomland hardwood or swamp forest species because they already have low tolerance for salinity.

ASSESS COVERAGES

Once the previous steps are performed, the vegetation coverage updates for the model year are complete. The following processing steps ensure the model performed without error and prepare outputs for use in the other subroutines of the ICM.

CHECK MINIMUM COVERAGE

As described in the mortality and establishment steps above, coverages are changed by adding and subtracting percentages of the existing coverage. The probability of mortality and tables, which are based on CRMS data, have some overlap. This overlap means a species can be completely removed in the mortality step and still have a non-zero expansion likelihood, which can lead to small fractions of vegetation coverage (e.g., $1e^{-16}$) remaining. This issue can be problematic when salinity regimes shift; due to the dependence on the presence of vegetation in the expansion likelihood, a small presence of a species can lead to unrealistic establishment.

To avoid this issue, fractions of vegetation below the minimum coverage threshold of 1 m^2 are removed. This minimum threshold value is $4.34e^{-4}$ % of the 480 m x 480 m cells. If the coverage of any species is less than 1 m^2, the coverage is set to 0%.

CHECK TOTAL SUM

All 46 coverages within each ICM-LAVegMod cell are summed, including the non-vegetation type coverages (e.g., *NOTMOD* coverage). If the total equals 100% ± 0.5%, it indicates the model performed as expected. If not, a warning is raised alerting the user that an error occurred.

CALCULATE FFIBS SCORE

The FFIBS score of each cell is an indicator of the salinity regime of the cell. FFIBS stands for **F**orested, **F**resh, **I**ntermediate, **B**rackish, and **S**aline. For analyses using previous versions of ICM-LAVegMod, the habitat type for each cell was determined by the dominant vegetation species. This calculation has been improved for the 2023 Coastal Master Plan modeling by accounting for all vegetation species within the cell. The FFIBS value of each species is weighted by the area it occupies, providing a more accurate representation of the salinity regime in the ICM-LAVegMod cell (Baustian et al., 2020). The weighted FFIBS values are passed to ICM-Morph, where they are used to calculate the OMAR in each cell, as described below.

The weighted FFIBS score of each cell is calculated as follows:

$$FFIBS_{weighted} = \frac{\sum_{i=1}^{n}(FFIBS_i * C_i)}{\sum_{i=1}^{n} C_i} \quad \text{Eq. 8}$$

Where $FFIBS_{weighted}$ is the weighted FFIBS score for the cell; $FFIBS_i$ = the FFIBS score for the i^{th} vegetation species; C_i is the coverage for the i^{th} vegetation species; and n is the total number of vegetation species. The flotant and barrier island species are not included in this calculation. If no coverages have a FFIBS score (e.g., the cell is 100% *water* or *old bareground*), then a score of -9999 is assigned to the cell. The FFIBS score for each species is listed in Table S2 in Supplemental Materials, below.

CALCULATE PERCENT VEGETATED LAND

The percent of each habitat type out of the total vegetation land in each ICM-LAVegMod cell is calculated. These values are used as inputs to the ICM-HSI subroutine. The habitat types include: bottomland hardwood forest, swamp forest, fresh marsh, intermediate marsh, brackish marsh, and saline marsh. Saline marsh includes barrier island species. The percentages are calculated based on the total vegetated land in the cell, not the total area. For example, if a cell only contains water and swamp forest species, the percent land of swamp forest species would be 100%, and all other habitat types would be 0%.

PREPARE OUTPUT

ICM-LAVegMod output for the model year is an asc+ file. The top portion of this file is a table indicating the column and row location of each cell ID in the ICM-LAVegMod grid. The bottom portion is a comma-separated table where every row is a cell and each column is an output value. There are 54 output values for each cell: the percent coverage for each of the 41 vegetation species; the percent coverage for the five non-vegetation coverage types, which are *water*, *old bareground*, *new bareground*, *flotant bareground*, and *NOTMOD*; the percent coverage of *dead flotant*; the percent of vegetated land that is bottomland hardwood forest (pL_BF), swamp forest (pL_SF), fresh marsh (pL_FM), intermediate marsh (pL_IM), brackish marsh (pL_BM), and saline marsh (pL_SM); and the cell weighted FFIBS score. These outputs can then be further processed to analyze and map different vegetation distributions.

3.0 WETLAND MORPHOLOGY SUBROUTINE

3.1 INTRODUCTION

ICM-Morph is a relative elevation model of wetland morphology developed specifically for use in coastal Louisiana. ICM-Morph originated in the Wetland Morphology model developed for the 2012 Coastal Master Plan and was subsequently integrated with other models to form the ICM for the 2017 Coastal Master Plan (White et al., 2017).

ICM-Morph updates the elevation of wetlands as a function of subsidence, erosion and deposition of water bottoms, mineral sediment deposition and organic matter accretion of vegetated wetlands, marsh edge erosion. Changes to inundation patterns are then modeled as a result of relative sea level rise (as modeled by the elevation change model and assumed rates of eustatic sea level rise). Inundation stress of vegetated marsh areas may lead to chronic stress and ultimately loss of vegetation and eventual loss of land to open water. These dynamics will then result in changing coastal hydrology (as modeled by ICM-Hydro), which in turn impact vegetation coverage (as modeled by ICM-LAVegMod); vegetation dynamics subsequently impact organic accretion rates, and the hydrologic changes impact mineral sediment deposition. Thus, the parsimonious relative elevation change model is the foundation for the morphological aspects of the ICM and all other modeling tools used for the development of the Louisiana Coastal Master Plan.

3.2 SOFTWARE ENVIRONMENT

Previous versions of the wetland morphology models used for the 2012 and 2017 master plans were largely built using proprietary geoprocessing software tools in the ESRI ArcGIS platform. In order to make the ICM completely platform-independent, the model algorithms were converted to Fortran, a compiled software language that is frequently used in high performance computing (HPC) systems. Both the ICM-Hydro and ICM-BI subroutines were already coded in Fortran; therefore, converting the ICM-Morph code to Fortran required no additional compilers or expertise that was not already needed for other ICM subroutines.

Once converted to Fortran, there were two distinct advantages as compared to the old ESRI-dependent versions of the model. First, Fortran programs are able to be compiled in both Windows and Linux computing environments; ICM-Morph has been tested, and shown to work, in both of these environments. Production runs for the 2023 plan were performed on Bridges-2, a Linux-based HPC hosted by the Pittsburgh Supercomputing Center. The second advantage of the Fortran ICM-Morph is the ability to utilize large memory arrays and binary data files. In previous ESRI-dependent versions of ICM-Morph, every calculation step required a raster file to be written to disc. While many of these temporary calculation rasters were not permanently stored, the reading and writing of files to disc is a potential performance bottleneck. Even more so, when moving to HPC environments, which are generally optimized for processors to utilize large memory arrays, and not around file read/write speeds.

FILE FORMATS

The file types used by ICM-Morph generally consist of three different types. First, raster based files are initially read into the program as ASCI XYZ text files where the first two columns are the X and Y coordinates (in UTM Zone 15N coordinates) and the third column (Z) contains the value for that pixel for whatever dataset is being represented in the raster. This could be elevation, landscape composition, subsidence rates, etc. A full accounting of the file types used are provided in the following section. Once these files are read into the program in XYZ format, ICM-Morph will save all outputs (and convert the input files at the end of the first year) into binary arrays that are an order—of-magnitude smaller in size. In addition to being substantially smaller in size, the reading and writing to text file in XYZ format is very time consuming; by using binary array files, the model run time was reduced from over four hours per simulated year to less than ten minutes. The third file format utilized by ICM-Morph is comma separated values (CSV) files. These files are used for storing a large amount of input and output data that does not need to be mapped, such as lookup tables and summary data that may be based on the ICM-Hydro compartment polygons, or the ICM-LAVegMod grid cells.

While the binary arrays that are used by ICM-Morph drastically improved model performance, with respect to memory usage and speed, there is one distinct downside; these files are not human- nor universally machine-readable. They can only be read by another Fortan program that is being run on a computer processor that has the same “endianness” settings as the computer used to originally generate the binary array. Since all of the master plan simulations are conducted on Bridges-2, this did not pose any issues with respect to the 2023 modeling efforts.

However, since there is a desire to use these data generated by ICM-Morph in perpetuity, new post-processing programs were developed that are able to be run, on Bridges-2, after the completion of the entire simulation. These post-processors are run on Bridges-2 and read in the binary arrays and convert them first back into ASCI XYZ text files, then converts them into TIF raster files that are readable on any computer that is equipped with GIS software. The TIFs are significantly smaller than the ASCI XYZ text-based rasters, however there is considerable computational time that is required to complete these file conversions. The model run times are not impacted, however, because all raster file conversions are now down outside of the ICM and can be done in parallel, not impacting the overall ICM simulation run times for production runs.

All of the raster post-processing Fortran source code files are available on the CPRA Master Plan GitHub site[5].

3.3 INITIAL CONDITIONS AND INPUT FILES

A number of input files are required to be prepared prior to running the ICM and ICM-Morph. As discussed in the previous section, many of these input files are raster datasets that must be pre-processed into ASCI XYZ format for initial use in ICM-Morph. While this pre-processing can be cumbersome, and care must be taken to ensure that all raster files are identical in resolution and extent, using these GIS-independent file formats result in simple Fortran compiler settings with no external dependencies such as NetCDF or GDAL libraries during model runtime (GIS-readable rasters were generated as a post-processing step upon completion of each simulation, as described in the previous section). The following datasets are required to run ICM-Morph:

TOPOBATHYMETRIC DIGITAL ELEVATION MODEL (DEM)

One of the primary datasets needed for ICM-Morph is a digital elevation model (DEM) for the water and wetland areas of coastal Louisiana. The preparation of a combined topographic and bathymetric (topobathymetric) DEM is a complicated and time consuming process, which is fully documented in Attachment B1: Landscape Input Data. Once the initial conditions DEM was developed for the 2023 Coastal Master Plan, minor edits were made to incorporate projects on the landscape that were assumed to be in the FWOA simulations, but were not present on the landscape when the elevation was collected. This updated initial conditions DEM was then converted into the ASCI XYZ format and read into ICM-Morph as the initial conditions elevation at the start of the model run. At the very end of the model year, ICM-Morph saves the DEM of the updated landscape to the model run folder, so that it can be used for the starting elevation during the next model year.

[5] https://github.com/CPRA-MP/ICM_MorphRasters

LANDSCAPE COMPOSITION/LANDTYPE

Similar to the DEM file, another important dataset for ICM-Morph is the landscape composition. This refers to the land/water status of each ICM-Morph pixel. In fact, ICM-Morph does not just differentiate between land and water, but also further defines the land into: vegetated wetland, unvegetated wetland, developed land/upland/fastlands, and flotant marsh (Table 2). Like the DEM, the methodology for developing the initial conditions version of this file is provided in Attachment B1: Landscape Input Data. This is also a file that is updated at the end of each model year by ICM-Morph so that the changing landscape will be used as starting conditions for each subsequent model year.

Table 2: Values used in ICM-Morph for landtype classifications.

Value	Landtype
1	Vegetated wetland
2	Open water
3	Unvegetated wetland/bareground
4	Developed/upland/fastland
5	Flotant marsh

POLDERS

Leveed areas across the coastal zone were identified and delineated. These poldered areas were mapped and are provided as an input file. All ICM-Morph pixels that are located within a poldered area are treated as developed/upland (landtype=4) and will not have any land change processes applied to them (with the exception of elevation change due to deep subsidence, as described below).

DEEP SUBSIDENCE

Subsidence in ICM-Morph is treated as two separate rates. The first, is a spatially heterogeneous rate that represents deep subsidence. This rate map was derived from GPS benchmarks throughout coastal Louisiana and remains unchanged in time; each year the same rates of deep subsidence are applied, although the rates do vary spatially. The methodology for deriving this input file is provided in Attachment B3: Determining Subsidence Rates for use in Predictive Modeling.

SHALLOW SUBSIDENCE

The second subsidence rate used in ICM-Morph is the shallow subsidence. This rate is meant to represent processes in the coastal wetland areas near surface – and the rates were derived from CRMS observations. These rates are provided as an input CSV file and include spatial averages for of shallow subsidence rates for each ecoregion (lower, upper, and median quartiles per ecoregion). Again, the methodology for deriving this input file is provided in Attachment B3: Determining Subsidence Rates for use in Predictive Modeling.

MARSH EDGE EROSION RATES

Edge erosion is not dynamically modeled within ICM-Morph, but instead is represented by projecting historic rates of edge erosion into the future. Historic rates of marsh edge erosion were calculated from high resolution aerial imagery; the methodology is provided in Attachment B1: Landscape Input Data. Once developed for initial conditions, this map of historic edge erosion was updated to represent newly built shoreline protection features. Edge erosion rates were set to zero for all areas assigned to be within the influence area of a shoreline protection project. The influence area was defined as within a 200 m buffer of shoreline protection feature's centerline.

ORGANIC MATTER ACCUMULATION RATES

As discussed in later sections, the organic matter accumulation rates used by ICM-Morph are provided as quartile ranges for each FFIBS category. The rates are further divided into Chenier Plain and Delta Plain regions. This information is passed into ICM-Morph via a CSV table that provides OMAR values for each FFIBS category *for each ecoregion*. Ecoregions were assigned to be either in the Delta Plain, or the Chenier Plain, and assigned appropriate OMAR values from these assignments. This allows for future changes where the OMAR values may be provided at a more granular (e.g., ecoregion) scale. These regional OMAR values (provided in

Table 3, below) were updated based on soil surveys conducted in 2018 and discussed in detail in Attachment D2: ICM-Wetlands, Vegetation & Soils Model Improvements (Baustian et al., 2020).

ACTIVE DELTAIC ZONES

In addition to the categorically defined OMAR values for the Chenier Plain and Delta Plain, a third region was also differentiated in order to better parameterize marsh accretionary processes within active, river-connected, delta splays. These active deltaic OMAR rates are applied only to fresh and/or intermediate marshes (e.g., river-connected) located within predefined footprints of active delta splays. These predefined footprints are based on the ICM-Hydro compartments. An input CSV file was prepared that flags each ICM-Hydro compartment as being an active delta, or not. This input file was initially set such that only ICM-Hydro compartments within the Bird's Foot Delta, the Atchafalaya/Wax Lake Deltas, and existing river diversions (e.g., Davis Pond and Caernarvon) were treated as active deltaic zones. However, for any simulation in which a newly proposed diversion was implemented in the model (e.g., the Mid-Barataria and Mid-Breton Sediment Diversions in FWOA simulations) this list of active deltaic compartments was updated so that newly built land within the diversion outfall areas would be treated, with respect to OMAR values, as an active river-connected delta splay.

MAINTAINED NAVIGATION CHANNELS AND RIVERS

Several water bodies in the Louisiana coastal zone receive regular dredging in order to maintain proper channel depths for navigational purposes. Therefore, all federal navigational channels in the coastal zone have a separate DEM file that contains the initial bathymetric elevation of the channel. This separate DEM is used, as described below, to ensure that the elevation within these channels are maintained throughout the entire simulation.

MODEL GRID LOOKUP MAPS

As described above, several input files and datasets used by ICM-Morph are provided via CSV tables that are based on ecoregions, ICM-Hydro compartments, and ICM-LAVegMod grid cells. In order to properly link to each of these lookup tables, three additional model grid map rasters are necessary that map each ICM-Morph pixel to the corresponding ICM-LAVegMod grid cell, each ICM-Hydro compartment, and each ecoregion. These lookup maps all have identical resolution, extent, and NoData settings as the DEM and landtype raster files described above.

INPUT PARAMETERS CONTROL FILE

The majority of information that is needed to run an instance of ICM-Morph is passed into the compiled code via a CSV control file titled *input_params.csv*. This file is generated programmatically by

ICM.py and is updated for every year of the simulation. Some of the parameters included are constant for every model year, whereas other parameters may change from one year to the next. An example of the latter would be the files that are used to implement a master plan project on the landscape during a specific year.

This file also contains the directory paths for the many input/output files generated for, and by, ICM-Morph. The variables that are passed into ICM-Morph via this *input_params* file are listed in the **set_io** subroutine - a description of each variable is also provided in **ICM.py**[6].

3.4 ICM-MORPH MODEL SUBROUTINES

The following section steps through the model subroutines that are contained in ICM-Morph. At the start of each section, two lists will be provided; the left column contains the subroutine name of the ICM-Morph code; the right column contains the name of the corresponding Fortran source code file available on the CPRA Github site[7]. Throughout this section, as various subroutines (either internal to ICM-Morph, or other ICM components) are referenced, the subroutine name will be **emphasized** so that the cross-subroutine connections within the model are evident.

MAIN CONTROL PROGRAM AND PARAMETER SETTINGS

Subroutine: **main**	**Source code:** WM_main.f90
Subroutine: **set_io**	**Source code:** WM_set_io.f90
Subroutine: **params_alloc_io**	**Source code:** WM_params_alloc.f90
Subroutine: **params_alloc**	**Source code:** WM_params_alloc.f90
Subroutine: **dem_params_alloc**	**Source code:** WM_params_alloc.f90
Module: **params**	**Source code:** WM_params.f90

The primary control program for ICM-Morph is housed within the **main** subroutine which steps through all subsequent subroutines of ICM-Morph. The first four subroutines that are called are **set_io**, **params_alloc_io**, **params_alloc**, **dem_params_alloc**, and **params**. These four subroutines are used to read input variables and allocate variables and memory arrays that are required to run ICM-

[6] *input_params.csv* with descriptions of variables, via Github

[7] https://github.com/CPRA-MP/ICM_Morph

Morph. Processing messages and model performance times are written to console and log files throughout this subroutine.

PRE-PROCESSING INPUT FILES

Subroutine: **`preprocessing`** **Source code:** WM_preprocessing.f90

Once input variables and file paths are initialized, the **`preprocessing`** subroutine programmatically steps through all input files and reads them into allocated memory arrays. This subroutine is passed a binary flag that indicates whether the binary files representing raster arrays (as discussed above) are used, or if the ASCI XYZ text-based raster files are utilized. If the ASCI XYZ rasters are used, this subroutine takes over 14 minutes to run on Bridges-2 for the 2023 Coastal Master Plan, whereas if binary files are used the subroutine finishes in 42 seconds.

INUNDATION DEPTHS

Subroutine: **`inundation_depths`** **Source code:** WM_inundation_depths.f90

The **`inundation_depths`** subroutine is used to calculate, for every pixel within the ICM-Morph domain, a water depth. This subroutine uses the initial topobathy DEM raster from the start of the model year to set a bottom elevation for any given pixel. The water surface elevation, however, can be calculated for one of fourteen different time periods; which is set by the variable *tp*, which is passed into the subroutine when it is called from **`main`**. This variable must have a value set to any integer from 1 to 14. If *tp* is a value less than or equal to a value of 12, then the *tp* represents the elapsed month of the year. If *tp* is set to 13, it represents the annual average; if the value is 14, it represents the annual average for the previous year. For example if **`inundation_depths`** is called and is passed (*tp=3*), then the subroutine will calculate the average inundation depth for the month of March during the current simulation year. The twelve monthly (and annual mean) water surface elevations are read into the model for each ICM-Hydro compartment in a CSV file that is processed during **`preprocessing`**. Both the current year and previous years' water surface elevations are read into the model. The previous year's average inundation depth is required since chronic inundation stress thresholds used to define inundation loss require inundation depth data for two consecutive years. This is discussed later during the section describing the **`inundation_thresholds`** subroutine.

In addition to providing arrays of inundation depth for each pixel, this subroutine also tabulates the number of pixels within each ICM-Hydro compartment that were wet during each respective month. This wetted area tabulation per compartment is utilized later during the **`mineral_deposition`** subroutine.

MARSH EDGE DELINEATION

Subroutine: **`edge_delineation`** **Source code:** WM_edge_delineation.f90

Marsh edge, as defined in ICM-Morph refers to a 30-m pixel that is classified as either vegetated wetland or bareground and is adjacent to at least one pixel classified as open water. The entire landtype raster is looped over using a 3 x 3 moving window; pixels that are classified as either upland or flotant marsh are excluded from analysis since neither of these two landtypes has any edge processes applied to them and are therefore not included in the definition of marsh edge. The identified marsh edge pixels are saved to a new raster with an assigned integer value of 1; all other pixels within the domain that are not marsh edge receive a value of 0.

MINERAL SEDIMENT DEPOSITION

Subroutine: **`mineral_deposition`** **Source code:** WM_mineral_deposition.f90

Mineral sediment deposition on the marsh surface and on water body bottoms is calculated at a monthly timestep[8]. This **`mineral_deposition`** subroutine utilizes two datasets; the monthly inundation depth data calculated during **`inundation_depths`** and mass per unit area sediment depositional loads calculated monthly by ICM-Hydro and read into ICM-Morph during **`preprocessing`**. The monthly sediment depositional mass loading data is tabulated in ICM-Hydro to be total mass of mineral sediment deposition over three different zones of each ICM-Hydro compartment: the open water area, the marsh edge area (same definition as used in **`edge_delineation`**), and the marsh interior (which is set equal to the total marsh area within the ICM-Hydro compartment less the area of marsh edge). ICM-Hydro uses average elevations for each of these three zones to calculate sediment deposition, it does not account for the topographical details at each pixel in the same way that ICM-Morph does. Therefore, the first step in this **`mineral_deposition`** subroutine is to correct the mineral sediment loading rates so that the area over which the monthly deposition occurs is only those areas within each ICM-Hydro compartment that was actually inundated at some point during the month for which sediment deposition is being calculated for. This is done by conserving the mass of sediment deposited during the month for a given ICM-Hydro compartment, but updating the area to include only those areas wetted during the month. For example, if a given compartment were calculated to deposit 100 g/m^2 of mineral sediment on the marsh interior area, but only 50% of the marsh interior were at elevations low enough to have been inundated during the respective month – then the areal loading of sediment would be pro-rated by this 50% factor. This would result in any marsh interior pixel inundated during the month to receive 200 g/m^2 and all dry marsh interior pixels

[8] Previous versions of the ICM mapped mineral sediment deposition annually. This resulted in a uniform sediment deposition thickness over all landscape pixels that had been inundated at least once during the simulated year. Improvements to the models for the 2023 plan converted this to the monthly depositional mapping that is described here.

would receive no mineral sediment deposition.

Flotant marsh areas are treated as having no inundation depth, since they will float on top of the water column; therefore, no mineral sediment deposition is modeled to occur on flotant marsh areas within ICM-Morph.

Once the mineral deposition mass per inundated area is determined, the mass loading is converted to a vertical accretion due to mineral deposition, in units of centimeters. This conversion to accretion depth is done by dividing the mineral mass loading per area (units of g/cm^2) by the mineral sediment bulk density (units of g/cm^3). Open water areas use a bed sediment bulk density value, and marsh areas use the mineral soil self-packing density as determined via an ideal mixing model (described in Attachment D2: ICM-Wetlands, Vegetation & Soils Model Improvements). The values for both of these density variables are passed into ICM-Morph via the input parameters control file. For 2023 modeling, the open water bed bulk density and mineral self-packing density values were 0.835 g/cm^3 and 2.106 g/cm^3, respectively.

The final step of the **`mineral_deposition`** subroutine is to apply low-pass filter on the total annual mineral accretion to ensure that any numerical instabilities that may have resulted in runaway accretionary rates are kept in check. The maximum allowable mineral accretionary rates are set in the input parameters control file and are set to 50 cm and 10 cm of mineral sediment accretion in open water bodies and marsh surfaces, respectively.

EROSION OF WATER BODY BOTTOMS

In addition to mineral sediment accretion, the **`mineral_deposition`** subroutine is also where erosion of water bottoms is calculated. For open water areas, ICM-Hydro will report out negative mass depositional rates if a water body is erosive, as opposed to depositional. Therefore, for open water areas, the calculated accretion depths may be negative, indicating net erosion for a given month. While the erosional mass-to-erosional depth is calculated in the same manner as deposition in water bodies (the same bulk density value of 0.835 g/cm^3), there is a separate erosion depth threshold applied for the total cumulative erosion of water bodies. Like the accretionary limits, the maximum erosion threshold value is passed into ICM-Morph via the input parameters control file. For 2023, a value of 50 cm was used, resulting in a maximum scour of water bodies of 50 cm in any given model year.

Unlike water body bottoms, erosion of sediments from the marsh interior surface are not modeled in ICM-Morph; only marsh edge erosional processes are incorporated. Marsh edge erosion is discussed in a later section of this report.

ORGANIC MATTER ACCUMULATION

Subroutine: **`organic_accretion`** **Source code:** WM_organic_accretion.f90

Once the mineral component of marsh accretion is calculated in the previous subroutine, the **`organic_accretion`** subroutine is used to determine the organic portion of marsh accretion. Organic accretion is calculated as a function of vegetation species coverage (represented by the weighted FFIBS score – as described above) and look-up tables of organic matter accumulation rates (OMAR) that vary based on FFIBS category and location. The OMAR values, like mineral sediment deposition, are in units of mass per unit area (g/cm^2); these rates are converted to a vertical accretion depth by dividing OMAR by the bulk density of the organic portions of the marsh soil. This organic bulk density is represented by the self-packing density of organic sediments, which was determined with the same ideal mixing model as used for mineral sediment accretion (again, see Attachment D2: ICM-Wetlands, Vegetation & Soils Model Improvements).

The lookup table (

Table 3) for OMAR by FFIBS category was derived from CRMS soil data which was partitioned into Deltaic Plain and Chenier Plain zones. In addition, separate OMAR values were used for fresh and intermediate marshes that are located within an active delta. The *active delta* locations were added to the OMAR tables to represent sites that are located in active delta splays with current river connectivity. The regions of the model that are treated as *active delta* are set via the active deltaic zone input file described above.

The OMAR lookup tables are derived from CRMS observations, and the rates were averaged categorically for each FFIBS classification category. However, ICM-LAVegMod calculates a weighted FFIBS score to better represent the mixture of species present within each ICM-LAVegMod grid cell. This weighted FFIBS score is used to linearly interpolate the categorical OMAR data so that the organic accretionary processes will represent the mixture of vegetation species present in each grid cell. For example, if one ICM-LAVegMod grid cell has an even 50/50 mixture of brackish and saline marsh vegetation than it will have a weighted FFIBS score of 11.5; subsequently an interpolated median OMAR of 0.735 g/cm^2 would be assigned to this grid cell.

Table 3. Organic matter accumulation rates (OMAR) and weighted FFIBS ranges for categorical FFIBS data used in ICM-Morph

ORGANIC MATTER ACCUMULATION RATES (G/CM^2) BY FFIBS CATEGORY AND LOCATION				
		DELTAIC PLAIN	CHENIER PLAIN	ACTIVE DELTA
FORESTED WETLANDS 0 ≤ FFIBS < 0.15	LOWER	0.079	0.079	-
	MEDIAN	0.093	0.093	-
	UPPER	0.11	0.11	-
FRESH MARSH 0.15 ≤ FFIBS < 1.5	LOWER	0.073	0.04	0.145
	MEDIAN	0.089	0.058	0.145
	UPPER	0.107	0.085	0.145
INTERMEDIATE MARSH 1.5 ≤ FFIBS < 5.0	LOWER	0.068	0.033	0.145
	MEDIAN	0.076	0.04	0.145
	UPPER	0.085	0.048	0.145
BRACKISH MARSH 5.0 ≤ FFIBS < 18.0	LOWER	0.058	0.035	-
	MEDIAN	0.065	0.048	-
	UPPER	0.074	0.05	-
SALINE MARSH 18.0 ≤ FFIBS	LOWER	0.07	0.038	-
	MEDIAN	0.082	0.038	-
	UPPER	0.097	0.038	-

During model calibration tests, the quartile ranges for the OMAR values were treated as a calibration parameter. Once the ICM-Hydro sediment parameters were calibrated and adjusted to best match observed suspended solids data, the modeled total accretion (e.g., mineral plus organic) was compared to observed total accretion data in the CRMS network. Three calculations of total accretion were made using the lower, median, and upper estimates of OMAR in Table 3; all using the ICM-Hydro determined rates of mineral sediment deposition. As seen in Figure 8, the median OMAR values provided the best performance with respect to total accretion. Therefore, for all 2023 Coastal Master Plan simulations, the median OMAR values for each FFIBS category were used.

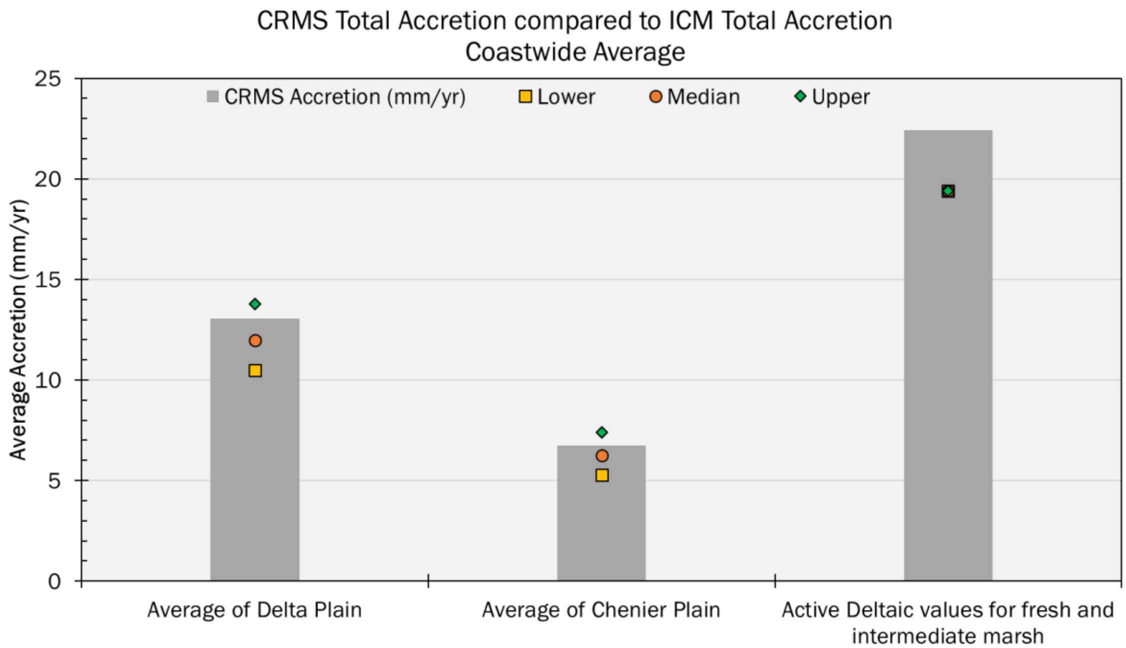

Figure 8. Calibration of total accretion using three different quartiles for organic matter accumulation rates.

Future improvements to ICM-Morph could allow for the OMAR quartile selection to be made by model ecoregion, allowing for greater spatial heterogeneity with how ICM-Morph models organic accretionary processes. For 2023, all ecoregions are assigned the median OMAR rates based on Figure 8.

FLOTANT MARSH LOSS

Subroutine: **`flotant`** **Source code:** WM_flotant.f90

The **`flotant`** subroutine is the first ICM-Morph subroutine that will start to track changes to the landscape as a result of hydrologic conditions for the given simulation year. This is done by updating a raster array of *land change flags*. ICM-LAVegMod reports out a percentage of flotant marsh within each grid cell that died during the current simulation year (see Flotant Mortality and Flotant Establishment sections above). ICM-Morph receives the percentage of flotant marsh within each grid cell and calculates the total number of flotant pixels within each respective grid cell that need to be converted to open water. This subroutine scans the landtype pixel on a grid cell by grid cell basis – flagging the appropriate number of flotant marsh pixels that are to be converted to open water. For any pixel flagged for conversion, the *land change flag* raster is updated to have a value of -2 for each respective dead flotant pixel (Table 4). This flag is later used by the **`update_landtype`** subroutine.

Table 4. Land change flag values.

LAND CHANGE FLAG VALUE	DESCRIPTION
0	NO CHANGE
-1	CONVERSION FROM VEGETATED WETLAND TO OPEN WATER DUE TO INUNDATION
-2	CONVERSION FROM FLOTANT MARSH MAT TO OPEN WATER
-3	CONVERSION FROM MARSH EDGE TO OPEN WATER DUE TO EROSION
1	CONVERSION FROM OPEN WATER TO NEW SUBAERIAL LAND ELIGIBLE FOR VEGETATION

IMPLEMENT SHORELINE PROTECTION PROJECTS

Subroutine: `build_shoreline_projects` **Source code:** WM_build_shorline_projects.f90

This subroutine, **`build_shoreline_projects`**, is the first step in ICM-Morph where the landscape processes are updated to account for a master plan project; specifically the two projects types (shoreline protection and bankline stabilization) that impact marsh edge erosion. This is accomplished by reading in a new raster data file (in ASCI XYZ format) that contains a map of multiplication factors, with a default value of 1.0. The area of edge that is protected by the proposed project will have mapped multiplication factors of 0.0; indicating that all edge erosion processes are zeroed out in this footprint. This subroutine reads in this map of erosion multiplication factors and multiplies them by the historic marsh edge erosion rates read in during **`preprocessing`**. This is done prior to the next subroutine, **`edge_erosion`**, so that the implemented shoreline protection projects are incorporated before marsh edge erosion is calculated for the simulation year. The overall control program **`ICM.py`** tracks which projects are active, and for all years after a shoreline protection project has been implemented, these multiplication factors will be read into ICM-Morph; this results in the impacts on marsh edge erosion rates are continuously applied in all model years after implementation.

MARSH EDGE EROSION

Subroutine: `edge_erosion` **Source code:** WM_edge_erosion.f90

After the locations of marsh edge are identified for any given model year by **`edge_delineation`**, these edge pixels are overlaid with a static raster of historic marsh edge erosion rates that were quantified from high resolution aerial imagery (see Attachment B1: Landscape Input Data). The historic rates are used, in conjunction with the number of elapsed model years to determine whether any given edge pixel would be eroded during a given model year. This subroutine reads the assigned historic marsh edge erosion rate (m/yr) for a given pixel and calculates the number of years needed to erode one 30-m pixel. For example, a pixel with an assigned historic edge erosion rate of 15 m/yr would only be subjected to edge erosion processes once every 2 years; a pixel with an edge erosion rate of 5 m/yr would be subjected to edge erosion processes once every 6 years.

If an edge pixel is identified as being subject to erosion loss during a model year, the subroutine updates the land change flag value for the respective pixel to an integer value of -3, which indicates conversion from marsh edge to open water due to erosion (Table 4).

This subroutine is only capable of removing one whole edge pixel in a given year, neither partial pixels, nor erosion events more frequent than once per year are able to be incorporated. Therefore, durations to erode one pixel are always rounded up to the next year; this has the possibility to lead to an under-representation of historic edge retreat. For example, if a location has an erosion rate of 29 m/yr, this would require 1.03 years to erode one 30-m pixel. However, this code rounds that up to erode one edge pixel every 2 years. Over a 50-year simulation, the historic erosion rate would have resulted in 1,450 meters of erosion, whereas this subroutine would only remove 25 pixels, resulting in 750 meters of modeled erosion. If the historic rate was 16 m/yr, this would result in 800 m over 50 years, or again 750 meters of modeled erosion. This could be changed by simply rounding instead of using a ceiling function on the year calculation.

MAP SPATIAL DISTRIBUTION OF BAREGROUND

Subroutine: `map_bareground` **Source code:** WM_map_bareground.f90

One change to the overall ICM-Morph and ICM-LAVegMod processes for 2023 was the spatial handling of bareground within each ICM-LAVegMod grid cell. ICM-LAVegMod tracks the percentage of a grid cell that is unvegetated land, but there is no spatial knowledge in ICM-LAVegMod of exactly which ICM-Morph pixels should be unvegetated. A decision was made during the model improvements process to assume that all bareground within a grid cell should be allocated to the lowest elevated pixels classified as land within each grid cell. This subroutine loops through the land pixels within each grid cell, and compares each respective pixel elevation to all other pixels within that grid cell.

ICM-LAVegMod classifies two types of bareground, *new bareground* that was vegetated in the previous year and lost vegetative cover due to hydrologic conditions, and *old bareground* that was previously unvegetated and remained so due to a lack of appropriate vegetation available for establishment (see Update Water Area and Update Vegetation Coverages sections of ICM-LAVegMod above).

Therefore this bareground assignment to the lowest elevation pixels is performed twice; first for the portion of each grid cell that is *old bareground* (this will be the lowest elevation land), and second for the portion that is *new bareground* (this will be higher in elevation than *old bareground* but lower in elevation than all vegetated land pixels). If the pixel is identified as *old bareground*, a bareground flag will be set to value of 1 for the given pixel; otherwise the *new bareground* will have a flag value of 2. This bareground flag is used later in the **`update_elevation`** subroutine.

CHRONIC INUNDATION STRESS THRESHOLDS

Subroutine: **`inundation_thresholds`** **Source code:** WM_inundation_thresholds.f90

Per the recommendations provided in Baustian et al. (2020), inundation depth thresholds are calculated for each landscape pixel to determine whether chronic inundation exists at a given location, which would result in the inability for vegetated wetland to persist. As stated in Appendix A of Baustian et al. (2020):

> The upper limit for vegetation occurrence can be defined as occurring at the upper bound of the 95th or 99th percentile confidence interval of the observed inundation depths, which varies as a function of the observed salinity at the same location over the same time frame. More specifically, this is the 97.5th and 99.5th quantile, respectively of the annual mean depth-salinity data pairs in CRMS from 2010 through 2017 and was calculated from a quantile regression analysis (Bolker, 2008) using the R statistical software (R Core Team, 2019). The 99.5th quantile of the data set was recommended as the water depth limitation which varies by salinity for vegetation occurrence. The depth limit, DL, at a given salinity, S, is:
>
> $$DL_S = \mu_{depth,S} + Z * \sigma_{depth,S} \quad \text{Eq. 9}$$
>
> $$\mu_{depth,S} = \beta_0 + \beta_1 * S \quad \text{Eq. 10}$$
>
> $$\sigma_{depth,S} = \beta_2 + \beta_3 e^{\beta_4 * S} \quad \text{Eq. 11}$$
>
> where a quantile regression was used to determine the mean and standard deviation of inundation depths as a function of salinity, $\mu_{depth,S}$ and $\sigma_{depth,S}$, respectively. The upper bounds on the 95th and 99th percentile confidence intervals are calculated with Z_{95} = 1.96 and $Z_{99.5}$ = 2.576, respectively.

So as to have flexibility with defining the salinity-inundation depth threshold curve, the parameter values for β_0, β_1, β_2, β_3, β_4, and Z_{pct} are all provided as input variables (written by **`ICM.py`** into the input parameters control text file) read into the program during **`preprocessing`**. The values selected by Baustian et al. (2020), representing the 99.5th percentile regression curve (Figure 9) are provided in Table 5.

Table 5: Values used to define the salinity-inundation depth threshold relationships for the 2023 Coastal Master Plan

VARIABLE	VALUE FOR 2023 COASTAL MASTER PLAN
B_0	0.0058
B_1	-0.00207
B_2	0.0809
B_3	0.0892
B_4	-0.19
Z_{PCT}	2.57

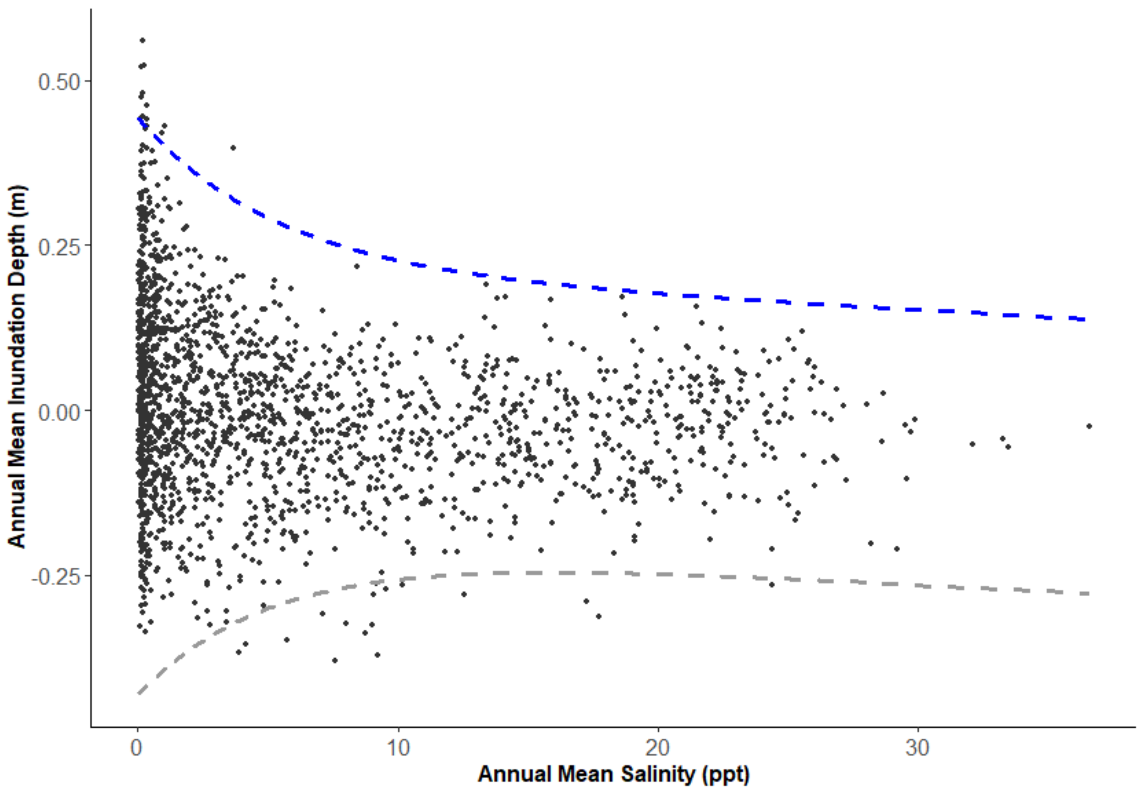

Figure 9. Salinity and water depth distribution of vegetation occurrence in coastal Louisiana with the blue line representing the salinity-inundation depth threshold curve used in ICM-Morph. Each point represents annual mean salinity and annual mean depth for a single CRMS station (2010-2017), n = 1944. The blue line is the 99.5th quantile, and the grey line is the 0.05th quantile from a quantile regression analysis.

If a given pixel is classified as non-flotant, non-forested wetland and it is inundated during both the present and previous model year to a mean annual depth that is greater than the inundation-salinity relationship defined by the above equations, then the pixel is flagged for inundation loss. The subroutine updates the land change flag value for the respective pixel to an integer value of -1 (Table 4), which indicates conversion from wetland to open water due to chronic inundation stress.

This chronic inundation stress criterion is not applied to wetland pixels that are either flotant marsh or fresh forested wetlands. The weighted FFIBS score from a pixel's overlying ICM-LAVegMod grid cell is examined, and if that score is less than or equal to 0.15, the vegetative cover is assigned as fresh forested wetlands and the inundation criterion is not applied to the respective pixel.

If a wetland pixel was already flagged for loss in **`edge_erosion`**, then the land change flag value is not overwritten by this subroutine and the pixel will be considered lost due to erosion during the year, not inundation.

UPDATE ELEVATION

Subroutine: **`update_elevation`** **Source code:** WM_update_elevation.f90

Information derived in previous subroutines (**`mineral_deposition`**, **`organic_accretion`**, **`flotant`**, **`edge_erosion`**, and **`map_bareground`**) are used in this subroutine to update the elevation of each pixel within the model domain. First, if a pixel is flagged as flotant loss, the elevation of the pixel is lowered to an elevation 1.0 m below mean water surface elevation. Second, if a pixel is flagged as edge erosion, the elevation of the pixel is lowered to an elevation 0.25 m below mean water surface elevation. Third if a pixel is flagged as being *old bareground*, the elevation of the pixel is lowered 0.05 m. These three values are each set in the input parameters control file passed into ICM-Morph.

After the three special treatments described above, each pixel's elevation is updated based on the following logic:

- If a pixel is vegetated land, the change in elevation is the sum of:
    - calculated mineral accretion,
    - calculated organic accretion,
    - deep subsidence, and
    - shallow subsidence.
- If a pixel is open water, the change in elevation is the sum of:
    - calculated mineral accretion and
    - deep subsidence.
- If a pixel is unvegetated land/bareground, the change in elevation is the sum of:

    - calculated mineral accretion,
    - deep subsidence, and
    - shallow subsidence.
- If a pixel is upland/developed land, or located within a pre-defined polder the change in elevation is equal to deep subsidence, only.
- If a pixel is flotant marsh, its elevation is unchanged (unless it was previously flagged as dead flotant, as described above).

The next step in this subroutine is to reset all elevation values for water pixels that are located within maintained (e.g., dredged) navigational channels. These locations are set to always maintain the initial elevation; this is handled via the *maintained navigation channels and rivers* input file.

Finally, if a pixel was identified as being located within the barrier island model domain, the elevations as calculated by ICM-BI, and processed by **`ICM.py`**, are used. These barrier island elevations are passed into ICM-Morph and handled during **`preprocessing`**.

CLASSIFY NEW SUBAERIAL LAND

Subroutine: `new_subaerial_land` **Source code:** WM_new_subaerial_land.f90

Once the landscape elevation has been updated, this subroutine compares the annual mean inundation depths (from **`inundation_depths`**) for each open water pixel for both the current and previous model years. If both inundation depths are less than 0.1 m, than the pixel is assumed to be shallow enough to allow for vegetation establishment and the *land change flag* value (Table 4) for the pixel will be set to 1, indicating new subaerial land eligible for vegetation establishment during the next model year. The depth criterion for vegetation establishment is set in the input parameters control file and passed into ICM-Morph during **`set_io`**.

UPDATE LANDTYPE CLASSIFICATION

Subroutine: `update_landtype` **Source code:** WM_update_landtype.f90

This subroutine updates the landtype raster to account for the updated *land change flags* (Table 4) that had been updated in **`edge_erosion`**, **`flotant`**, **`inundation_thresholds`**, and **`new_subaerial_land`** subroutines.

CALCULATE INUNDATION FOR USE IN HSI EQUATIONS

Subroutine: `inundation_HSI_bins` **Source code:** WM_inundation_HSI_bins.f90

This subroutine is used solely to summarize seasonal water depths that are required by some of the water fowl habitat suitability indices within ICM-HSI (see [Attachment C10: 2023 Habitat Suitability Index (HSI) Model]()). The various HSI equations use different seasons that are important to the individual waterfowl species, so the monthly inundation depths calculated in **inundation_depths** are used here to develop the appropriate mean depths important to each species. The calculated mean depths are then tabulated, for each grid cell, for a variety of depth bins that are used directly in the HSI equations.

IMPLEMENT MARSH CREATION AND LANDBRIDGE PROJECTS

Subroutine: **build_marsh_projects** **Source code:** WM_build_marsh_projects.f90

The last step in ICM-Morph for a given model year is to build landscape projects so that the newly built projects are on the landscape for the start of the next model year. This is first done by building marsh creation and landbridge projects (see Appendix F: Project Concepts for descriptions). These project types must have a pre-built raster file (in ASCI XYZ format) and during the year of implementation **ICM.py** will pass the filepath to these rasters into ICM-Morph. The format for these project files should be a XYZ map that has a value of NoData for all non-project areas, and a value of for the design elevation within the project footprint. The design elevation is defined here as the *height above mean water surface elevation*. When run, this subroutine will take this value, determine the background water surface elevation at the project site, and determine what the vertical elevation of the built marsh should be relative to the vertical datum used by ICM-Morph.

Once the design elevation has been determined, this subroutine will examine all pixels within and compare the water depth to the marsh creation depth threshold value assigned to each project. For most marsh creation projects, this depth threshold is set to 0.76 m; any pixel that is water and has a depth greater than this threshold will be ineligible for marsh creation. Landbridge projects due not have this same threshold applied – they are modeled to build marsh throughout the entire project footprint, regardless of water depth.

For all areas that are within the project footprint, and not flagged by the depth threshold, the pixel elevation will be set to be equal to the design elevation. The landtype of that pixel will also be set to 3, indicating the land is newly built, unvegetated, and available for vegetation to establish in ICM-LAVegMod during the next model year.

IMPLEMENT RIDGE RESTORATION AND LEVEE PROJECTS

Subroutine: **build_ridge_projects** **Source code:** WM_build_ridge_projects.f90

This subroutine is very similar to **build_marsh_projects**, but is instead used to update the landscape for ridge restoration and structural risk reduction project types (e.g., levees). There are two minor differences though. First, there is no water depth threshold applied to ridge and levee project footprints; all pixels under the project footprint will be built. Second, the input files for these project types use a simple design elevation (relative to the ICM-Morph vertical datum); unlike the marsh creation rasters which had provided an elevation relative to the mean water surface.

POST-PROCESSING/SUMMARY OUTPUTS

Subroutine: **`summaries`** **Source code:** WM_summaries.f90

Subroutine: **`write_output_summaries`** **Source code:** WM_write_output_summaries.f90

Subroutine: **`write_output_QAQC_points`** **Source code:** WM_write_output_QAQC_points.f90

Subroutine: **`write_output_binary_rasters`** **Source code:** WM_write_output_binary_rasters.f90

Subroutine: **`write_output_asci_rasters`** **Source code:** WM_write_output_asci_rasters.f90

After the implementation of marsh creation, ridge restoration, and levee features, the landscape is done being modified for the model year. All of the subroutines within ICM-Morph are simply post-processing data and writing output files for use in other ICM subroutines. This includes several CSV files that contain spatially averaged data for each ICM-Hydro compartment that is used to define the landscape in ICM-Hydro the following model year. Additional spatial averages are prepared for the ICM-LAVegMod grid cells that are used in ICM-LAVegMod as well as ICM-HSI. These various files, as well as additional summary output files are written to files in **`write_output_summaries`** subroutine.

For 2023, ICM-Morph was updated to include a new output file that was used for quality assurance/quality control (QAQC) during model simulations. These files, referred to as QAQC save points, contain a snapshot of all pertinent variables that are used throughout ICM-Morph to define how a given pixel changes in land elevation, and/or landtype, for any given model year. All data is saved for the year and appended as a new row to the end of the file. Therefore, at the end of the multidecade simulation, for each QAQC save point, there will be one file that tracks all elevation and land change data at that point for all model years. The locations used for the QAQC save points were randomly placed throughout the entire model domain. In addition to the random locations, QAQC save points were also placed at select transects that had been pre-identified at areas of interest (Wax Lake Outlet, near proposed diversions, etc.). Finally, QAQC save points were placed at every CRMS location within the model domain. In all, there are 2,941 locations where 16 different variables from across ICM-Hydro, ICM-LAVegMod, and ICM-Morph are all reported out. These files are written during the **`write_output_QAQC_points`** subroutine.

In addition to the summary CSV files saved to disk, ICM-Morph also exports raster based datasets to disk so that they can be used, in binary format, as the starting conditions for the next model year in ICM-Morph. These binary rasters can also be converted, using various post-processsing scripts (described above), to file formats that are GIS-readable. When output rasters are saved as binary files, the **`write_output_binary_rasters`** subroutine completes in just 4 seconds on Bridges-2 for the 2023 Master Plan. If chosen in the input parameters control file, ICM-Morph can also be used to export the rasters in ASCI XYZ format. This is considerably slower, and would also impact run times in the subsequent model year. Therefore, all model simulations currently export to binary, and utilize external post-processing script if and when GIS-readable versions of the data are needed.

3.5 MODELING SUBMERGED AQUATIC VEGETATION (SAV)

In addition to the modeling processes described in the sections above, ICM-Morph is also where the newly developed model for submerged aquatic vegetation (SAV) is housed. To incorporate the SAV model, two additional subroutines were added to ICM-Morph. These are the **`distance_to_land`** and **`sav`** subroutines. The first of these two subroutines is the most time consuming subroutine of the entire ICM-Morph model; it takes approximately 1 hour to complete on Bridges-2. This subroutine calculates, for every pixel classified as open water, how far that pixel is from land. This calculation must be omnidirectional; however, the SAV model has an upper distance of 500 m from land, so the search can be abbreviated once the subroutine determines a pixel is at least 500 m from land.

The second subroutine is the Fortran representation of the statistical model for SAV presence, as discussed in depth in Attachment D3: ICM-Wetlands – Submerged Aquatic Vegetation (SAV) Updates.

In addition to the spatial data that is already used by and available in ICM-Morph, there are several statistical parameters that must be read into ICM-Morph. These are passed into the model via the input parameters control file.

4.0 REFERENCES

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5.0 SUPPLEMENTAL MATERIALS

Table S1. List of Coverage types (vegetation and land) within ICM-LAVegMod and the corresponding coverages from the USGS LULC dataset

Full or Scientific Name of ICM-LAVegMod Coverage Type	**ICM-LAVegMod Symbol**	**USGS LULC Dataset Classes**
Water	WATER	Water; Palustrine Aquatic Bed; Estuarine Aquatic Bed
Not Modeled	NOTMOD	Developed, High Intensity; Developed, Medium Intensity; Developed, Low Intensity; Developed, Open Space; Cultivated Crops; Pasture/Hay; Grassland/Herbaceous; Upland - Mixed Deciduous Forest; Upland - Mixed Evergreen Forest; Upland Mixed Forest; Upland Scrub/Shrub
Old Bareground	BAREGRND_OLD	Unconsolidated Shore; Bare Land
New Bareground	BAREGRND_NEW	None
Quercus laurifolia	QULA3	Cottonwood - willow mixing - bottomland hardwood sites - occasional flooding
Quercus lyrate	QULE	Lower site bottomland hardwoods such as overcup oak and water hickory
Quercus nigra	QUNI	Lower site bottomland hardwoods such as water oak - lower site ash
Quercus texana	QUTE	Sweetgum/nutall/willow oak - bottomland hardwoods seasonal flooding
Quercus virginiana	QUVI	Bottomland hardwoods/longleaf/slash pine mix infrequent flooding; Bottomland hardwoods/loblolly pine mix infrequent flooding; Sycamore/pecan/american elm - infrequently flooding; Sweetgum/yellow poplar; Swamp chestnut oak/cherrybark oak - bottomland hardwoods - infrequently flooding; River birch / sycamore - bottomland hardwood sites - infrequent flooding; Live oak / bottomland hardwoods mix
Ulmus americana	ULAM	Higher site bottomland hardwoods such as sugarberry/elm/greenash

Full or Scientific Name of ICM-LAVegMod Coverage Type	**ICM-LAVegMod Symbol**	**USGS LULC Dataset Classes**
Nyssa aquatica	NYAQ2	Swamp tupelo dominant - Sweetbay mixing; Sweetbay dominant - swamp tupelo mixing; Tupelo dominant - cypress co-dom - low sites - freq. flooded
Salix nigra	SANI	Willow - low sites - wax myrtle mixing
Taxodium distichum	TADI2	Red maple lowland; Cypress dominant - tupelo mixing - low sites - frequently flooded
Eleocharis baldwinii	ELBA2_Flt	ELBA2_FLT
Panicum hemitomon	PAHE2_Flt	PAHE2_Flt
Flotant Bareground	Bareground_flt	None
Colocasia esculenta	COES	COES
Morella cerifera	MOCE2	MOCE2
Panicum hemitomon	PAHE2	PAHE2
Sagittaria latifolia	SALA2	None
Zizaniopsis miliacea	ZIMI	ZIMI
Cladium mariscus	CLMA10	CLMA10
Eleocharis cellulose	ELCE	ELCE
Iva frutescens	IVFR	Deciduous shrub scrub species - mixed; IVFR
Paspalum vaginatum	PAVA	PAVA
Phragmites australis	PHAU7	PHAU7
Polygonum punctatum	POPU5	POPU5
Sagittaria lancifolia	SALA	SALA
Schoenoplectus californicus	SCCA11	SCCA11
Typha domingensis	TYDO	TYDO
Schoenoplectus americanus	SCAM6	SCAM6
Schoenoplectus robustus	SCRO5	SCRO5
Spartina cynusuroides	SPCY	SPCY
Spartina patens	SPPA	SPPA
Avicennia germinans	AVGE	AVGE
Distichlis spicata	DISP	DISP
Juncus roemerianus	JURO	JURO

Full or Scientific Name of ICM-LAVegMod Coverage Type	ICM-LAVegMod Symbol	USGS LULC Dataset Classes
Spartina alterniflora	SPAL	SPAL
Baccharis halimifolia	BAHABI	None
Distichlis spicata	DISPBI	None
Panicum amarum	PAAM2	None
Solidago sempervirens	SOSE	None
Spartina patens	SPPABI	None
Sporobolus virginicus	SPVI3	None
Strophostyles helvola	STHE9	None
Uniola paniculate	UNPA	None

Table S2. Vegetation species modeled in ICM-LAVegMod and their attributes

Scientific Name	Dispersal Class	Habitat Type	FFIBS score
Quercus laurifolia	Low	Fresh	0
Quercus lyrata	Low	Fresh	0
Quercus nigra	Low	Fresh	0
Quercus texana	Low	Fresh	0
Quercus virginiana	Low	Fresh	0
Ulmus americana	Low	Fresh	0
Nyssa aquatica	Low	Fresh	0
Salix nigra	High	Fresh	0
Taxodium distichum	Low	Fresh	0
Eleocharis baldwinii	Medium	Fresh	-9999
Panicum hemitomon	Low	Fresh	-9999
Colocasia esculenta	High	Fresh	0.25
Morella cerifera	Medium	Fresh	0.25
Panicum hemitomon	Low	Fresh	0.25
Sagitttaria latifolia	High	Fresh	0.25
Zizaniopsis miliacea	High	Fresh	0.25
Cladium mariscus	Medium	Intermediate	1.5
Eleocharis cellulosa	Medium	Intermediate	1.5
Iva frutescens	Medium	Intermediate	2.75

Scientific Name	Dispersal Class	Habitat Type	FFIBS score
Paspalum vaginatum	Medium	Intermediate	2.75
Phragmites australis	High	Intermediate	2.75
Polygonum punctatum	High	Intermediate	1.5
Sagittaria lancifolia	Medium	Intermediate	1.5
Schoenoplectus californicus	Medium	Intermediate	2.75
Typha domingensis	High	Intermediate	2.75
Schoenoplectus americanus	Medium	Brackish	7.15
Schoenoplectus robustus	Medium	Brackish	11.5
Spartina cynusuroides	Medium	Brackish	11.5
Spartina patens	Medium	Brackish	7.15
Avicennia germinans	High	Saline	24
Distichlis spicata	Medium	Saline	17.5
Juncus roemerianus	Medium	Saline	17.5
Spartina alterniflora	Low	Saline	24
Uniola paniculate	NA	NA	-9999
Strophostyles helvola	NA	NA	-9999
Sporobolus virginicus	NA	NA	-9999
Spartina patens	NA	NA	-9999
Solidago sempervirens	NA	NA	-9999
Panicum amarum	NA	NA	-9999
Distichlis spicata	NA	NA	-9999
Baccharis halimifolia	NA	NA	-9999