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2017 Coastal Master Plan

Attachment C3-22.1: ICM-Hydro Flow Calculations

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Coastal Protection and Restoration Authority

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

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DEM	Digital Elevation Model
ICM-Hydro	Integrated Compartment Model Hydrology Subroutine
cms	Cubic Meters per Second
ppt	Parts per Thousand

1.0 Introduction

The following is a brief overview of the 12 types of hydraulic links that were used in the Integrated Compartment Model Hydrology Subroutine (ICM-Hydro), along with descriptions of certain coding procedures that were used and challenges that were encountered. Each link type has its own equation for water discharge between compartments, and therefore requires different parameters, all of which are described in this report. Additionally, an overview of the general assumptions that were made and the guidelines that were followed to delineate the links are also included in this report.

2.0 Links Descriptions

An input text file table was used to assign parameters to each link type in ICM-Hydro. There are 12 link types used in the ICM, not including the negative link flag mentioned in Section 2.12. Table 1 identifies the link types and the parameters used for each link type. The column headers are generic because they were used specifically for the modelers to identify the approporiate column for the parameters. When estimating the discharge, the ICM-Hydro Fortran code utilizes a specific flow equation depending upon the link type value. Entrance, exit, and structure energy losses were calculated if a loss coefficient was provided for a given link (as specified in columns numbered 6 through 8 of Table 1).

Table 1: Attributes of Each Link Type Modeled in ICM-Hydro.

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

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

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

2.1 Open Channels

Channel links were used to represent real channels, as well as to connect open water areas between compartments. The link features are simplified into rectangles with a depth and a width. Channel depth (which was hard-coded as a link attribute in the 2012 Coastal Master Plan) was replaced with the *invert elevation* and the *crown elevation*. The depth is now calculated internally by the difference between the water elevation and the maximum invert or crown elevation of the upstream and downstream compartments. This allows for the invert elevation to be updated based on the maximum of the change in bed elevation between the upstream and downstream compartments (see Section 2.2). The invert elevation is updated by the ICM code every year; the elevation increases as deposition occurs, and thereby reduces flow capacities in time. Similarly, the invert decreases as erosion occurs, which increases the flow capacities. This allows for a more dynamic modeling approach than was previously used. To ensure model stability throughout long-term simulations, the updating of invert elevations can be activated or deactivated.

The minimum invert in the offshore compartments was set at -30 m. This is related to the offshore salinity boundary condition calculation. Depth averaged salinity was calculated for the 30 m depth water column, and therefore it is acceptable to omit the deeper inverts because the isohaline is located at this invert. If the digital elevation model (DEM) provided an invert (or bottom elevation) that was deeper than 30 m, then -30 m was used. If a hydrology cell was not included in the DEM (the offshore compartments extend beyond the extent of the topobathymetric DEM), -30 m was used. Otherwise, the DEM invert was used for the offshore compartments.

Discharge in the channel links was estimated using the Manning's Equation as defined below:

$$Q = d^{5/3} \frac{W}{n} \left(\frac{\Delta h}{L}\right)^{1/2} Z \qquad (1)$$

where:

Q	=	*discharge (cms)*
n	=	*Manning's roughness coefficient (see Table 2 for default values)*
W	=	*width of link (m)*
d	=	*depth of link (m)*
L	=	*length of link (m)*
Δh	=	*differential stage (m)* = $\lvert E_{upstream} - E_{downstream} \rvert$
Z	=	*direction of flow* = $(E_{upstream} - E_{downstream}) / \lvert E_{upstream} - E_{downstream} \rvert$

The channel link water depth, *d*, at each model time step was calculated in ICM-Hydro as the difference between the invert of the channel and the average water surface elevation between the upstream and downstream model compartments, $E_{upstream}$ and $E_{downstream}$, respectively. Table 2 provides pre-calibration values for the roughness coefficient. During calibration, these values were adjusted individually to acquire a better fit to the observed data.

Table 2: Default Link Roughness Values.

Link Description	**Default Manning's *n* (unitless)**
Offshore open water links	0.018
Other open water links (e.g., lakes)	0.02
Channels/waterways	0.025
Meandering Channels (through marsh)	0.03

2.2 Weirs

Weir links were used for existing weirs in the domain along with connections from compartments with much higher elevations than the adjacent compartments. Weir links used the weir equation from Chow (1959). Figure 1 below helps illustrate the terms used in the standard homogeneous weir Equation 2 and the weir coefficient Equation 3 shown below:

$$Q = KWH\sqrt{2g\Delta h} \quad (2)$$

where:

Q	=	*discharge (cms)*
W	=	*crest length (perpendicular to the flow) (m)*
g	=	*acceleration due to gravity (9.81 m/s^2)*
H	=	*water depth over the weir, max of H_1 & H_2* (see *Figure 1*) *(m)*
Δh	=	*differential stage (m) (equation 3)*
K	=	*weir coefficient (equation 4)*

The weir coefficient and differential stage terms in Equation 2 vary as a function of weir submergence. If the flow depth over the weir is sufficient (<95% submergence), the flow rate is assumed to be solely a function of the flow depth over the weir crest. If the weir is greater than 95% submerged, the differential stage is used to determine the flow rate (Equation 3):

$$\Delta \mathrm{h} = \begin{cases} \max[\, H_1, H_2 \,] \;, & \frac{H_2}{H_1} < 0.95 \\ |H_1 - H_2| \;, & \frac{H_2}{H_1} \geq 0.95 \end{cases} \quad (3)$$

where:

$H_{1,2}$	=	*water depths over the weir, (see Figure 1) (m)*

If the weir is less than 95% submerged, the weir coefficient is adjusted to account for partial submergence as shown in Figure 1 and Equations 4 and 5:

$$K = \begin{cases} K_{sub}\left(C_w + \frac{H}{20y}\right) \times Max\left[0.6, \left(1 - \frac{0.2H}{y}\right)\right], & \frac{H_2}{H_1} < 0.95 \\ 0.6\,, & \frac{H_2}{H_1} \geq 0.95 \end{cases} \tag{4}$$

$$K_{sub} = \begin{cases} 1\,, & \frac{H_2}{H_1} < 0.85 \\ -14.137\left(\frac{H_2}{H_1}\right)^2 + 23.567\left(\frac{H_2}{H_1}\right)^{-8.815}, & 0.85 \leq \frac{H_2}{H_1} < 0.95 \end{cases} \tag{5}$$

where:

H	=	*water depth over the weir, max of H_1 & H_2 (see Figure 1) (m)*
y	=	*height of the weir relative to the bed elevation of the compartment contributing flow (m)*
C_w	=	*weir coefficient (approximately 0.4 for a sharp-edged weir)*
K_{sub}	=	*the submergence reduction factor (see equation 4)*

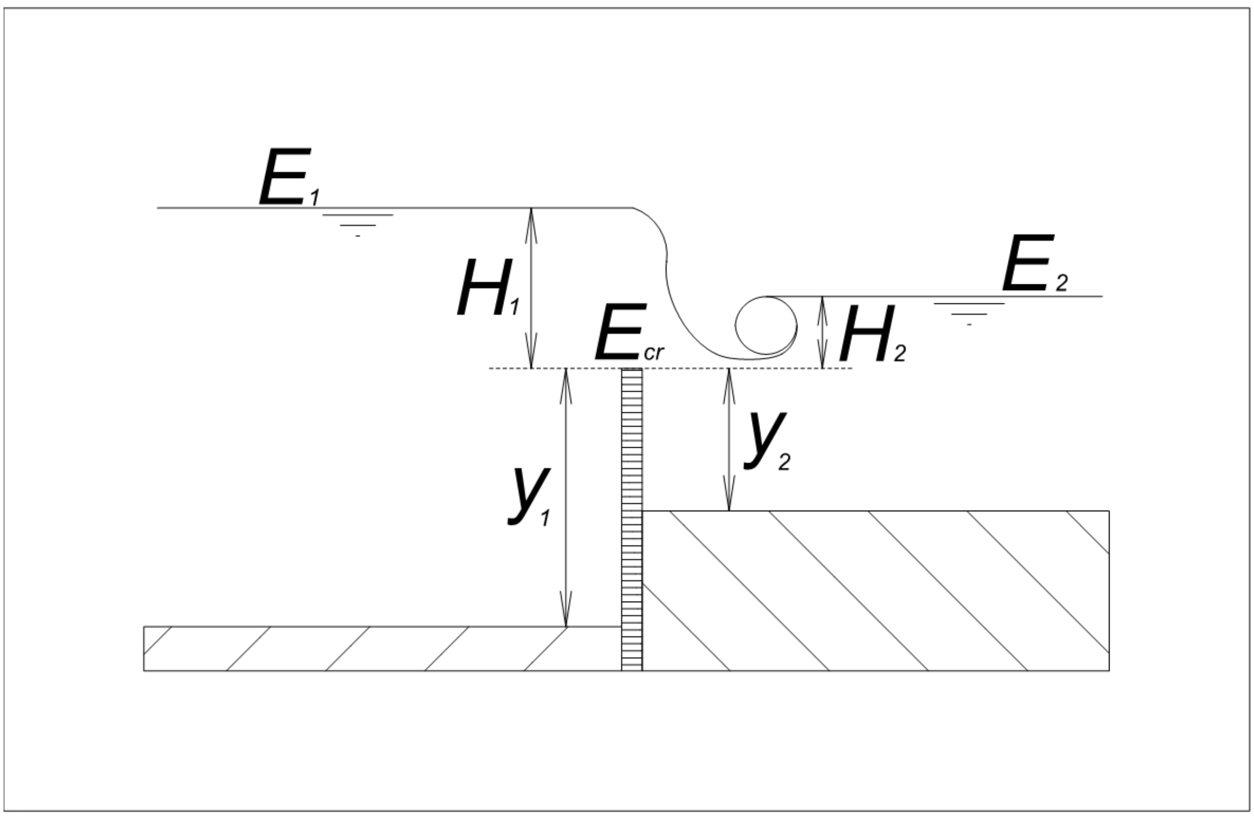

Figure 1: Depiction of Flow over a Weir between Two Compartments. E_1 and E_2 are the water surface elevations of the upstream and downstream compartments respectively. E_{cr} is the crest elevation of the weir, which is provided in the links attribute table (Table 1). H_1 and H_2 are the upstream and downstream water depths respectively, over the crest elevation. The heights, y_1 and y_2 represent the height of the weir With respect to the upstream or downstream compartment.

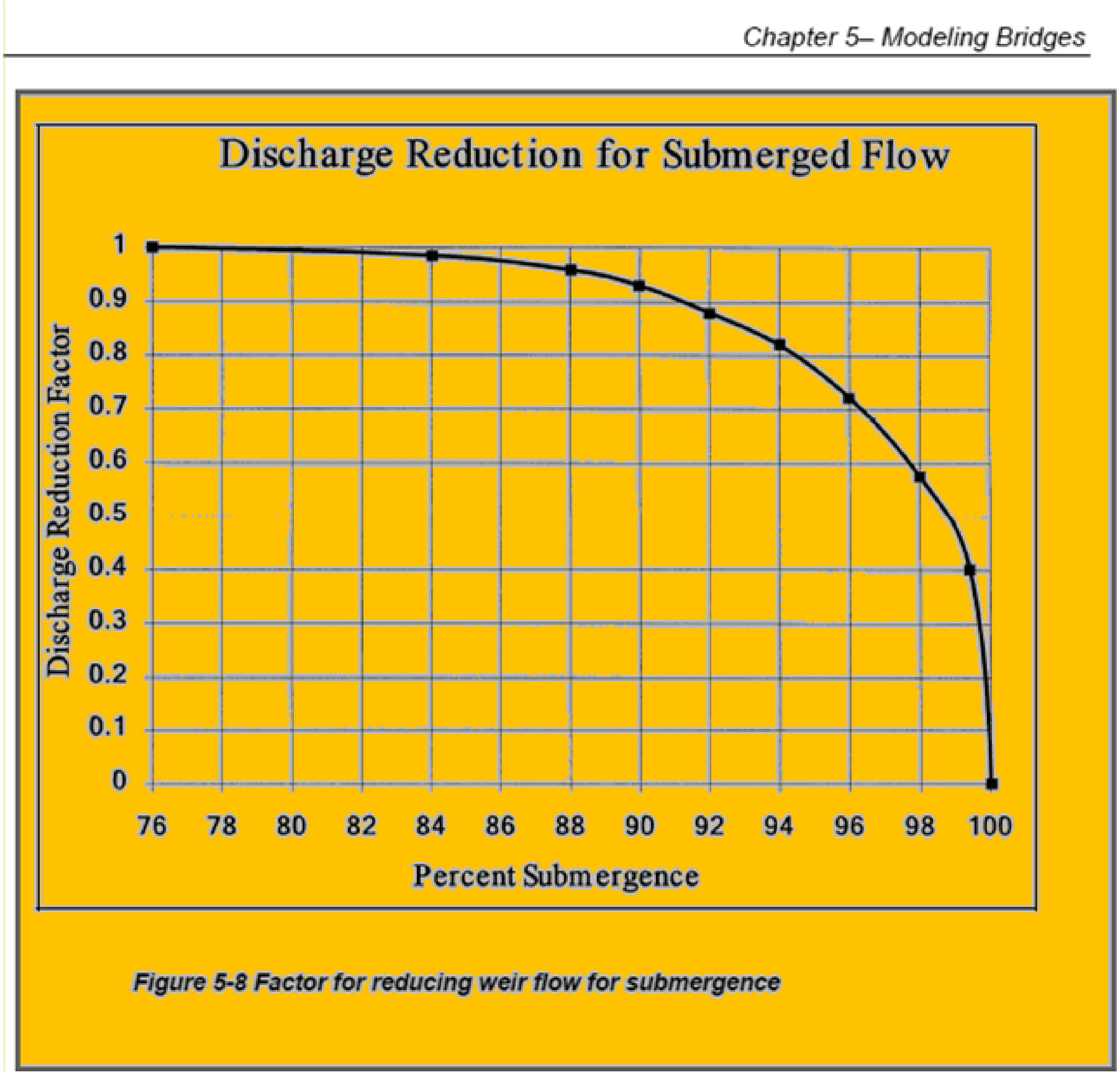

Figure 2: Chart for Discharge Reduction Factor for Submerged Flow (Figure from USACE HEC-RAS Manual, 2016).

2.3 Control Structures

There are existing locks and gates throughout coastal Louisiana. The control structure links were used to estimate the flow through these structures. There are six operational conditions for these links:

1. Differential stage (m)
2. Hourly schedule of when the structure is open/closed (repeated daily)
3. Downstream water surface elevation (m)
4. Downstream salinity (ppt)
5. Downstream salinity (ppt) and downstream water surface elevation (m)
6. Observed time series of openings

For conditions 1, 3, 4, and 5, the structures were either opened or closed when the stage or salinity reached the specified trigger(s). For conditions 2 and 6, at each model time step an open/close flag was generated by cross-referencing the time of day or observation schedule.

Once the operation was set for each time step, if flow was allowed through the control structure, the flow rate was calculated in the same manner as open channel links (Equation 1). An optional structure loss coefficient could be applied to the control structure links to account for any energy losses through the structure itself that were not captured in the standard entrance/exit loss coefficients.

2.4 Tide Gates

There are several tide gates located in the model domain. Tide gate links only allow flow in one direction, from upstream to downstream, and similar to control structure links, they have operational regimes. Tide gates are in line with the main channel and are the flow limiting structure between two compartments. Therefore, the entire link between these two compartments is modeled as this link type, using the orifice flow equation below:

$$Q = AvC_{orifice} \tag{6}$$

where:

A	=	*cross-sectional area of the orifice (m²)*
v	=	*water velocity (m/s)*
$C_{orifice}$	=	*orifice coefficient (from Links Attribute Table)*

If, however, the structure is a culvert through an embankment, two links would connect the compartments: 1) an orifice at a lower invert elevation with 2) a weir at a higher elevation that may have flow under high water conditions. The flow for the weir link would be estimated using Equation 2. The flow for the orifice link would use the orifice Equation 6. If the flow depth through the orifice was low enough such that the crown of the opening was not submerged, the orifice was treated as a sharp crested weir and flow was calculated using Equation 2.

2.5 Orifices

Orifice links differ from tide gate links in that orifice links allow for bi-directional or two-way flow. When orifices are in line with the main channel and are the flow limiting structure between two compartments, the entire link between these two compartments is modeled as this link type, using the orifice flow equation (Equation 6). If, however, the structure is a culvert through an embankment, two links would connect the compartments: 1) an orifice at a lower invert elevation with 2) a weir at a higher elevation that may have flow under high water conditions. The flow for the weir link is estimated using Equation 2 and the flow for the orifice link is estimated using Equation 6.

2.6 Culverts and Bridges

Culvert or bridge links are a combination between an orifice and an open channel link. Like the orifice link, a culvert or bridge is bounded on four sides, resulting in higher frictional losses than a free surface open channel link. Unlike the orifice links, which do not have a length characteristic, a culvert or bridge has a length component and therefore frictional losses along the flow direction, just like the open channel links. Therefore, the open channel equation (Equation 1) was used for calculating flow in culvert or bridge links. Once the flow depth reached the crown of the culvert or bridge opening, the wetted perimeter was increased by the fourth bounding wall (the crown), resulting in higher frictional losses. At this point, the standard Manning's flow rate calculation used an updated hydraulic radius value for this new wetted perimeter.

2.7 Pumps

Pump links have three operational conditions (controls):

1) the upstream stage at which the pump turns on,
2) the upstream stage at which the pump turns off, and
3) the discharge *capacity* of the pump.

Any flow exceeding the pump's capacity is stored within the cell. The upstream stage 'on' and upstream stage 'off' parameters ensure that the cell is never pumped dry. To avoid excessive pump cycling, the equations for the discharge in the pump and the discharge due to overland runoff are as follows:

$$Q = Min\left[Q_{pump}, \left(Q_{pump} + Q_{runoff}\right)/2\right] \quad (7)$$

$$Q_{runoff} = Max[(P_R - ET_R - \emptyset), 0] * A_{comp} \quad (8)$$

where:

Q_{pump}	=	allowable pump discharge or pump capacity (cms)
P_R	=	*precipitation rate (mm/hr)*
ET_R	=	*evapotranspiration rate (mm/hr)*
ϕ	=	*effective infiltration index (~2.54 mm/hr for urban upland areas)*
A_{comp}	=	*surface area of the compartment (m^2)*

This equation only applies to upland areas; therefore, compartments connected via pump link are entirely upland. If the pump capacity for any pump link was unknown, it was assigned a rate such that it can convey ½ inch of rainfall per hour over the catchment area. If pump capacities were known, these approximate rates were replaced with the known rates.

2.8 Overland Flow – Marsh

The purpose of these links is to capture the flow due to a surge from one compartment to an adjacent compartment that may or may not be connected via a traditional hydraulic flow path during low flow periods. Depending on the features of the adjacent compartments, the overland marsh links could be the only link type connecting the compartments or it could one of several link types connecting the compartments. An example of this is when two compartments share a marsh area with intermittent water bodies. In this situation, a composite channel link (Section 2.10), which connects marsh areas through un-channelized water bodies, and an overland marsh link would be used. The composite link captures the flow through the water areas and the overland link captures the flow over the marsh areas as flooding occurs. Figure 3 illustrates this example.

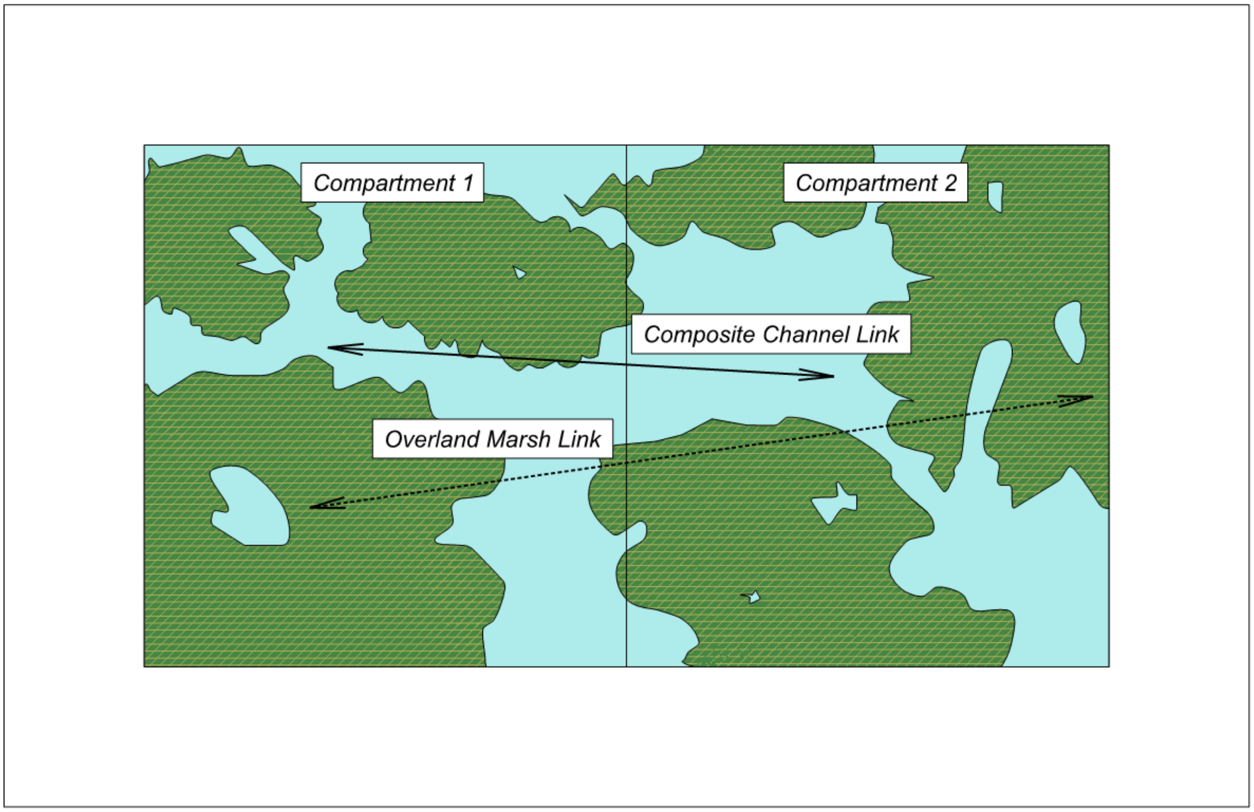

Figure 3: Depiction of Adjacent Compartments Connected Via a Composite Channel Link With an Overland Marsh Flow Link to Capture Overland Flooding.

The flow for the overland marsh links is calculated using Manning's Equation. The threshold for initiation of marsh flow, or minimum depth, is defined as 'ε' and was set to 0.1 m. The depth (*d*) must exceed this to have flow in the marsh link. The depth and flow are calculated as follows, and Figure A4 illustrates three scenarios for flow via the overland marsh links (Figure 4).

$$d = \frac{[Max(E_1,0)+Max(E_2,0)]}{2} - E_h \tag{9}$$

where:

E_1	=	*upstream water elevation* ($E_1 > E_2$) *(m)*
E_2	=	*downstream water elevation (m)*
E_h	=	*marsh elevation (m)*

For $d > \varepsilon$ Manning's Equation (Equation 1) applies, where Manning's roughness coefficient is 0.1 for overland links.

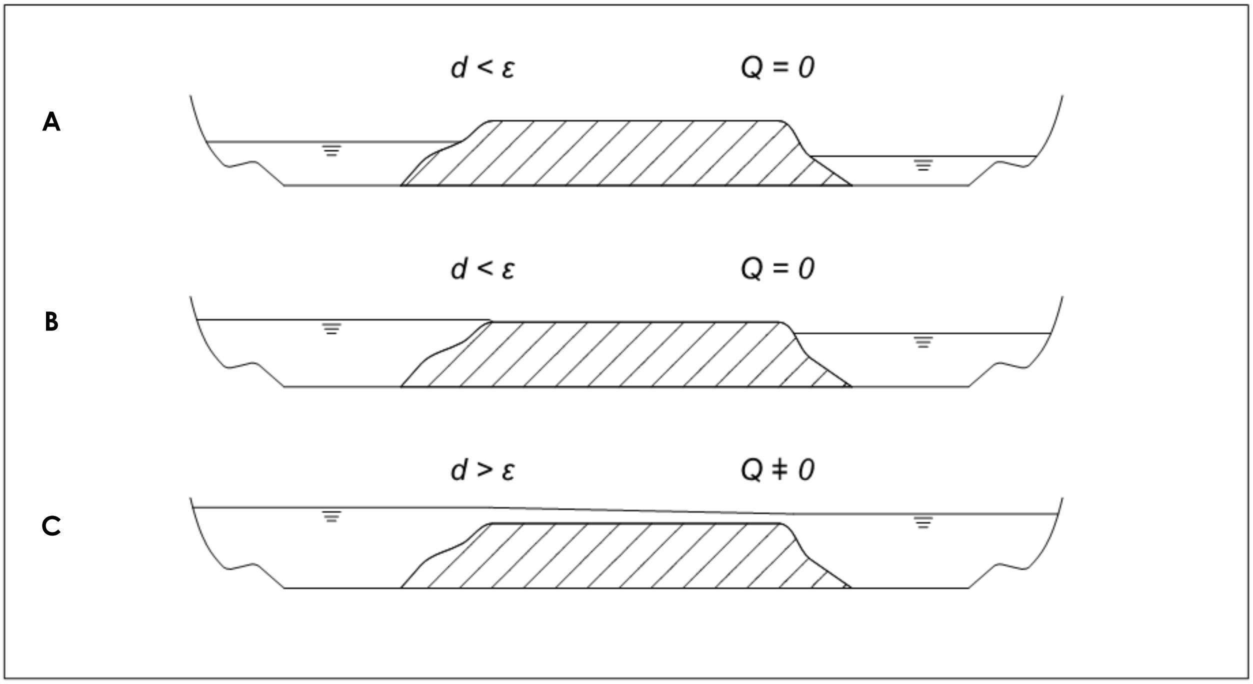

Figure 4: Scenarios for Estimating Discharge (Q) for Overland Marsh Flow Links. A) Both upstream and downstream water elevations are lower than the marsh elevation, yields zero overland flow. B) Upstream water elevation is higher than the marsh elevation and downstream water elevation is lower than the marsh elevation, but the depth (d) is less than the minimum depth (ε) needed for overland flow, yields zero flow. C) Both upstream and downstream water elevations are higher than the marsh elevation and the depth is greater than the minimum depth (ε), Manning's Equation is used to estimate overland flow.

2.9 Overland Flow – Ridges

The overland ridge links are similar to the overland marsh links in that their purpose is to capture the flow during flooding conditions. The overland ridge links represent the levees or ridges in the model area that obstruct the flow. These obstructions are modeled similar to the weir links, following the standard homogeneous Weir Equation from Chow (1959) shown in Equation 2, along with the weir coefficient equation shown in Equation 3. For these links, the weir coefficient, C_{weir}, ranged from 0.2 to 0.3 for a rough-crested ridge. Figure 4 shows the flow passing from one compartment to another over through an overland ridge flow link.

Given their length, the overland ridge links also have a friction loss component to the flow. The friction effect for overland ridge flow and the average depth over a ridge are approximated by the following equations:

$$h_f = L\left\{\frac{nQ}{W(d)^{5/3}}\right\}^2 \tag{10}$$

$$d = \frac{(E_1 - E_2)}{2} - E_{cr} \tag{11}$$

where:

h_f	=	*friction loss (m)*
L	=	*length of ridge link (parallel to the flow) (m)*
W	=	*ridge crest length (perpendicular to the flow) (m)*
n	=	*Manning's roughness coefficient (0.1 for ridges)*
E_1	=	*upstream water elevation ($E_1 > E_2$) (m)*

E_2 = *downstream water elevation (m)*
E_{cr} = *crest elevation (m)*

Combining the friction effects with the weir equation (Equation 2) leads to an equation for the overland ridge link flow as:

$$Q_{n+1} = KW\sqrt{2g}\left\{E_1 - E_{cr} - \frac{n^2}{W^2 d^{10/3}} Q_{n*}^2\right\}^{3/2} \quad (12)$$

where:

K = *weir coefficient (from Equation 2)*
Q_{n+1} = *the new flow (cms)*
Q_{n^*} = *the flow at the previous time step (cms)*

2.10 Regime Channels

To aid in the sediment distribution at a diversion, a predesigned grid of links, referred to as regime channel links, and hydrology cells that mimic the present subdeltas in the lower Mississippi River delta, were incorporated in the ICM. Regime links are channel links used for modeling diversions in the delta and/or diversion outlet compartments (refer to Attachment C3-1: Sediment Distribution for a complete description). These links were anticipated to experience sediment deposition. The regime channel dimensions are assigned as a function of predominant flowrate (e.g., design flowrate for diversion projects) and typical particle size. The particle size was assumed (D_{50} = 0.18 mm), and the proposed diversion flowrate was included in the links attribute table. The total diversion flow was manually divided among the links. The regime links were placed radially from the source (see Figure 5), and were projected radially until open water is reached (typically ~3 tiers).

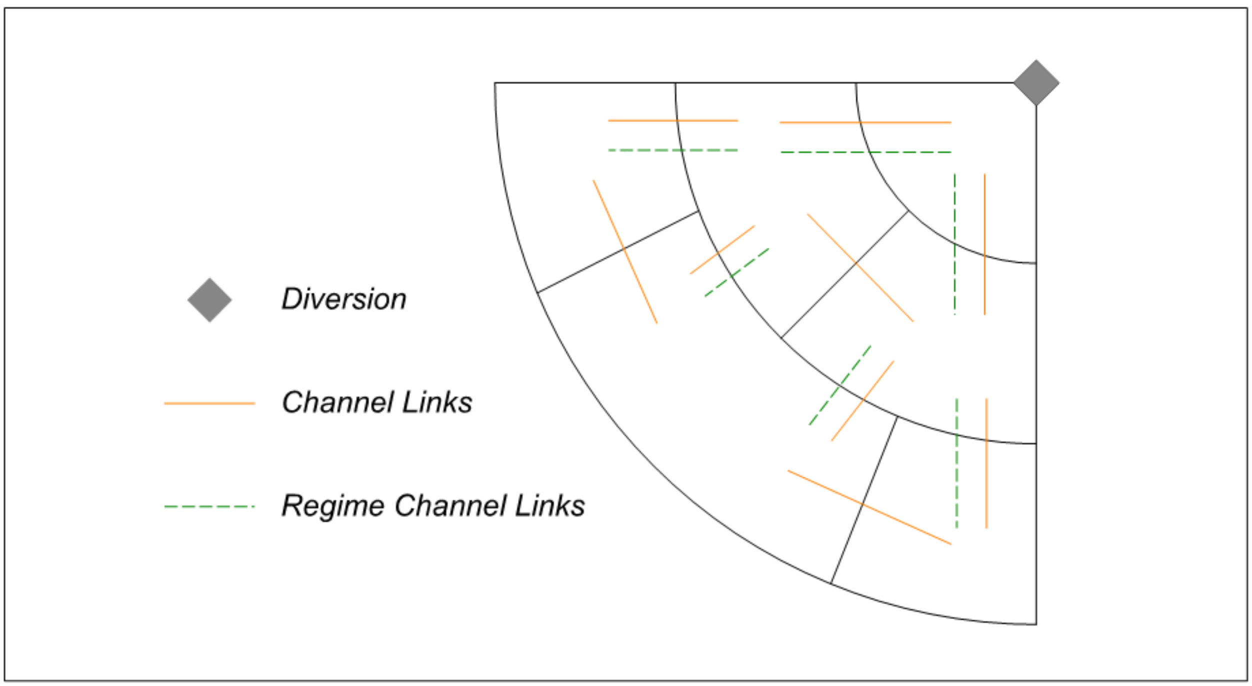

Figure 5: Overview of How Regime Channel Links were Delineated for Diversions in the ICM. The regime channel links have the same length as the standard channel links.

The ICM tracks the elevation of the water portion of the compartments – as sediment is deposited, this elevation increases. The link's invert elevation subsequently increases as well. As the link's invert elevation increases, the bank elevation remains constant, decreasing the cross-sectional area of the links over time. As the cross-sectional area of the channel link decreases, its capacity approaches the regime channel flow capacity. Once these capacities are equal, the regime channel is activated and open water sediment deposition no longer occurs in this compartment. This prevents excessive land building at the diversion outlet. Below are the Lacey Regime Equations used for estimating the flow in the regime channel links. See Attachment C3-1 for a full description.

$$P_w = K_1 Q^{1/2} \quad (13)$$

$$R = K_2 \left(\frac{Q}{f_s}\right)^{1/3} \quad (14)$$

$$S = K_3 \frac{f_s^{5/3}}{Q^{1/6}} \quad (15)$$

$$f_s = K_{fs} \sqrt{D_{50}} \quad (16)$$

where:

P_w	=	*wetted perimeter (~ link width) (m)*
Q	=	*dominant discharge (cms)*
R	=	*hydraulic Radius (~ link depth) (m)*
S	=	*channel slope (m/m)*
D_{50}	=	*median grain size in the bed (0.18 mm)*
f_s	=	*silt factor*
K	=	*Lacey Regime Coefficient (values are defined in Table 3)*

Table 3: Coefficients in Lacey Equations.

Coefficient	US (cfs)	SI (m³/s)
K_1	2.67	4.84
K_2	0.468	0.468
K_3	0.000572	0.000316
K_{fs}	8	1.587

(Note that the K_{fs} US value is 8 if D_{50} is in inches and is 1.587 if D_{50} is in millimeters.)

2.11 Composite Channels

When the boundary of two connecting compartments that are predominantly marsh intersect open water areas that are dispersed between the marsh areas, a composite channel link was used to represent the hydraulic connectivity across that boundary. Figure 3 shows an example where a composite channel link would be used. The composite link incorporates all open water areas along the boundary by summing the widths of the connections. An equivalent channel is created using this total width and an average invert. The depth is calculated similarly to the channel links. The flow through these composite channel links is estimated using Manning's Equation (Equation 1) and a roughness value (*n*) of 0.04.

When implementing marsh creation projects, some of these composite links will lose their hydraulic connectivity. As a result, the model code captures this reduction in capacity.

2.12 Maintained Open Channels

Several channels in the model domain are dredged and maintained regularly to a set depth or invert. The flow in these channels is calculated using Manning's Equation (Equation 1), similar to the channel links. The only difference is that the inverts of the maintained channel links remain the same over time and are not altered by deposition or erosion.

2.13 Negative Link Flag

In preparation for proposed diversion projects and barrier island breaches, certain links were created between ICM-Hydro model compartments to allow for possible future connectivity. These links were delineated in the domain and assigned the necessary attributes, with one exception. Rather than providing a link type number from 1 through 12, these links were given a negative number from -1 through -12, depending on its characteristics. For instance, a regime channel connecting two delta grid compartments for a potential diversion project was initially assigned type -10. The model does not calculate flow for these links until the -10 is made into a +10, at which point that link will be activated. The activation of links with a negative assigned type is accomplished in the higher-level ICM Python program call by multiplying the link type number by -1 at the start of the model year in which it should be activated. Similarly, if a link needs to be deactivated, say when a ridge restoration project completely covers the waterways of a previously open area, the model will multiply the link type by -1 to deactivate it from 1 to -1.

2.14 Direction of Flow

In the links input file, the modelers assigned the upstream and downstream compartments for each link. These are hard-coded in the model and are arbitrary. The direction of flow factor, Z, is applied as a means of establishing positive or negative flow depending on if the designated upstream compartment actually has the higher stage. If the upstream compartment does have the higher stage, then Z is +1. If not, then Z is -1 which means the upstream compartment is receiving flow from the downstream compartment.

3.0 References

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