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Non-orthogonal Channel and Reservoir Routing in GSSHA

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PURPOSE: The purpose of this System-Wide Water Resources (SWWRP) technical note is to describe the development, implementation, and applicability of enhanced channel routing for the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model (Downer et al. 2005).

INTRODUCTION: The GSSHA model is a continuous, physics based, distributed hydrologic model intended for general hydrologic/hydraulic analysis. A previous limitation of the model has been the inability to simulate reservoirs and hydraulic structures that typically control the flow from reservoirs. Reservoirs are widespread in many watersheds such that the ability to simulate them is critical to basic hydrologic analysis. In many hydrologic studies, the focus is on the reservoirs. The GSSHA model has been modified to include reservoirs and many common hydraulic structures that control flow from reservoirs, as well as flow at road crossings, flow through embankments, and other flow altering features.

Another previous limitation of the GSSHA model has been the need to represent the stream network in an orthogonal fashion. That is, stream cells had to be aligned with overland flow cells, in the x- and y-directions, and be the same size as the stream cells (blocks in Figure 1). This requirement limits the accuracy of the stream network to the accuracy of the overland grid. Requiring orthogonal channels also tends to make the stream segments longer in the model than they are on the ground, forcing the use of less physical parameters for channel flow. These limitations have been eliminated by allowing non-orthogonal stream networks to be included in the GSSHA model. That is, stream cells do not have to correspond to overland flow cells, and do not have to be aligned in the x- and y-planes (lines in Figure 1). Along with the new freedom of channel alignment comes the ability to decouple the stream cells discretization from the overland flow plane discretization and to vary the channel discretization throughout the network.

METHODOLOGY

Non-orthogonal Channels: The concept of non-orthogonal channels is simple. Streams can be constructed independent of the overland flow and groundwater grids. Development of the network by the user is also simple. Tools in the Watershed Modeling System (WMS) allow the user to import digital line graph (DLG) stream files into the model and convert them to a stream network, and/or be used to trace the stream network with mapping feature tools. Once the stream network is constructed, each stream reach (link in GSSHA) is subdivided into cells (nodes) for computational purposes. Channel properties, cross section, roughness coefficient, bed properties, etc., are assigned to each cell.

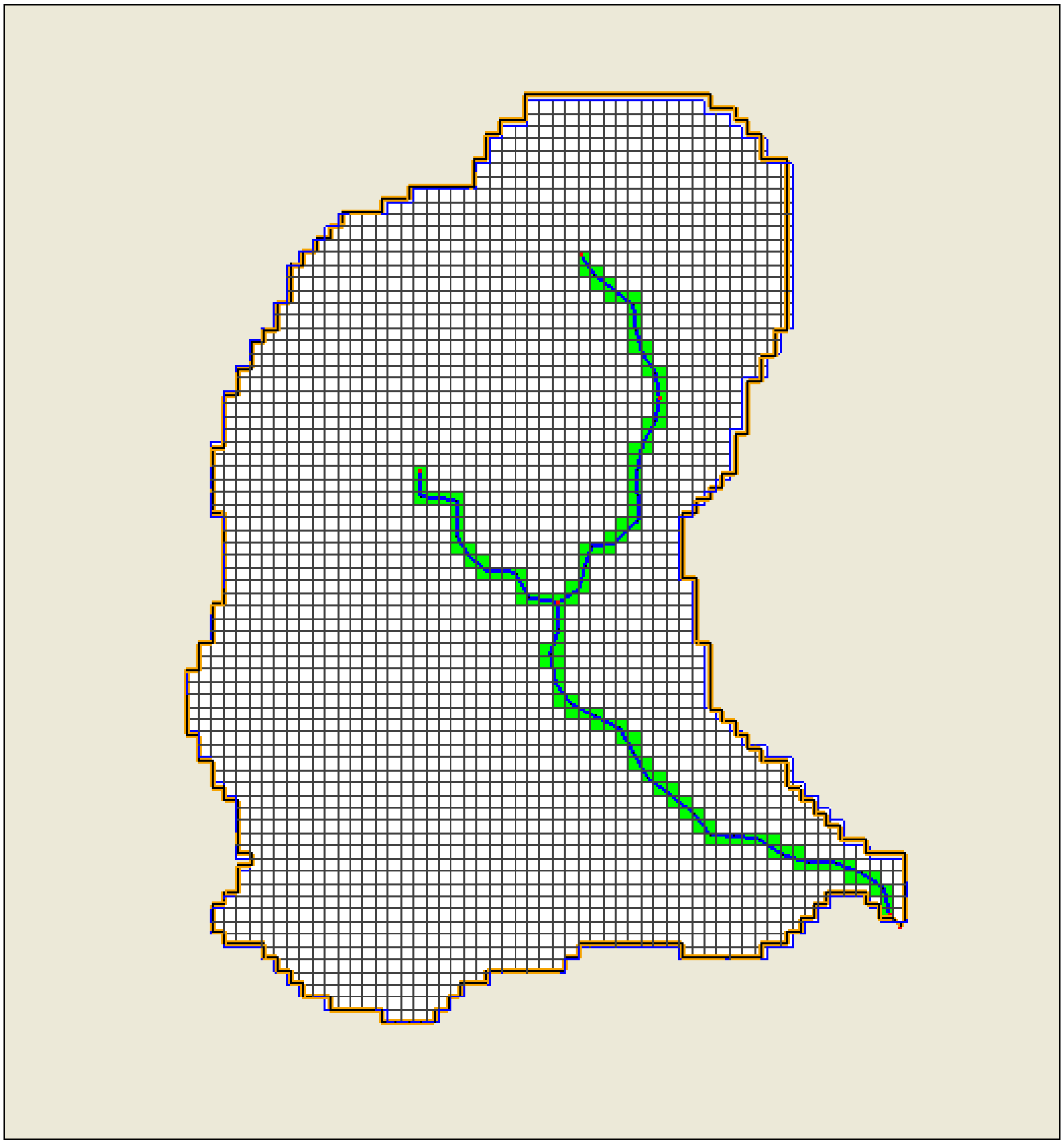

Figure 1. Orthogonal (blocks) versus non-orthogonal (lines) stream channel representation.

With the input files created, GSSHA does the complex work of locating the stream network within the grid network and computing the interactions with the gridded solutions, overland flow, and groundwater. Compared to the orthogonal channels, this task is much more complicated as stream cells and grid cells are neither aligned nor of the same size. Internal to GSSHA, calculations must be performed on stream segments (fragments of stream cells within grid cells). The position of the segments in the grid cell must be located by looping through the stream network by segment, and matching the segment to the appropriate grid cell. The need to continually look for and locate the stream cells within the grid for tasks such as computing lateral inflow to the channel and groundwater interaction, results in increased computation time. This increase in computation time may be offset by increasing the size of stream nodes, which are no longer constrained by the size of the overland flow cells.

The primary advantage of the non-orthogonal (vector) channel approach is that channel lengths and slopes are accurately described. The requirement that channels be aligned with grid cell faces leads to overestimation of channel lengths and underestimation of channel slopes, which subsequently require that smaller values of the Manning roughness coefficient n be used for correct hydrograph timing. The non-orthogonal approach allows the use of accurate Manning's n that are transferable to/from other one-dimensional (1-D) channel routing codes.

Channel Routing Scheme: The previous channel routing scheme in GSSHA was inherited from the CASC2D model (Ogden and Julien 2002). That scheme was a simple two-step finite volume solution. As described by Downer and Ogden (2006), the original scheme in CASC2D was modified to improve stability and accuracy, but the basic method remained the same. Flows are calculated based on the friction slope and volumes calculated based on the channel flows along with sources and sinks: lateral inflow, groundwater recharge, pumping, etc. This simple scheme proved useful for many purposes, especially when enhanced with a variable time-step based on the Courant number (Downer and Ogden 2006).

However, the addition of lakes and complicated structures introduces shocks into the stream network. Introducing shocks into the system tends to cause oscillations around the shocks. Unless these oscillations are damped the oscillations tend to build upon themselves. While small oscillations can generally be considered harmless, oscillations that continue to grow result in negative consequences: model crashes, mass balance errors, and excessive run times incurred when the variable time-step is employed to control the oscillations.

Oscillations are related to the time-stepping and can be controlled by two basic methods: decreasing the time-step when conditions are conducive to oscillations, and employing higher order temporal schemes. Controlling the time-step to control oscillations is difficult because the oscillations are not dependent on the Courant number, but rather on changes in volume in the oscillating cells. Employing a volumetric time-step limitation on top of a Courant number limitation leads to excessive run times, with a less than satisfactory solution.

Schemes that are higher order in the temporal derivative allow accurate solutions with a larger time-step. A MacCormick (1971) type scheme was employed for the solution. The scheme employs a prediction step and a correction step.

1. Initial estimates of flows across cell faces are calculated from the friction slope.
2. Initial estimates of volumes at the end of the time-step are calculated based on the initial estimate of flows, including sources and sinks: lateral inflow, groundwater exchange, pumping.
3. These volumes are used to estimate flows at the end of the time-step.
4. The two sets of flows are averaged to compute flows at the middle of the time-step.
5. These average flows are then used to compute the volumes at the next time level.

Because of the degree of instability introduced by the reservoirs, additional steps were needed to eliminate the oscillation such that the solution becomes iterative. The flows are estimated using the procedure previously described until the areas computed from successive iterations are within a given tolerance, 0.01 m^2. The flows computed from the last iteration are used as the first estimate of flow for the next iteration. This method of iterating is known as Picard iterations. Generally only two iterations are required to meet the tolerance. The method greatly improves the solution when oscillations are prone to occur without an excessive increase in simulation time. The finite volume approach employed in GSSHA channel routing is mass conserving with or without the iterative solution.

Reservoir Operation: Reservoirs are represented in GSSHA as part of the stream network (Figure 2). The reservoir occupies space in the overland grid (Figure 2), but these grid cells are deactivated and not considered in computations for infiltration, evapotranspiration, or overland flow. In Figure 2 the reservoir is shown with the light blue line. The dark blue lines show the channel stream segments. As indicated by the contours in the figure, elevations are assigned to each cell in the overland flow plane, including those within the reservoir. The reservoir volume/area/depth relationship is derived from the elevations in these cells.

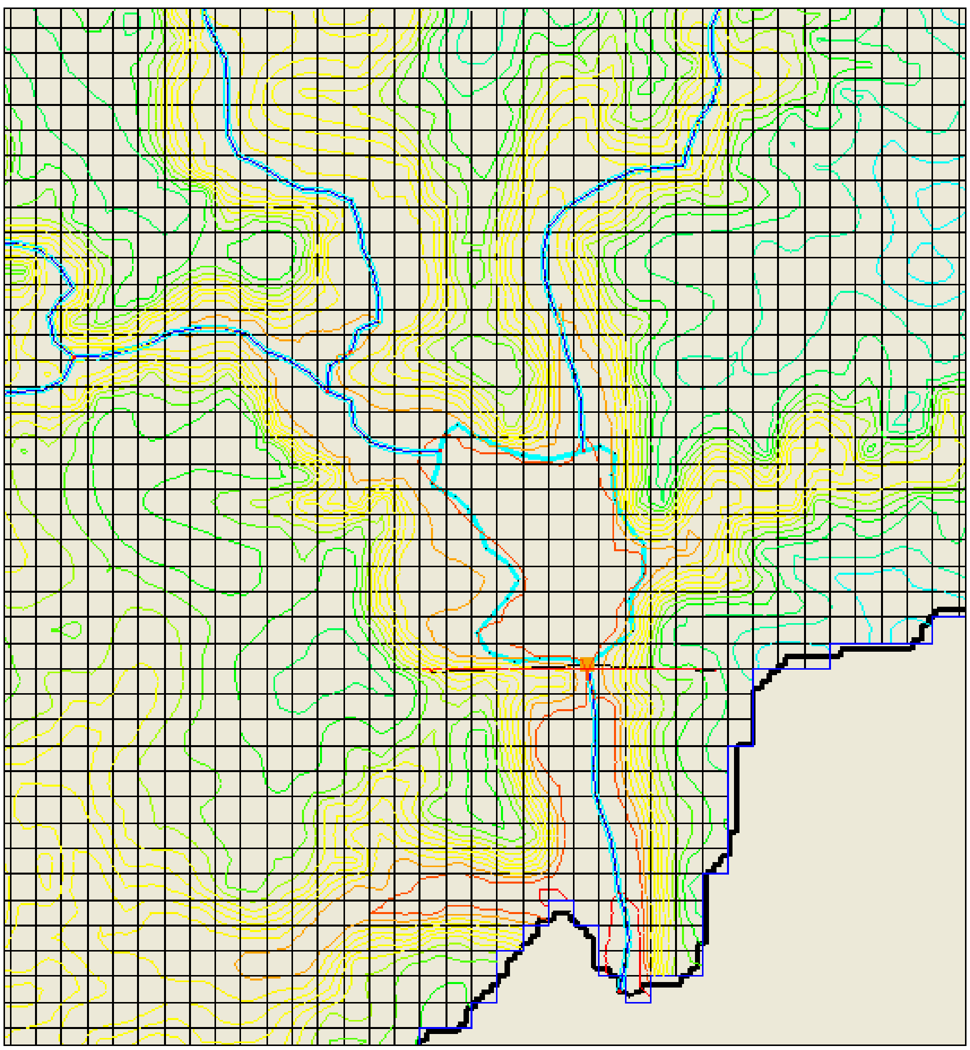

Figure 2. Reservoir representation in GSSHA stream network and 2-D grid.

Reservoirs are defined in the model by locating an outlet and then providing the minimum, maximum, and beginning water-surface elevation. During simulations, the reservoir is not allowed to exceed the maximum water surface, nor drop to levels below the minimum. If this occurs, the simulation is halted.

The reservoir represents another computational domain, in addition to the stream network, overland flow, and groundwater domains. Water, sediments, and constituents must be conserved within these domains and in the overall system. The reservoir interacts with these other domains in two ways: fluxes are passed between domains, and the reservoir domain can change in relation to both the stream network and the overland flow plane. A preprocessing exercise, usually performed with WMS, is needed to provide GSSHA with information to determine where the reservoir will reside in the overland flow plane (Figure 2). This information can also provide the model with the order adjacent overland flow cells that may become flooded as described in the next section.

Sources and sinks. Reservoirs may receive inflow from the following sources:

- **Precipitation** – all precipitation falling on cells defined as lake cells enters the reservoir. No interception occurs for these cells.
- **Inflow from upstream channels** – flow from upstream channels can be simple open channel flow or can be controlled by structures. The location of the confluence between the reservoir and the lake can change, as described here.
- **Overland flow** – overland flow is into the reservoir if the water surface on the overland flow plane is greater than the reservoir water surface. Flow is calculated using the diffusive wave calculation.
- **Groundwater** – groundwater flows into the reservoir if the groundwater surface elevation is greater than the water surface of the reservoir. The flux is controlled by the sediments under the reservoir. The depth of the sediments is specified for each reservoir for which groundwater interaction is desired. The vertical hydraulic conductivity of the sediments is defined from the soils index map. Flow is calculated based on Darcy's equation.

Reservoirs may lose water due to the following sinks:

- Outflow to downstream channels is controlled by a hydraulic structure specified for each reservoir outlet.
- Spillage to overland – When the reservoir level exceeds the level of water in an active overland cell adjacent to the reservoir, the water will flow from the reservoir back onto the overland flow grid. To put water onto overland flow plane active cells, water must be removed from the reservoir. Flow from the reservoir to the overland flow cell is calculated using the diffusive wave equation. Flow from the reservoir to the overland flow plane occurs when the reservoir is rising due to stream flow and overland flow from other adjacent cells.
- Groundwater recharge occurs when the reservoir level is higher than the water table level.
- Evaporation is calculated according to Dingman (1994) with modifications as discussed in the "Lake Evaporation" section.

Reservoir simulations. A key component of reservoirs in the GSSHA model is the ability of the reservoirs to vary in size during the simulations. Reservoirs receive inflow and provide outflow to the channel network, the overland flow plane, and the groundwater. Reservoirs also lose water due to evaporation. This gaining and losing of water results in the reservoir varying in size, and changes both the overland and channel configurations, as described here.

As the reservoir increases in size, it may capture cells from the overland flow domain. This occurs when the reservoir water-surface elevation is greater than an adjacent overland flow cell's water-surface elevation. When an overland flow cell is captured by the reservoir, the cell is removed from overland flow computations. To maintain mass conservation, any water on the newly captured overland cell must be added to the reservoir volume. When all the overland flow cells corresponding to all the fragments of a stream node are captured by the reservoir, that stream cell is removed from the channel network. To maintain mass conservation, any water in a captured stream node must be added to the reservoir volume. Numerical stability requires that stream cells be taken in order from the confluence with the lake.

As the reservoir decreases in size, the elevation of the reservoir surface may drop below the ground surface elevation of some grid cells. When this occurs, these cells are taken from the lake. The cells are activated in the overland flow plane, so that infiltration, evapotranspiration, interception, and overland flow resume in the cells. If all the overland flow cells that compose a stream cell are released by the reservoir, then the stream cell is also released from the reservoir. To make the stream water-surface elevation smooth, water is taken from the reservoir and added to the new stream cell.

Reservoir evaporation. Evaporation from the lake is calculated by a simplified version of the Dalton-type equations developed by Dingman (1994). The equation to govern instantaneous free water body evaporation for lakes, as shown by Dingman, is:

$$E = K_e \upsilon_a \left(e_s - e_a\right) \tag{1}$$

where:

E = evaporation rate
K_e = water vapor vertical transport efficiency coefficient due to turbulent eddies in the wind
υ_a = wind speed
e_s = air saturation vapor pressure at the current temperature of the lake surface
e_a = air vapor pressure

With this approach there are two main concerns. The first concern is that this equation is for instantaneous, not average, evaporation rates. The second concern is that the GSSHA model includes neither measurements nor estimates of lake surface temperature.

In GSSHA, evapotranspiration is calculated on an hourly basis using hourly hydrometeorlogical data. In citing studies by Jobson (1972), Dingman indicates that errors in the estimate of lake evaporation obtained by averaging the instantaneous measurements over periods up to one day were on the order of 10 percent. As the averaging period was reduced, errors were also reduced, with errors generally less than 5 percent at a 3-hour averaging period. Based on these results, the instantaneous estimates evaporation used in GSSHA should be within 5-10 percent of the actual hourly values.

The lack of a lake surface temperature is more problematic. Using only information currently available in the model, the air temperature is assumed to be the lake surface temperature. The impact of this assumption was analyzed by computing a difference in predicted evaporation rate for a specified data set with and without the application of this assumption to Equation 1. The specified data set included a range of lake temperature, air temperature, and relative humidity values. These sets of values were used to compute air vapor pressure and air saturation vapor pressure at the lake temperature, as used in Equation 1. The air temperature ranged from 10 to 22 °C, and the lake temperature was set to range +/- 3 °C of the air temperature, with relative humidity values of 0.4, 0.6, and 0.8 for each air and lake temperature combination.

For each set of values of air temperature, lake temperature, and relative humidity the estimated evaporation rate was computed two ways using Equation 1. The first method used the given air and lake temperatures to determine the actual predicted evaporation rate. The second method applied the assumption that the lake and the air were at the same temperature by substituting the air temperature for the lake temperature. The difference between these resulting evaporation values determined the error inherent in this assumption for each data point. Generalizing the results, the assumption that the lake temperature is equal to the air temperature will produce significant overestimations of lake evaporation, by as much as 300 percent, when the lake is cooler than the air with high relative humidity, as may occur during summer afternoons, and underestimations of lake evaporation from 0-60 percent under other conditions.

The final equation used in GSSHA is as follows:

$$E = K_e v_w \left(1 - W_a\right) e_a \tag{2}$$

where:

W_a = relative humidity
K_e = $1.69 \times 10^{-4}\ A_l^{-0.05}$ (Dingman 1994)
A_l = lake surface area as derived from the current number of cells the lake occupies.

This approach should be used for now as a rough estimate and should be an area of improvement in the future.

Hydraulic Structures: Hydraulic structures are found in all but the most natural of watersheds. Hydraulic structures simulated in GSSHA include both passive types, such as culverts, and active structures with control systems, such as gates. Both types can have significant effects on both the quantity and timing of flow. The current version of GSSHA has the following structure types and related features.

- Broad crested weirs
  - Horizontal
  - Parabolic
- Culverts
  - Circular
  - Rectangular
- Active control structures
  - Rule curve
  - Scheduled discharge
- Generic structure rating curve

Broad crested weirs can have either horizontal or parabolic crests. Detention basins often have horizontal weirs as the outlet control. Parabolic crests are excellent for describing the overflow characteristics of highway sag-vertical curves that become hydraulic controls during roadway overtopping in extreme events. Flow over weirs can be in either direction, depending on water levels on either side of the weir. Furthermore, weirs can have different discharge coefficients depending upon the flow direction, which accounts for asymmetry of the structure. Weir submergence is accounted for if the tailwater depth is high enough to affect the flow rate over the weir.

Flow through circular or rectangular culverts is simulated considering all possible flow conditions (Chow 1959). These include: inlet control, outlet control, or barrel control, in steep, mild, or adverse-sloped culverts. In the case of steep or hydraulically short culverts with low tailwater, inlet control is simulated by solving for the critical depth at the culvert inlet. If the headwater depth exceeds 1.5 times the culvert diameter for circular culverts or height in the case of rectangular culverts, flow will transition to orifice inlet control. Rising tailwater elevations can force the flow to transition to barrel control. Flow through hydraulically-long culverts with barrel control is calculated using the Manning equation. Flow through culverts with adverse slopes is assumed to be governed by outlet control. Finally, if the tail water depth rises above the headwater depth, reverse flow occurs. Culverts can have different inlet loss coefficients depending upon the flow direction.

Stormwater detention basins and reservoirs in the channel network must have a hydraulic structures link specified at the outlet to regulate the flow from the basin or reservoir. To allow maximum flexibility in the simulation of these types of hydraulic features, active control structures can be specified at the outlets. The active control structure types are:

- Rule curves - discrete discharge versus stage relationship
- Scheduled releases – time series of specified discharges typically associated with releases for irrigation or power generation

If the structure at the outlet of a detention basin or road crossing, etc., is a passive structure other than weir or culvert, the user can specify points on the rating curve (depth, discharge). The use of a generic rating curve does not allow for submergence effects. The rating curve points are linearly interpolated to calculate the discharge based on the upstream depth only.

Structures are added to the GSSHA model as a point feature "hydraulic structure link" in the channel network. Links are added anywhere structures are desired. Multiple hydraulic structure types can be assigned to a hydraulic structure link. For instance, culverts are often paired with weirs, to represent a typical channel road crossing. When the water level is below the weir crest elevation, flow passes solely through the culvert. When the water level exceeds the weir crest elevation, flow passes through the culvert and over the weir simultaneously. Adjacent structures are assumed to not interfere with each other. A hydraulic structure link can consist of any number of structure types. Different sizes and shapes of weirs and culverts may be combined, each structure having its' own elevation. This allows simulation of complex structures such as detention basins that have multiple outlets at different elevations.

APPLICABILITY: This version of the GSSHA model is intended to be used for general hydrologic/hydraulic analysis in watersheds that contain one or numerous reservoirs. The temporal variations in size and location of the reservoir can be tracked over time. The model accounts for major fluxes into and out of the reservoirs. Limitations on the use of reservoirs include the need to impose one of the hydraulic structures listed in this technical note as the reservoir outlet, and the restriction that reservoirs not merge on the overland flow plane during the simulation. The improved GSSHA model has been tested at the Eau Galle watershed in Wisconsin (Downer 2008a), and has proven its ability to simulate the watershed with a reservoir, as well the reservoir itself. This study is described in a companion tech note. The model has also been tested on the Goodwin Creek Experimental Watershed in Mississippi (Downer 2008b) and has been shown to reproduce results from previous versions of the models.

SUMMARY: The GSSHA model has been significantly enhanced by the inclusion of non-orthogonal stream networks, hydraulic structures, and reservoirs. The new channel routing code has been tested and the methods are shown to be capable of reproducing results of previous versions of the model. In addition, the methods have been applied to a watershed with features that could not be simulated with previous editions of the model. The new model is considered applicable for general hydrologic analysis in watersheds with and without reservoirs.

ADDITIONAL INFORMATION: This technical note was prepared by Dr. Charles W. Downer, research hydraulic engineer, Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC) (Charles.W.Downer@usace.army.mil), Fred L. Ogden, professor, Civil and Environmental Engineering, University of Wyoming, Dr. Justin Niedzialek, civil/hydrologic engineer, Devine Tarbell & Associates, Syracuse, NY, and Aaron Byrd, research hydraulic engineer, CHL, ERDC. The study was conducted as an activity of the Coastal Morphology Modeling and Management work unit of the System-Wide Water Resources Program (SWWRP). For information on SWWRP, please consult *https://swwrp.usace.army.mil/* or contact the Program Manager, Dr. Steven L. Ashby at Steven.L.Ashby@usace.army.mil. This technical note should be cited as follows:

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