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ABSTRACT

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) is designed for computing water surface profiles and inundation maps, but it is also able to handle flow through gated structures using a variety of equations and techniques. HEC-RAS has a small selection of built-in gate types, representing some of the more common gates that are used for controlling flow at dams and canal structures. Each gate type in HEC-RAS has a set of empirical equations that are used to compute head loss through the structure for a given flow. There are also two operational schemes that can be chosen for gates: Time Series Gate Openings, and Elevation Controlled Gates.

While the built-in gate types and operational schemes in HEC-RAS might be appropriate for some of the more common gate structures, it is quite common to have a gate system or other flow control device that simply does not fit within the confines of the built-in techniques in HEC-RAS. In these cases, the user has the option to take advantage of some lesser known techniques both within HEC-RAS and by external applications.

This paper will discuss four gate and operation strategies that can be used with HEC-RAS that allow the user to handle any flow control scheme possible. These include Navigation Dams, User Defined Curves, Rules, and the HECRASController API.

Keywords: *HEC-RAS, Gate, Operation, Rules, Automation, Rating Curve*

1. INTRODUCTION

HEC-RAS is a software application designed to perform one and two-dimensional hydraulic calculations for a full network of natural and constructed channels. Although its original and primary intent is to develop water surface profiles and inundation maps in rivers and streams, additional functionality added over the years has allowed HEC-RAS to be used successfully in simulating reservoir operations, specifically the operation of different types of flow control gates. HEC-RAS computes unsteady flow water surface profiles using conservation equations developed for gradually varied flow conditions. The rapidly varied flow that occurs in and around gate structures cannot be explicitly modeled using the HEC-RAS unsteady flow solver. Therefore, in HEC-RAS, modelers typically use built-in gate equations and/or rating curves to determine energy loss through gate structures.

HEC-RAS's built-in gate types are limited to sluice gates, radial gates (i.e. tainter gates), and overflow gates (both open air and closed top). Specific equations are used for each of these gates at three different flow regimes: low flow, free flow, transitionary flow, and fully submerged flow. If these built-in gates and their associated equations do not fit a specific gate type that needs to be modeled, the user has the option of defining the "non-standard" gate using a series of rating curves (User Defined Curves); each curve representing a specific gate opening. As long as the gate can be described with rating curves and it remains tailwater independent throughout the simulation, this option provides a useable method for modeling any type of hydraulic control at a dam. At certain low-head dams, tailwater may play a very important role in the discharge of flow through a gate and the User-Defined Curves will not work. In this case, the user can implement scripts to further define the characteristics of the gate. Gate Rules are technically a boundary condition and are meant for describing the operation of gates. However, there are some script commands that will allow the user to either explicitly define the flow through the gates under a range of conditions or access an unlimited number of rating curves (i.e. one family set for each tailwater condition) that can be changed automatically during run-time, based on conditions at the reference points.

Operation of the built-in gates and gates defined by User Defined Curves is handled in the boundary condition editor in HEC-RAS, which consists of four boundary condition types. Two relatively unsophisticated control options include Time Series, where a gate opening is set by the user for each computation interval, and Elevation Control, based on either the water surface elevation at a reference location or the difference in stage between two reference locations. Navigation Dams is another available boundary condition type for gates and is specifically used for optimizing gate settings in simulation time in order to maintain a target water surface elevation, or range of elevations, during an event. If complex operations are required, scripting can be implemented using the Gate Rules boundary condition.

It is quite possible that none of the standard features included in HEC-RAS can properly simulate either the gate type or the operation the user wishes to implement into the model. The HECRASController API is a library of programming procedures that can be called from programming code in external applications. This gives the user flexibility to simulate just about any flow control device and operational scheme that can be conceived. The HECRASController capabilities in modeling gate types and gate operations is limited only by the programming skill of the user.

In any computational model, it is important to construct the model to provide the user an appropriate level of confidence in the results but not to make the model unnecessarily complex. As Albert Einstein is purported to have said, "Everything should be as simple as it can be, but no simpler." This is a skill that typically takes years of experience to develop. HEC-RAS provides functionality to allow the user to simulate gates and gate operations with either very simple and easy-to-use methods or very complex and wide-ranging methods, depending on the user's objectives.

2. GATE TYPES

2.1. Standard gates

Radial gates and sluice gates use essentially the same equations. The difference is that for the free flow condition, the radial gate will use a version of the orifice equation that is heavily dependent on the shape and position of the gate relative to its opening.
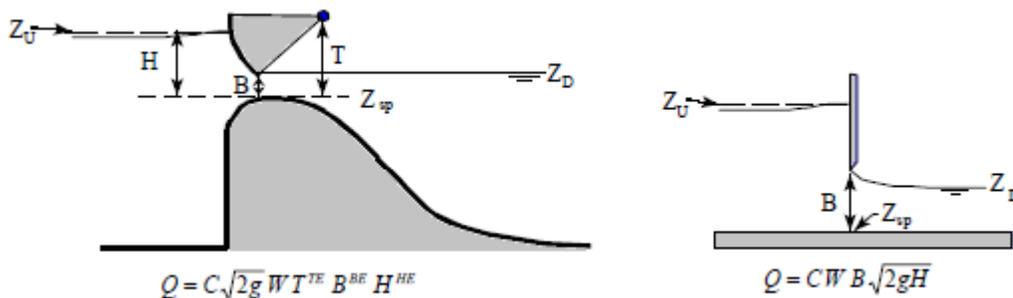

$$Q = C\sqrt{2g}\, W\, T^{TE}\, B^{BE}\, H^{HE} \qquad\qquad Q = C W B \sqrt{2gH}$$

Figure 1. Free flow gate equations for radial and sluice gates.

In Figure 1, Eqs. (1) and (2) are presented where Q is the discharge, C is the sluice gate discharge coefficient, W is the crest length, B is the gate opening, and T is the radial gate trunnion axis height. The head, H, is measured from the headwater energy level, Z_U, to the gate seat elevation, Z_{sp}. HEC-RAS provides the option to instead measure H from the headwater energy level to the center of the gate opening if the user desires. The HEC-RAS default exponent values are $TE = 0$, $BE = 1$, and $HE = 0.5$. With these defaults, the equation for radial gate flow and sluice gate flow become the same.

Submergence on the gate is defined as the tailwater depth ($Z_D = Z_{sp}$) divided by the headwater energy depth ($Z_U - Z_{sp}$). Once the submergence on the gate increases to 67%, HEC-RAS will begin to transition from free flow gate equations to the fully submerged gate flow equation. At 80% submergence, HEC-RAS uses the fully submerged orifice equation for both gate types:

$$Q = C_{sub}WB\sqrt{2gH_{sub}} \tag{3}$$

where C_{sub} is the submerged orifice discharge coefficient and H_{sub} is the head differential between the headwater energy, Z_U, and the tailwater elevation, Z_D.

Under low flow conditions, the gate is raised higher than the upstream water surface elevation, and HEC-RAS will use the weir equation:

$$Q = C_{weir}WH^{3/2} \tag{4}$$

where C_{weir} is the weir discharge coefficient.

Overflow gates are also available in HEC-RAS. Overflow gates can either be set as "open air," or "closed top." Open air overflow gates only use the weir coefficient Eq. (4). However, as the gate crest (Z_{sp}) moves up and down, H will change accordingly. Closed top overflow gates work the same as sluice gates, only the gate crest (Zsp) with a corresponding top will move up and down, rather than the gate lip.
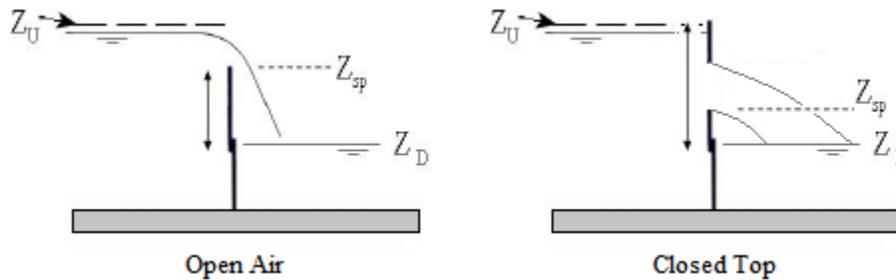

Figure 2. Open air and closed top overflow gates.

Note that in HEC-RAS under standard operational boundary conditions, C, C_{sub}, and C_{weir} are fixed for all hydraulic conditions for the entire simulation. This is a limitation in HEC-RAS when using the standard gate operations, since discharge coefficients are known to vary over a range of heads.

2.2. User-Defined Curves

If the user intends to simulate a hydraulic control structure that is not simulated properly with any of the standard gates, User-Defined Curves can be used instead. This option allows the user to enter in a family of rating curves (one per gate opening) that are used in place of the gate equations. This option only works when tailwater does not have a submergence effect on the flow through the gate. Figure 3 provides an example of a typical family of rating curves for a gate. Note that in HEC-RAS, the free discharge curve is called "Low Flow," but, ironically, this is typically anything but low flow.

Although User-Defined Curves are technically a gate "type," they can be used to simulate any hydraulic control structure for which one could generate a rating curve as long as flow control remains independent of tailwater. This feature has been used successfully to simulate flow over spillway structures whose discharge coefficients and/or crest lengths change significantly with different head levels. Labyrinth weirs and piano key weirs are examples where this is the case. User-Defined Curves can also be used quite easily to simulate hydraulic structures that

exhibit distinctly different flow controls for varying head levels, such as morning glory spillways. Morning glory (shaft) spillways are unique flow control structures with two different, distinct flow controls: a free overfall, where the circular crest controls flow, and the submerged condition, where the shaft controls flow.
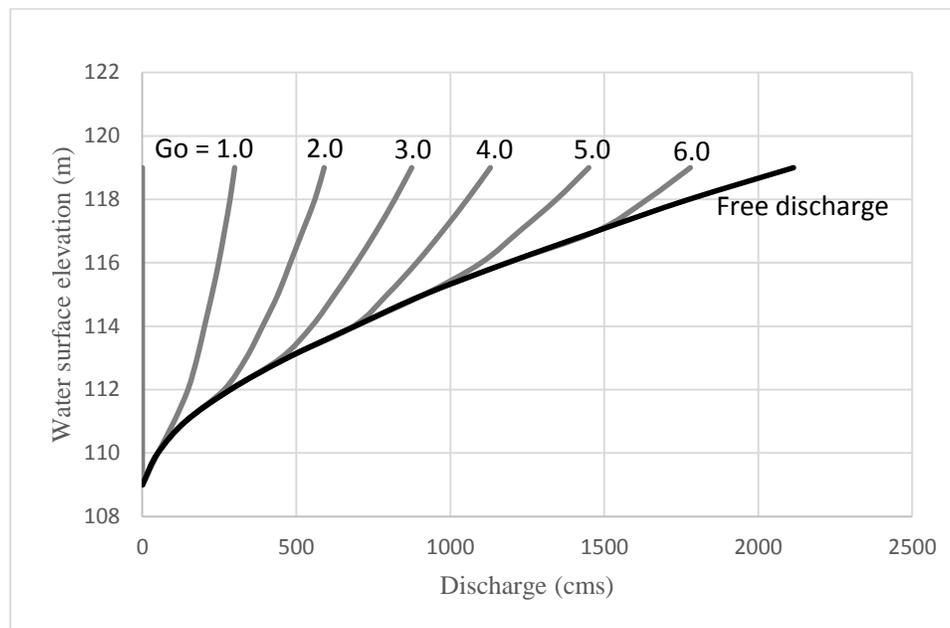

Figure 3. Typical gate rating curve.

3. GATE OPERATION

HEC-RAS comes with four boundary conditions that can be applied to gates: Time Series Gate Openings, Elevation Controlled Gates, Navigation Dams, and Rules. Time Series and Elevation Control are simple, unsophisticated methods for describing gate operations, while Navigation Dams is an optimization scheme that determines the best sequence of gate openings to meet a target water surface elevation (or range of water surface elevations) at a reference point in the model. Rules is a scripting tool that allows the user to operate the gate in almost any way desired.

3.1. Standard Operational Schemes

Time Series Gate Openings is very easy to use and simply requires a gate opening height for each prescribed time interval over the entire model simulation period. The gate settings are determined prior to the run by the user and are set as they are, for the entire simulation (i.e. there is no feedback applied to the settings). With Elevation Controlled Gates, HEC-RAS will monitor one or two reference locations and open or close the gates based on the water surface elevations at those locations. Figure 4 shows the HEC-RAS Elevation Controlled Gates input dialog with the gate set to operate based on a single reference cross section just upstream of the gate. The user sets when the gate opens and when it closes, as well as the opening and closing rates. Based on the reference point, HEC-RAS will determine what the gate setting should be for each computation interval. Although simple to use, elevation control is limited to control based on one location's water surface elevation or a head difference between two reference points. Beyond this, there is no logic programmed into the gate's operation. For example, if a user desires the gate to operate to maintain a certain water surface elevation in the reservoir, or would like to have more control on how the gate operates, either navigation dams or rules must be used. Alternatively, the HECRASController API can provide near limitless operational control (discussed in Section 4).
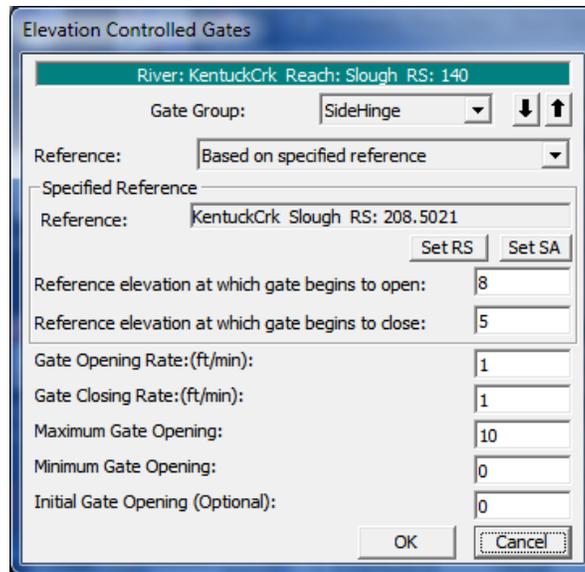
Figure 4. Elevation Controlled Gates Input Dialog

3.2. Navigation Dams

When Navigation Dams is used as a gate boundary condition, HEC-RAS will attempt, during run-time, to maintain a minimum and maximum water surface elevation at some reference point by opening or closing the gate. As the name implies, this feature is advantageous when trying to maintain a certain draft upstream of a dam for navigation traffic. The user enters a target water surface elevation along with some rather obscure calibration data, and HEC-RAS will try to meet the target as closely as possible. This technique frequently requires a number of iterative runs to achieve the desired results. There are four optimization methods available for Navigation Dams: Pool Only Control, Hinge Point Only Control, Hinge Point and Minimum Pool Operations, and Hinge Point and Minimum and Maximum Pool Control. Each method is progressively more complicated. Pool Only Control is discussed herein.

Pool Only Control attempts to maintain a user-specified target water surface just upstream of the gate structure. Since there is some delay between the arrival of a flood wave and the pool elevation change from a gate setting, HEC-RAS needs to forecast the flow rate at the gate structure. This is done by monitoring flow at some point further upstream of the gate structure. The user specifies this flow monitor location and frequently requires some iteration to achieve the proper response. A good initial guess is to select a flow monitor location so that the river travel time between the monitor location and the gate structure is similar to the normal gate change time increment (Brunner, et al. 2010a).

The Pool Control dialog gives the user some calibration control over how the target is met. The user enters in a series of water surface elevations that set the desired target as well as the "urgency" of gate operation at various water surface elevations away from the target. First, a primary water surface elevation range is bracketed around the target water surface elevation by selecting a target high and target low. As long as the water surface elevation is within this range, HEC-RAS will simply use the average flow rate between the gate structure and the monitor location and set the gate opening accordingly to achieve the target water surface elevation. As the pool elevation moves outside of this range, the average discharge between the gate structure and the reference location is multiplied by factors (also provided by the user). Once the flow in the river exceeds the user-specified "Flow Open River," HEC-RAS will open the gates to their maximum opening. If the flow falls below the user-specified "Flow Minimum," the gates will be set to the gate minimum opening. Figure 5 shows the Navigation Dams boundary condition dialog using Pool Only Control. Aside from the Target Water Surface Elevation and the Flow Open River and Flow Minimum, the water surface elevations and flow factors are largely calibration parameters. The user must run the program, evaluate the results, and adjust these parameters accordingly until the target water surface elevation range is met for the entire simulation.
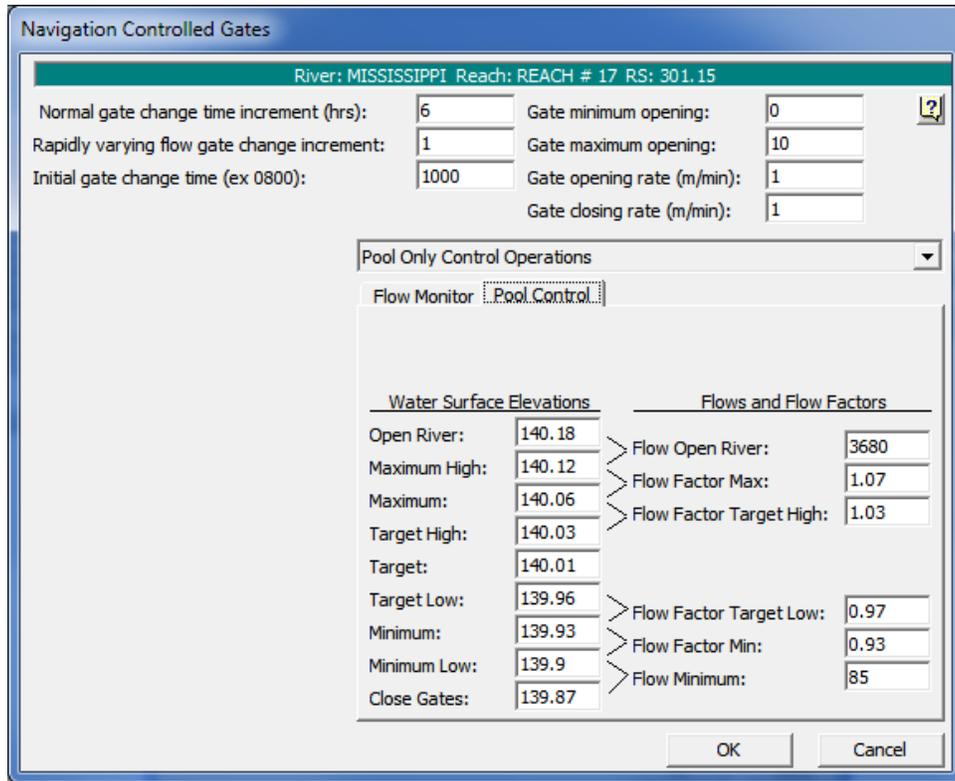
Figure 5. Navigation Dams Gate Operation - Pool Only Control

3.3. Rules

Rule Based Operations is an embedded scripting feature in HEC-RAS meant to offer a high degree of flexibility and customization of gate operations beyond what is available in the standard gate boundary conditions and navigation dams. With Rules, the user can give HEC-RAS the ability to operate gate openings or override the standard gate openings by specifying flows at a gate structure. The user can script operations based on input or computed variables at various locations including current and previously computed flows, water surface elevations, and even based on time considerations such as time of day or season. The user also has the ability to change input parameters during run time such as weir/gate coefficients or rating curve tables based on computed output. Basic math and conditional operations provide the user a great deal of flexibility in simulating complex gate operational procedures. All of these controls are pre-programmed into the Rules Operations Editor as shown in Figure 6.

Unlike typical programming code, Rules are scripted inside the Rules Operations Editor by clicking buttons and filling out input and dropdown boxes. With this editor, the user can define new variables, retrieve simulation values, set operational parameters, program conditional statements, perform mathematical computations, and set up tables of paired data.

A simple Rules operation might be set up to open or close a gate based on a computed flow at a reference location. If a certain flow rate is exceeded, the gates will open by a predetermined amount. On the other hand, if the computed flow is less than an input value, the gates will close by a predetermined amount. Figure 7 demonstrates the conditional scripting statement required to handle this simple operation in the Rules Operations Editor.
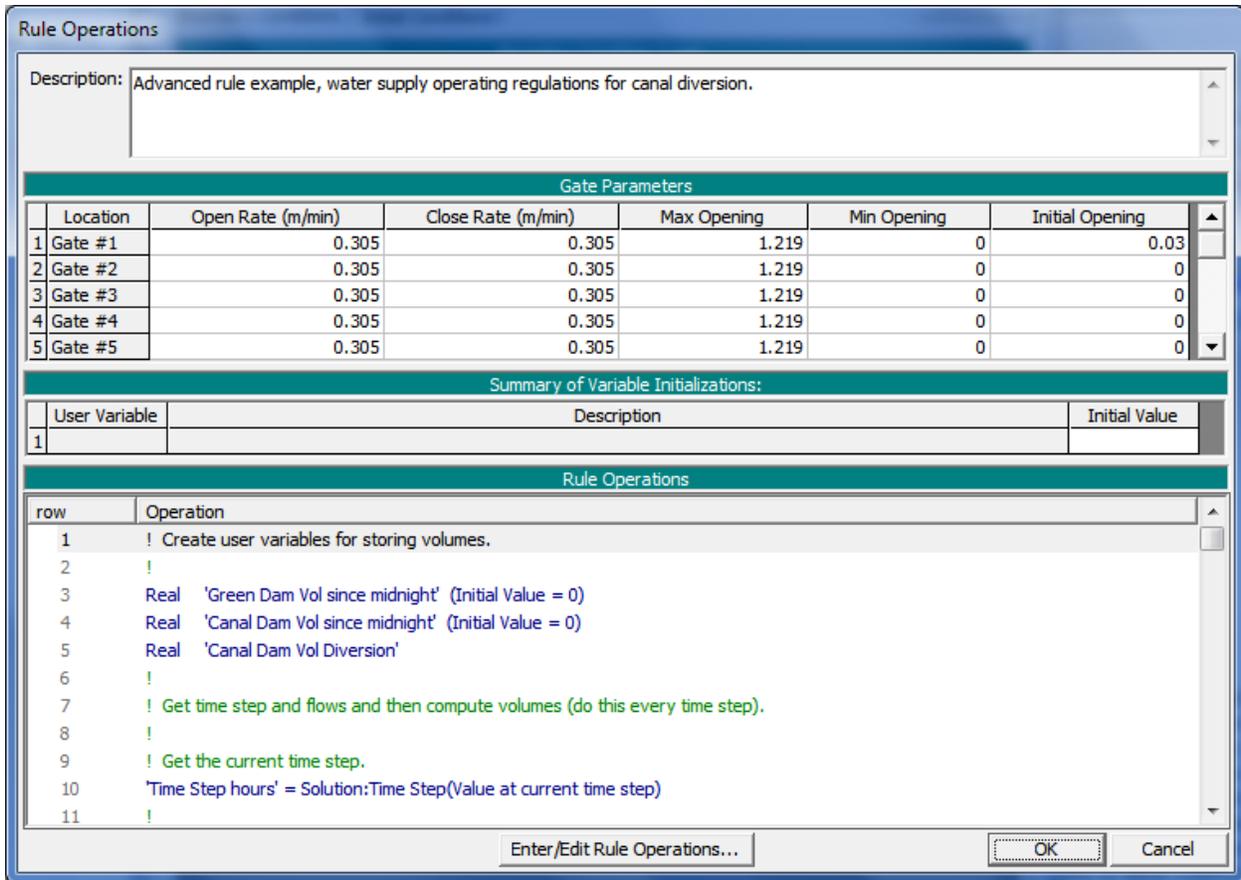
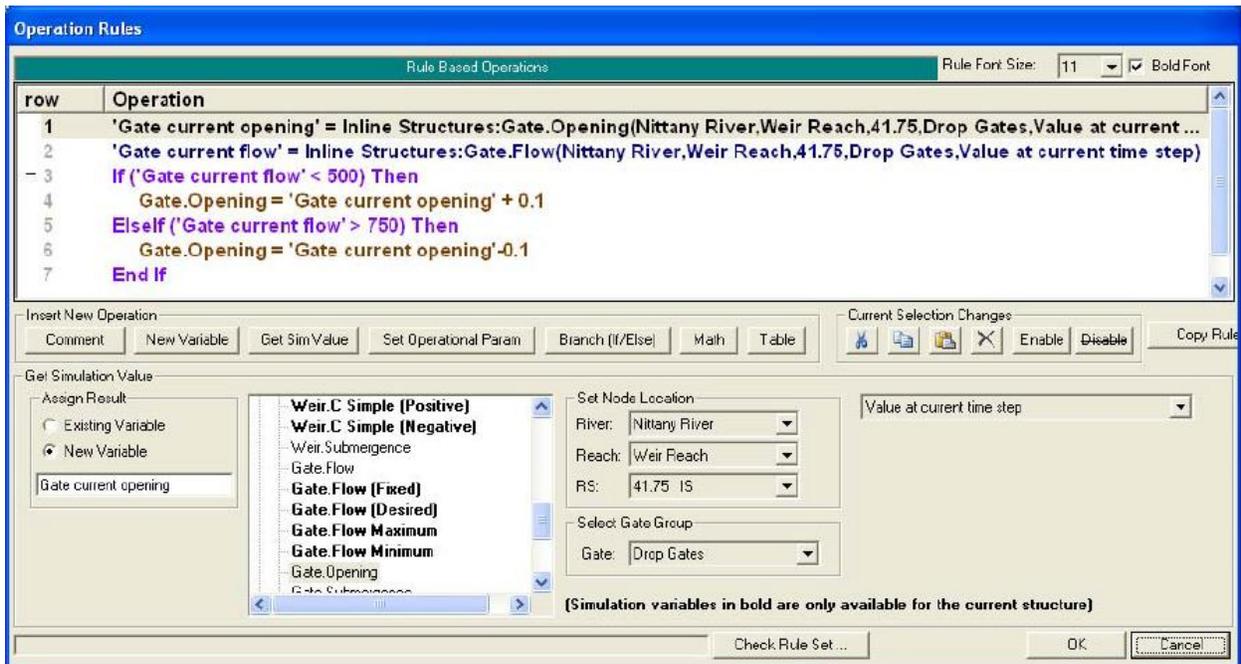Figure 6. Rules Operations Editor

Figure 7. Conditional Statements in the Rules Operations Editor.

While the Rules Operations Editor is designed to offer the user a great deal of flexibility and control over gate operations, it is somewhat limited in that the user can only apply changes to gate structures and it only works for structures connected to cross sections and storage areas (not 2D areas). Furthermore, the user must use the somewhat restrictive buttons and dropdown boxes provided in the Rules Operations Editor. This can be an advantage for users that are new to or otherwise unfamiliar with programming code, as the editor will effectively write the code for the user. For the seasoned programmer; however, scripting rules in the Rules Operation Editor will feel archaic and cumbersome. Programming gate operations in an external programming platform can provide the user even more operational control and a wider range of applications, and it also offers the scripting elegance sought after by experienced programmers.

4. HECRASCONTROLLER API

A relatively unknown but powerful feature embedded in HEC-RAS is the HECRASController. The HECRASController is part of an application programming interface (API) that includes a library of programming procedures that work directly with HEC-RAS from any external programming platform that can read in component object module (COM) version of a dynamic link library (DLL) (Goodell, 2014).

The HECRASController comes with the installation of HEC-RAS and can be used to control the functions of HEC-RAS, manipulate input, and retrieve output, all during run-time. With regard to gate structures, this gives the user near limitless options for operational control and physical characteristic definition. "Breaking the HEC-RAS Code" (Goodell, 2014) is a book that explains how to use the HECRASController both to read and write to HEC-RAS input files and to read results from the output file. To do this during run-time for gate operation requires the user to make use of a "pausing" technique. The pausing technique is described in "Breaking the HEC-RAS Code" on page 116 and follows these steps:

1. Set your simulation window to one day (or whatever increment suits your needs).
2. Set your model to create a restart file at the end of the run. This is done in the Output Options menu item under Options in the unsteady flow analysis window. Run the model once to create the first restart file; then set the unsteady flow editor to read that restart file as its initial conditions.
3. Run the one-day simulation through the programming code using the HECRASController procedures.
4. Using programming code and the HECRASController, read the output file and then make changes to the flow file based on computed results at specific output locations.
5. Repeat steps 3 and 4 for a full (multiple-day) simulation.

In this manner, gate settings can be chosen based on water surface elevations, velocity, flow rates, or any HEC-RAS output at any reference point or points during the simulation. Furthermore, gate characteristics can also be changed during runtime, such as the gate discharge coefficient or the gate rating curve. Describing and setting the gate operations and characteristics are really only limited by the programming skill and creativity of the user.

5. CONCLUSIONS

Methods for defining and operating gates in HEC-RAS are presented. They range from simple and easy-to-use methods, like the built-in standard gate types and standard operational boundary conditions, to the rather complex Navigation Dams and Rules operations editor. The HECRASController API makes gate definition and operation schemes near limitless and applicable during run-time. With these options, just about any gate type and operation can be simulated in HEC-RAS.

It is prudent to acknowledge that HEC-RAS is first and foremost a model designed to simulate rivers with an objective of evaluating reach-wide conditions, such as increases in flood risk, extents of inundation, and changes in velocity and flow patterns. HEC-RAS should be used to assess the reach-wide implications of various alternatives over existing conditions, rather than near-field design activities. To gain a true understanding of the hydraulics in and around different types of gates and gate structures, a more sophisticated computer model (e.g. 3D or computational fluid dynamics (CFD)), physical model, or combination of both should be used.

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