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Implementation of Structures in the CMS: Part II, Weir

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the mathematical formulation, numerical implementation, and input specifications of weir structures in the Coastal Modeling System (CMS) operated through the Surface-water Modeling System (SMS). A coastal application at Rudee Inlet, Virginia is provided to illustrate the implementation procedure and demonstrate the model capability.

INTRODUCTION: A weir is an overflow structure built across a river or an open channel, allowing water to flow over the top. Weirs are commonly used for flow and flooding control and salinity and sediment management. Weirs are also constructed as nearshore coastal structures, such as weir jetties, to control longshore sediment transport, stabilize channel morphology, and protect harbors and navigation channels (Figure 1). In coastal applications, weirs represent unique features of solid structures and it is necessary to incorporate the structures into coastal hydrodynamic and sediment transport modeling systems.

Figure 1. (a) Coburg Lake, Victoria (Australia) (http://en.wikipedia.org/). (b) Rudee Inlet, VA.

COASTAL MODELING SYSTEM: The CMS, developed by the Coastal Inlets Research Program (CIRP), is an integrated suite of numerical models for simulating water surface elevation, current, waves, sediment transport, and morphology change in coastal and inlet applications. It consists of a hydrodynamic and sediment transport model, CMS-Flow, and a spectral wave model, CMS-Wave (Sanchez et al. 2011a; Sanchez et al. 2011b; Lin et al. 2011). Both are described in Part I of this series (Li et al. 2013).

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MATHEMATICAL FORMULATION: Two approaches are developed to implement weir structures in the CMS. In the first approach the standard weir equation for a rectangular cross-section is introduced in the model as follows (HEC 2010):

$$Q = C_{df} C_w L_w h^{1.5} \tag{1}$$

where Q is the flow rate over the weir crest, C_w is the weir coefficient, L_w is the weir crest length, h is the upstream water depth above the crest, and C_{df} is the submergence correction factor (also referred to as the drowned flow reduction factor). A definition schematic for both the free flow and submerged flow conditions is provided in Figure 2.

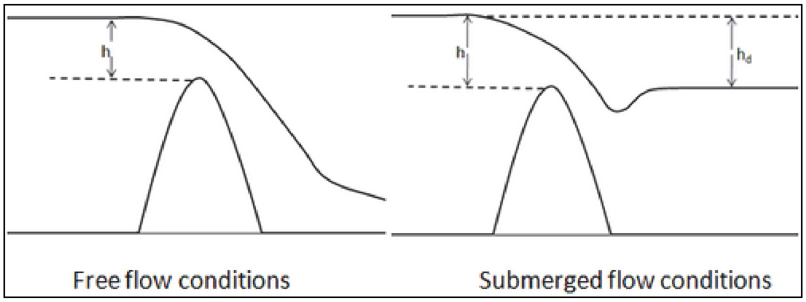


Figure 2. Schematic showing weir flow conditions.

To obtain a non-dimensional weir coefficient, Equation (1) can be re-written as (Reed and Sanchez 2011)

$$Q = C_{df} C'_w \sqrt{g} L_w h^{1.5} \tag{2}$$

where $C'_w = C_w / \sqrt{g}$. Ranges for C'_w were suggested in HEC (2010). For a sharp-crested weir, it is between 0.55 and 0.58, and a broad-crested weir between 0.46 and 0.55.

The submergence coefficient (C_{df}) is determined using different methods. For a sharp-crested weir, the Villemonte formula is used,

$$C_{df} = \left[1 - \left(\frac{h_2}{h_1} \right)^{1.5} \right]^{0.385} \tag{3}$$

where h_1 and h_2 are the upstream and downstream water levels above the weir crest elevation, respectively. For a broad-crested weir, C'_w is calculated as

$$C_{df} = \begin{cases} 1 & h_2/h_1 \le 0.67 \\ 1 - 27.8(h_2/h_1 - 0.67)^3 & h_2/h_1 > 0.67 \end{cases} \tag{4}$$

For a spillway-type weir, C_{df} is obtained by fitting a curve to data (Reed and Sanchez 2011),

$$C_{df} = 1 - \exp\left(-8.5\frac{h_d}{h_1}\right) \tag{5}$$

Super-critical flow conditions occur when the tail-water elevation is sufficiently low. Under these conditions, the submergence coefficient, C_{df} is equal to 1.0.

The second approach treats the structure cells as other internal cells by adding the x- and y-components of the resistance force terms M_x and M_y induced by the weir structures in the depth-averaged momentum equations. The resistance forcing is represented by a quadratic drag law and the Manning's (n) needs to be specified as the drag coefficient.

NUMERICAL IMPLEMENTATION: A specially designed implicit scheme is developed to couple the flow computations of the upstream and downstream of weir structures (Wu 2012). Multiple weirs can be specified in the CMS and each weir is implemented on a line of cells (cell string), as shown in Figure 3. The model assumes the same fluxes across the upstream and downstream interfaces of each weir cell, and the flux is calculated with the following equation that is modified from Equation (2):

$$q = C_{df} C'_w C_{wl} \sqrt{g} h^{1.5} ds \tag{6}$$

where ds is the length of the face upstream or downstream of a weir cell, and C_{wl} is a coefficient of distribution of flow discharge over the cells of each weir structure. Since $\sum q = Q$, the following constraint should be applied to the distribution coefficient, C_{wl}:

$$\sum C_{wl} ds = L_w \tag{7}$$

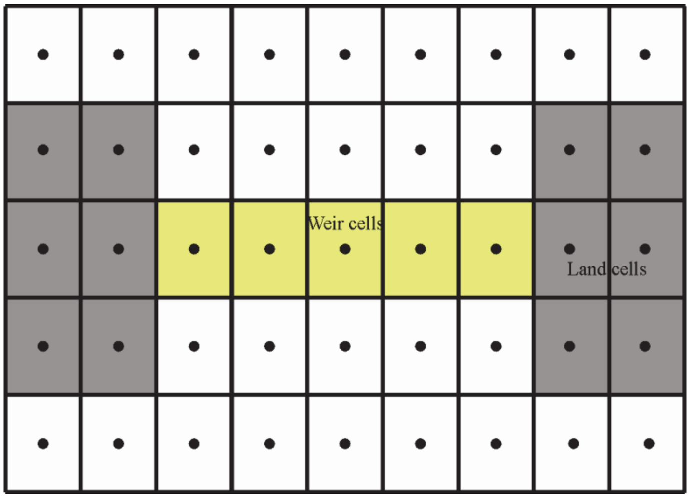


Figure 3. CMS grid with weir cells.

where the summation is applied over all the cells of each weir structure. If a constant C_{wl} is assumed, $C_{wl} = L_w / \sum ds$. One may also specify different values for C_{wl} on the cells according to their locations, bottom elevations, etc. For example, a smaller value can be given to the cells near the banks, and zero for those cells where the weir is blocked or inactive.

The implicit CMS-Flow model uses the SIMPLEC algorithm to solve the continuity and momentum equations (Wu et al. 2011). The flux (q) in Equation (6) is calculated using an implicit scheme by expanding q to a first-order Taylor series and deriving the flux and water level corrections. In the simulations of salinity or sediment transport with weirs, the salinity and suspended sediment will be transported over weir structures, but the bed load will be trapped.

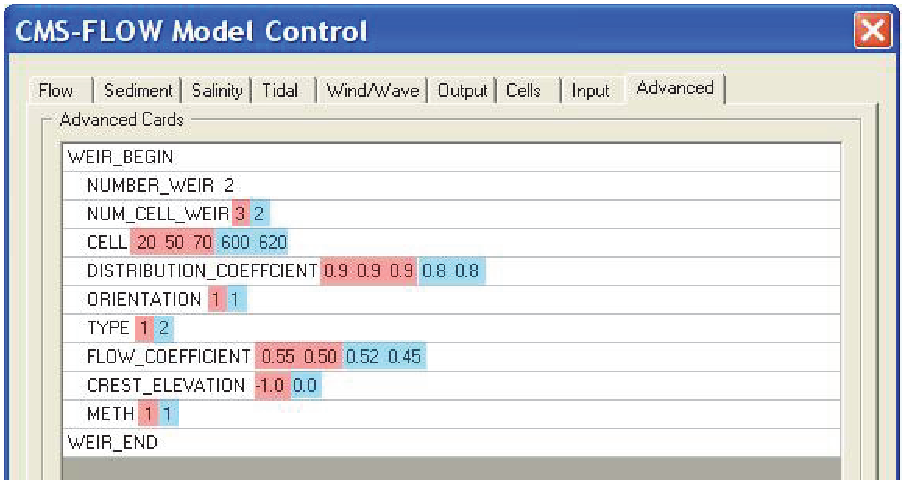
INPUT SPECIFICATIONS: An advanced card is designed for the specifications of weir structures (Wu 2012) by using the modular format in the SMS-CMS interface, which starts with “WEIR_BEGIN’ and ends with “WEIR_END”. A description of the weir parameters is shown in Table 1.

Table 1. Specifications of weir parameters in the CMS.

Input	Format	Note
Number of Weir	[card=NUMBER_WEIR] [name=numweir, type=integer]	Number of weir structures
Cell ID	[card=NUM_CELL_WEIR] [name=idweir, type=integer]	IDs of cells occupied by all weir structures (the ID is the cell counter on the flow grid)
Distribution Coefficient	[card=DISTRIBUTION_COEFFICIENT] [name=CoefWeirLateral, type=float]	Lateral distribution coefficient Cwl
Orientation of Weir	[card=ORIENTATION] [name=OrientWeir, type=float]	Orientation of weir, defined as the direction of sea side: 1=north, 2=east, 3=south, 4=west
Type of Weir	[card=RADIUS] [name=WeirType, type=float]	Type of weir: 1=sharp-crested, 2=broad-crested
Flow Coefficient	[card=FLOW_COEFFICIENT] [name=CoefWeir, type=float]	A pair of coefficients, C'w, for flow over weir from the bay to sea side and from the sea to bay side
Weir Crest Elevation	[card=CREST_ELEVATION] [name=ElevWeir, type=float]	Crest elevation of weir relative to the Mean Water Level (positive is upward)
Method	[card=METH] [name=MethWeir, type=integer]	Method to calculate the flux over weir: 1=Approach 1, 2=Approach 2

Similar to the specifications for culvert structures (Li et al. 2013), weir structures are divided into segments (number of weirs), and each segment consists of the IDs of cells occupied by one weir structure. For example, the simulation case with two weir structures, A and B, are considered at this point. Weir A distributes on the cells with ID numbers 20, 50, and 70, and weir B distributes on the cells with ID numbers 600 and 620. Therefore, the ID array for the specifications consists of cells 20, 50, 70, 600, and 620. The first 3 elements are IDs of weir A’s cells, and the last two elements are IDs of weir B’s cells.

Assume the coefficient (C_{wl}) has a value of 0.9 on all the three cells of weir A, a value of 0.8 on all the two cells of weir B. The other properties of weir A are C'_w =0.55 for flow from bay to sea side and 0.50 for flow from sea to bay side, crest elevation of -1.0 (ElevWeir=-1.0), sea side facing to north (OrientWeir=1), and sharp-crested (WeirType=1). The other properties of weir B are C'_w=0.52 for flow from bay to sea side and 0.45 for flow from sea to bay side, crest elevation of 0.0 (ElevWeir=0.0), sea side facing to north (OrientWeir=1), and broad-crested (WeirType=2). Approach 1 (MethWeir =1) is used for both weirs. The advanced card is given in Figure 4, with red marked for weir A and blue for weir B.



```
WEIR_BEGIN
  NUMBER_WEIR 2
  NUM_CELL_WEIR 3 2
  CELL 20 50 70 600 620
  DISTRIBUTION_COEFFCIENT 0.9 0.9 0.9 0.8 0.8
  ORIENTATION 1 1
  TYPE 1 2
  FLOW_COEFFICIENT 0.55 0.50 0.52 0.45
  CREST_ELEVATION -1.0 0.0
  METH 1 1
WEIR_END
```

Figure 4. Weir Specifications in the SMS/CMS.

WEIR JETTY AT RUDEE INLET, VIRGINIA: Rudee Inlet, Virginia, is located on the US Atlantic coast, approximately 7.5 miles south of the Chesapeake Bay Entrance. Navigation through the inlet is protected by a rubble mound jetty on the northern side and a weir jetty on the southern side (Figure 1). In this application, the weir jetty is specified in the CMS and the hydrodynamic simulations demonstrate the implementation of weir structures under the influence of tide and waves.

Figure 5 shows the CMS domain and the weir jetty at Rudee Inlet. Based on the measurements, the crest elevation of the weir jetty is not uniform, which is -0.22 m from the mean sea level at the offshore end and 0.0 m at the nearshore end. Therefore, two weirs are specified to represent the weir jetty in the CMS (blue bars in Figure 5). Three locations (points 1, 2, and 3 in Figure 5) are selected north of the weir jetty inside the inlet, and water depths at the locations are 2.1, 1.7, and 1.2 m, respectively. Time series of fluxes are compared for the numerical experiments with the weir structures.

Figure 6 shows the specifications of the weir jetty at Rudee Inlet in a SMS/CMS advanced card. Two weirs are specified for this simulation, each consisting of 8 cells. The black color marks the nearshore part and the blue color the offshore part of the weir jetty, which correspond to the black and blue bars in Figure 5, respectively. The flow regime over a weir jetty in coastal zones is usually different from that over a river weir because of the water level difference that a weir jetty or a river weir creates between the upstream and downstream of the weir. Using Approach 1, detail features of a weir structure need to be specified. The CMS can produce more stable results and better incorporate supercritical flow around a weir into model simulations. Therefore, as shown in Figure 6, this approach is used to calculate flows over the Rudee Inlet weir jetty. A weir coefficient, C'_w, of 0.46 at weir jetty cells is specified for flows from bay to sea side and from sea to bay side, and a distribution coefficient over the weir cells is 0.95. This setup is also treated as the base case in the study. With other experiments all weir specifications are listed in Table 2. The fluxes at points 1, 2, and 3 are compared between different cases (base, and S1 through S5).

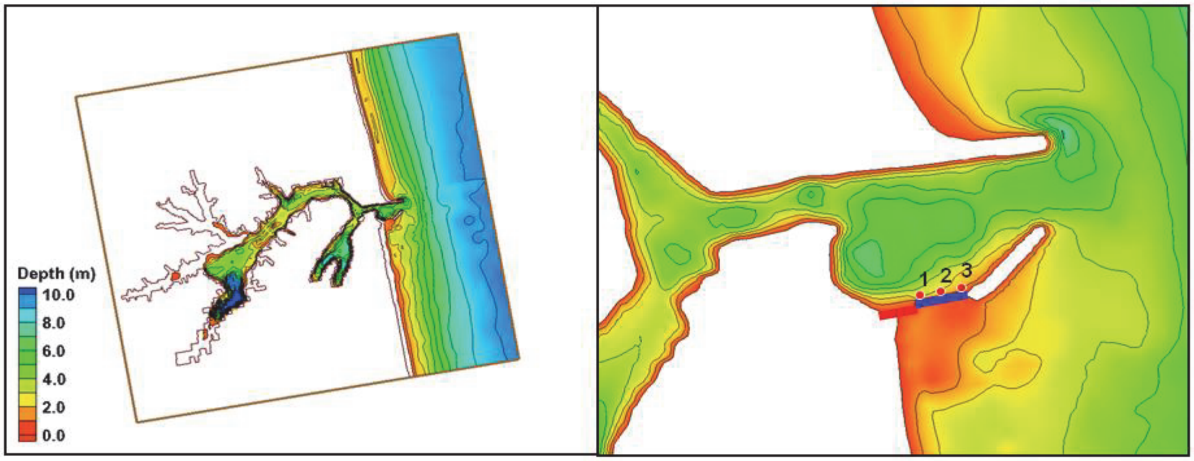
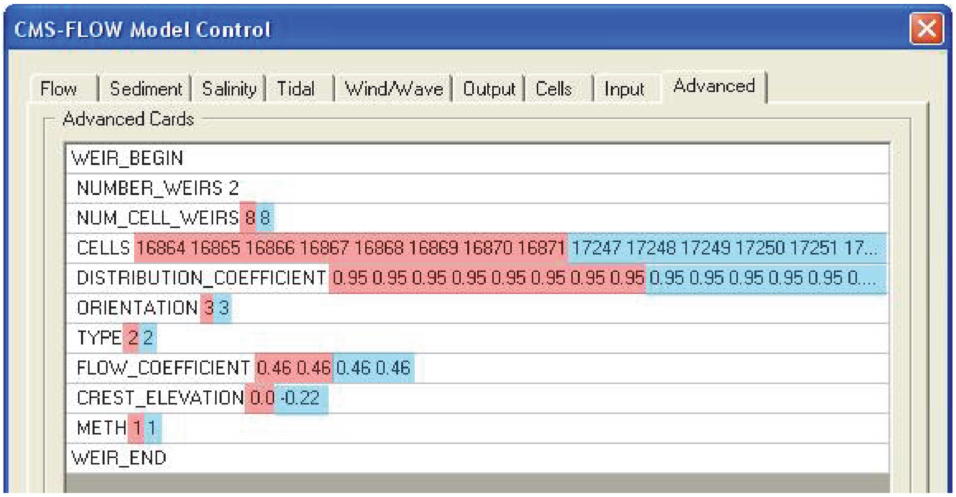


Figure 5. CMS domain: Rudee Inlet and the surrounding area. The black and blue bars denote the weir jetty and the red dots represent the selected time series locations.



```
WEIR_BEGIN
 NUMBER_WEIRS 2
 NUM_CELL_WEIRS 8 8
 CELLS 16864 16865 16866 16867 16868 16869 16870 16871 17247 17248 17249 17250 17251 17...
 DISTRIBUTION_COEFFICIENT 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0.95 0...
 ORIENTATION 3 3
 TYPE 2 2
 FLOW_COEFFICIENT 0.46 0.46 0.46 0.46
 CREST_ELEVATION 0.0 -0.22
 METH 1 1
WEIR_END
```

Figure 6. Weir specifications for the weir jetty at Rudee Inlet.

Table 2. Weir specifications in the CMS.

Weir Simulation	Weir Parameter				
	Distribution Coefficient	Weir Coef/ Manning (n)	Crest Elevation (m)	Weir Type	Approach
Base	0.95	0.46	0.0/-0.22	Broad-crested	1
S1	0.76	0.46	0.0/-0.22	Broad-crested	1
S2	0.95	0.55	0.0/-0.22	Sharp-crested	1
S3	N/A	0.05	0.0/-0.22	N/A	2
S4	N/A	0.10	0.0/-0.22	N/A	2
S5	No Weir				

Using the weir flow equation (Approach 1) one may specify different values for the distribution coefficient on the cells according to their locations, bottom elevations, etc. For example, a smaller value can be given to the cells near the banks, and zero for those cells where the weir is blocked or inactive. As a sensitivity test, the distribution coefficient is reduced by 20 percent over the weir cells. Figure 7a shows that flux decrease corresponding to the reduced distribution coefficient is not significant in simulation S1. In the CMS implementation, different weir coefficients are specified for the weir structure design, sharp-crested or broad-crested weir. The lowest value in the coefficient range is used for the sharp-crested (0.55) and broad-crested (0.46) weir, respectively; the flux comparison between these two designs is shown in Figure 7b. Corresponding to the broad-crested weir is a smaller weir coefficient, which should result in relatively larger fluxes at the selected locations. Again, the flow over the structures is not sensitive to change in the weir coefficient.

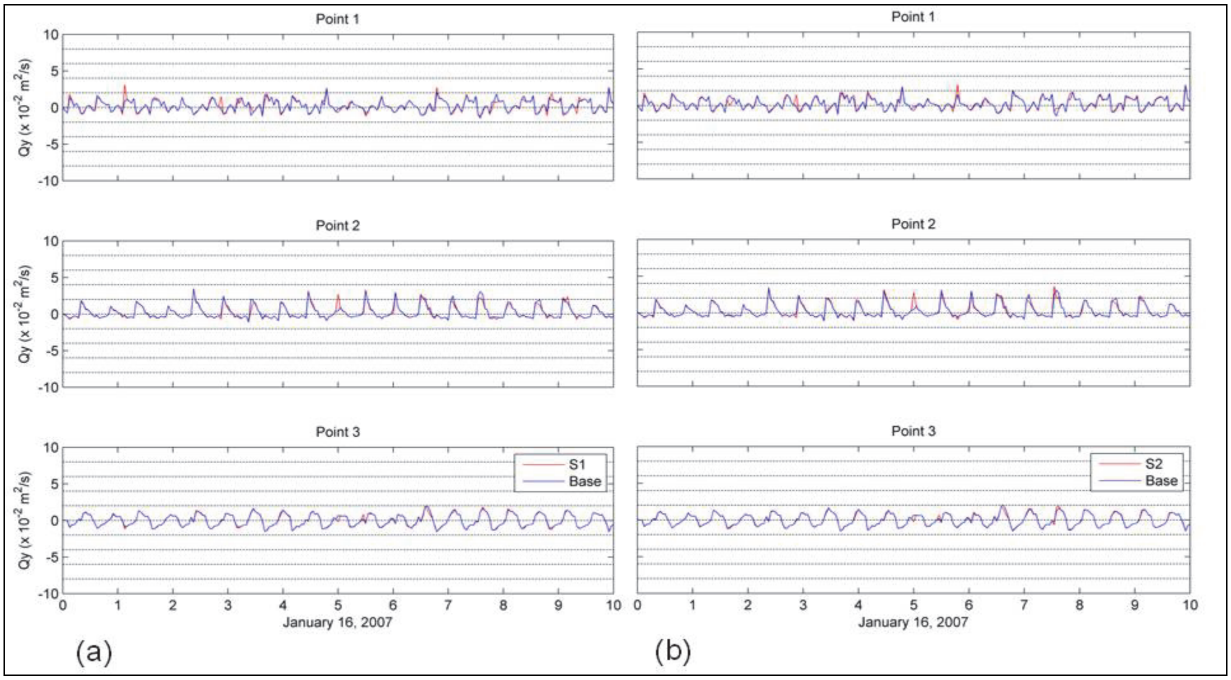


Figure 7. Volume flux comparisons between the base case and simulations S1 and S2 at the bayside of the weir jetty, Points 1, 2, and 3.

For Approach 2, Manning's (n) is increased from 0.05 in simulation S3 to 0.1 in simulation S4 over the weir cells and the flux results at points 1, 2, and 3 show corresponding decreases as shown in Figure 8a. Comparing the calculations by Approaches 1 and 2 (Figure 8b), the results of Approach 1 (base case) show stable, more appropriate flux calculations at the three selected locations, especially at point 1 where the crest elevation is higher than at points 2 and 3, and a smaller weir flow should be obtained based on equation (2). On the other hand, Approach 2 calculates much larger volume fluxes at point 1 and shows that changes in fluxes are correlated with total water depths from the nearshore to offshore locations.

Considering that Approach 2 calculates the weir flow in the momentum equation, the results by this approach should be very close to those by removing weir structures in the CMS, i.e., the calculations over the structures are conducted through the model's wetting/drying capability.

Figure 9 shows the flux comparison between simulations S3 (with weirs) and S5 (without weirs). It can be seen that the weir structures reduce the volume fluxes because of the additional resistant term in the momentum equation.

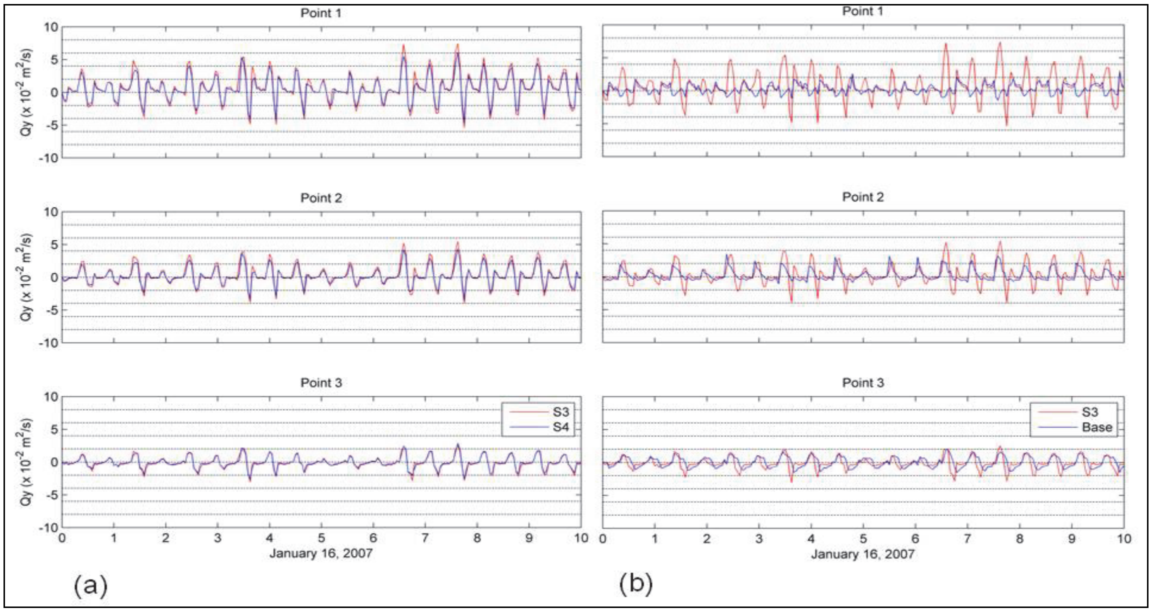


Figure 8. Volume flux comparisons between the base case and simulations S3 and S4 at the bayside of the weir jetty, Points 1, 2, and 3.

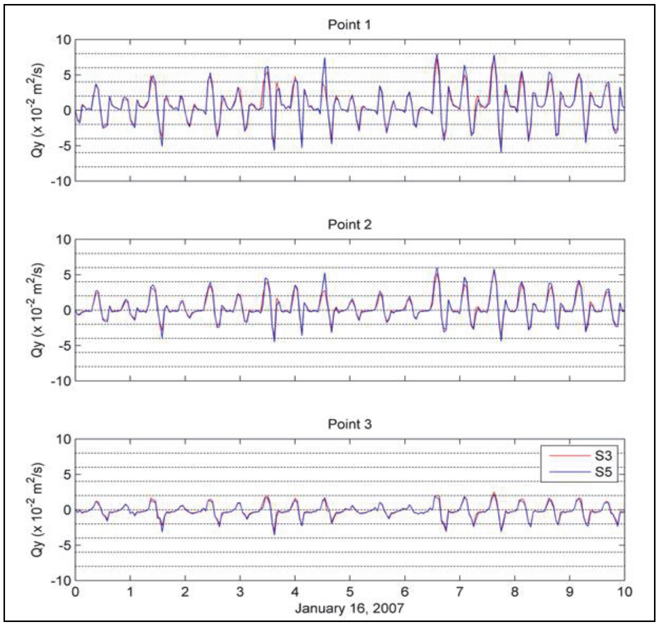


Figure 9. Volume flux comparisons between simulations S3 and S5 at the bayside of the weir jetty, Points 1, 2, and 3.

SUMMARY: Weir structures are incorporated into the CMS and the implementation procedure was described in this note. The application of the algorithms and selection of the parameters in the

CMS are demonstrated and flows over a weir jetty are compared via the volume fluxes at the bayside of Rudee Inlet. The results indicate that the weir equation is more appropriate in the CMS implementation of weir structures.

ADDITIONAL INFORMATION: This CHETN was prepared as part of the CIRP and was written by Dr. Honghai Li (Honghai.Li@usace.army.mil, voice: 601-634-2840, fax: 601-634-3080), Alejandro Sanchez of the US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Dr. Weiming Wu of University of Mississippi, and Dr. Christopher W. Reed of URS. The CIRP Program Manager, Dr. Julie D. Rosati (Julie.D.Rosati@usace.army.mil), the assistant Program Manager, Dr. Zeki Demirbilek, and the Chief of the Coastal Engineering Branch at CHL, Dr. Jeffrey P. Waters, reviewed this CHETN. Files for the study may be obtained by contacting the author. This CHETN should be cited as follows:

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An electronic copy of this CHETN and I/O files for the example are available from: *http://chl.wes.army.mil/library/publications/chetn/*

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