

Dam breach modeling using HEC-RAS and GIS

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Riley Asbury¹ and Christopher Goodell²

¹WEST Consultants, 8950 South 52nd Street, Suite 210, Tempe, AZ 85284, USA, rasbury@westconsultants.com

²WEST Consultants, 2601 25th St SE, Suite 450, Salem, OR 97302, USA, cgoodell@westconsultants.com

A flood caused by a dam breach may be much larger in magnitude and behave much differently than a natural flood. Mapping such a flood wave requires an accounting of hypothetical conditions that could lead to a dam breach, as well as extreme flow dynamics downstream of the breach. The Hydrologic Engineering Center's River Analysis System (HEC-RAS) computational program has the ability to model such flood waves and produce water surface profiles over the length of the modeled area. With the companion program HEC-GeoRAS which is an ArcGIS extension, water surface profiles can easily be converted to flood inundation maps. This paper will address the steps required to perform dam breach flood wave mapping using HEC-RAS and will present a case study, demonstrating the capabilities of HEC-RAS and HEC-GeoRAS.

Keywords: dam breach, flood, HEC-RAS program, water surface profiles

Una inundación causada por la falla de una presa podría ser mucho mayor en magnitud y comportarse de diferente manera que en el caso de una inundación natural. Trazar los límites de una ola de inundación requiere considerar hipótesis que pudieran resultar en la falla de una presa, así como una dinámica de flujo extrema aguas abajo de la falla. El programa computacional Sistema de Análisis de Ríos del Centro de Ingeniería Hidrológica (HEC-RAS) tiene la cualidad de modelar tales olas de inundación y entregar perfiles de agua superficial a lo largo del área modelada. En conjunto con el programa HEC-GeoRAS, el cual es una extensión de ArcGIS, perfiles de agua superficial pueden ser fácilmente convertidos a mapas de inundación. Este artículo trata sobre los pasos requeridos para trazar una ola de inundación debido a la falla de una presa usando HEC-RAS y presenta un caso de estudio, demostrando las capacidades de HEC-RAS y HEC-GeoRAS.

Palabras clave: falla de presa, inundación, programa HEC-RAS, perfiles de agua superficial

INTRODUCTION

Modeling a dam breach flood wave is a critical step in helping to identify potential damage to structures and property, and most importantly, to prevent casualties. Dam Breach models can predict the behavior of the flood wave allowing for urban growth planning and warnings where development exists. When used properly the program HEC-RAS can be a helpful tool for this application. Before modeling the dam breach flood wave it is necessary to understand the characteristics of the breach; in particular the hypothetical cause of the breach. In the following case study for Bear Creek Reservoir, an HEC-RAS model has been created with two different breach scenarios simulated.

BACKGROUND

Figure 1 shows that Bear Creek Reservoir is located

approximately 6.5 km southwest (upstream) of the city of Drain, Oregon, in the United States. Drain is located in a valley along the Elk Creek. Pass Creek empties into Elk Creek at the east end of the city of Drain. Bear Creek Reservoir is contained by an earthen dam and flows into Bear Creek. Bear Creek is a tributary to Billy Creek which empties into Elk Creek on the west end of Drain.

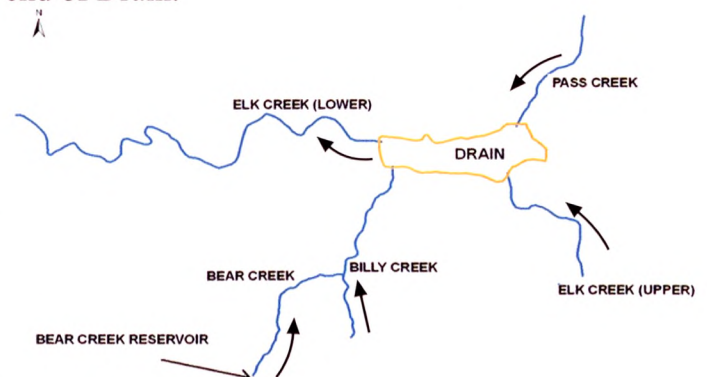


Figure 1: Bear Creek basin

The purpose of the study was to determine flood boundaries and the time interval of a flood resulting from the failure of the earthen dam and/or excessive flooding. Two scenarios were created using HEC-RAS, the first scenario is the Probable Maximum Flood (PMF) Dam Breach and the second is the Sunny Day Dam Breach.

HEC-RAS is a one-dimensional unsteady flow hydraulic model that has the capability of simulating highly dynamic flood events such as a dam breach. HEC-RAS uses an implicit finite difference scheme to approximate the St. Venant equations of Conservation of Mass and Conservation of Momentum. More detail on the solution scheme used in HEC-RAS can be found in the HEC-RAS Hydraulic Reference Manual (U.S. Army Corps of Engineers, 2008). The PMF Dam Breach model was created to simulate the results of an excessive rain storm which would fill the reservoir from the contributing watershed. This extreme storm event would raise the reservoir water level high enough to overtop the earthen dam, causing it to fail. The Sunny Day Failure was created to simulate the possibility of a dam breach caused by piping or structural failure on a day without rain while the reservoir is at its normal level. This type of failure can occur as a result of animal burrows or decomposing tree roots weakening the soil compaction or in the event of an earthquake or any combination of similar events.

MODEL DEVELOPMENT WITHIN GIS

The Bear Creek Dam Breach was modeled using the ArcGIS extension of the computational program HEC-GeoRAS as a pre- and post-processing tool (U.S. Army Corps of Engineers, 2005). The National Elevation Dataset (NED) of the United States Geologic Service (USGS) was used to create a three dimensional terrain model in GIS (Geographic Information System). Using HEC-GeoRAS the necessary geometry layers were created to best represent the area affected by a possible dam breach. The city of Drain and surrounding area was represented in the model as a level-pool storage area. The main rivers surrounding Drain were broken into six different reaches. Elk creek from the southeast where it enters Drain is referred to as Elk Creek (upper) and where it leaves Drain to the west it is referred to as Elk Creek (lower). Pass Creek enters Drain from the northeast and Billy Creek enters from the southwest. Billy Creek was divided into two reaches: one above the confluence with Bear Creek and one below it.

It is important to capture tributaries to the dam breach flood as they may serve as a significant source of flood attenuation. Bank lines and flow paths were drawn along each river reach using aerial photography and the terrain model as a guide. Bank lines are used in GeoRAS to define the extents of the main channel for each cross-section. Flow lines are used to define each cross-section's reach lengths for its overbanks and main channel.

Next, cross-sections were drawn in using Samuel's equation (Samuels, 1989) as an initial spacing guide. The aerial images and terrain model, using the hillshade and contouring features, were used as a reference for correctly placing channel cross-sections. Using the Spatial Analyst tool a hillshade or contour representation of the surface can easily be created. It is vital to the final model creation that the cross-sections are drawn in perpendicular to anticipated flow lines and cover the full extent of flooding to best approximate the total flow conveyance through the system. Two check procedures can help greatly in this process and may alleviate larger mistakes that would require lots of time to correct in the end.

The first check is to use the "Plot Cross-Section" tool provided in the HEC-GeoRAS tool bar. This tool allows the user to view the cross-section as it will appear in HEC-RAS. With this information it is easy to see if the drawn cross-section represents a fully contained channel or if the cross-section is too short or needs to be shifted laterally. Figure 2 presents the cross-sections used to define the Bear Creek Dam Breach model. It is important to note from Figure 2 that the Bear Creek reach just downstream of the dam required very tight cross-section spacing (on the order of 15 meters) to achieve numerical stability. Steep reaches require much closer spacing, particularly in a dynamic model such as a dam breach.



Figure 2: Cross-Section Spacing



The second check procedure is the creation of a “rough model” in HEC-RAS and the quick export/import back into GIS. This is a good test run on all of the geometry created so far and can be done as follows: once the user is comfortable with the geometry data, the HEC-GeoRAS tool is used to export the geometry data to HEC-RAS. Then, open HEC-RAS and import the geometry file from GIS. If Manning’s n values were not defined in GIS they must be defined in the HEC-RAS model. For this rough model an estimated best guess of Manning’s n values can be quickly inserted into the table. A more precise estimation of Manning’s n values should be conducted for the final simulation. Next, insert estimated boundary conditions including a steady flow at the upstream end, preferably similar to an assumed peak flow from a dam breach, and a downstream boundary condition such as a downstream slope for a normal depth calculation. To quickly estimate the downstream slope using the profile plot in HEC-RAS, hold down the Ctrl button and click twice on the downstream portion of the profile drawing a line parallel to the slope of the channel (US Army Corps of Engineers, 2008).

With these basic variables set the model will be ready for a quick test run. If more information is needed to run the model these values should be quickly estimated. If the model runs with no errors the user can do a quick visual check of the geometry and ineffective flow area, to verify that all flood inundation is accounted for. Ineffective flow areas in HEC-RAS are areas where water may pond, generally in the overbank areas, but the velocity of the water in that area is close to or equal to zero. Areas designated as ineffective flow are included in the storage area and wetted perimeter of the HEC-RAS calculations, but do not contribute to the active flow calculations (US Army Corps of Engineers, 2008). The rough model may then be helpful in verifying user suspicion of ineffective flow areas and also helping the user recognize other possible ineffective areas.

This rough model can also be a convenient tool for trouble shooting since a steady flow model is less complicated and more numerically stable than an unsteady model and it may be easier to find simple errors that would cause trouble later. Once the user is comfortable with this rough estimation the data can be exported from HEC-RAS and imported back into the GIS model. This new water surface can be laid over the existing geometry and used as a check. It is easy to see with the estimated water surface where

cross-sections may need to be adjusted. This technique may also reveal side channels and or low lying areas that were initially overlooked. Again this water surface is a steady flow approximation and should be used only as a guide for refining the geometry to best represent the surface being modeled.

GEOMETRY WITHIN HEC-RAS

With the geometry model completed in GIS for the Bear Creek Dam Breach model the data was once again exported from GIS. The river, banks, flow paths, and cross-section geometry data from GIS were imported into an HEC-RAS model. The imported geometry is a good start but is not yet a complete representation of the system. More features are available within GIS to more accurately represent river systems, but for this example most of the remaining information was added within the HEC-RAS program. Manning’s n values were further refined through the reaches using information gathered during field visits and using aerial photos as a base reference. When an image has been georeferenced in GIS along with the geometry data, the image may be brought directly into the HEC-RAS model as a background layer. This helps to facilitate the selection of Manning’s n values in addition to other input parameters. When setting n values for a dam breach model it is important to keep in mind that flood waters may behave differently than under normal flood circumstances. Flood waters downstream of a dam breach are typically more sediment and debris-laden. Flows through the channel might experience higher resistance due to the accumulated debris. Manning’s n values for the Bear Creek model ranged from 0.075 to 0.12.

Ineffective flow areas were also designated in HEC-RAS using cross-section plots and aerial photos. Once again special consideration is given to the possible flow depth after a dam breach. What might be considered an area of ineffective flow under normal flood conditions might easily carry flows in a larger flood. This is accounted for by setting the ineffective flow trigger height to an appropriate elevation. When flow depths reach this trigger height the ineffective flow areas become areas of effective flow. Solid structures and permanent buildings can be blocked out using blocked obstructions and permanent ineffective flows (US Army Corps of Engineers, 2008).

The earthen dam is entered into the HEC-RAS model as an inline structure. From survey data and field visits

it is known that Bear Creek Dam has a spillway on the west end and a gate structure with an outlet conduit through its center. The physical dimensions of the dam are entered in the Weir Station Elevation Editor along with other relevant information including upstream and downstream embankment side slopes, distance to upstream cross-section, dam top-width, and the overtopping discharge coefficient. Gate information is entered using the Inline Gate Editor.

The dam failure itself is defined in the Inline Structure Data editor by clicking on the “Breach (Plan Data)” button. Breach parameters and the failure trigger are defined, as is the type of failure that will occur (Failure Mode), and the breach progression. For the Bear Creek Reservoir, two scenarios were modeled: the PMF and the Sunny Day Failure. In the Dam Breach model the Failure Mode was set to “Overtopping” and the Trigger Failure option was set to “WS Elev.” (Water Surface Elevation). This allows a certain level of overtopping of the dam before the breach development is initiated. In the Sunny Day Failure model the parameters were set to “piping” as the Failure mode and “Set Time” for the Trigger Failure option. This assumes that a piping conduit will be established through the dam at a pre-defined time in the simulation. In order to calculate the flow through the breach, the HEC-RAS program uses the orifice equation first, for piping flow. Once the hole in the dam grows large enough to reach the top of the dam, the breach is considered “collapsed” and HEC-RAS will switch to the weir equation for the remainder of the simulation. Bear Creek dam with the assumed breach geometry is presented in Figure 3. The coefficients for both the orifice equation and the weir equation must be established by the modeler, and can be a significant source of uncertainty in the results. A sensitivity analysis should be run on these coefficients, and also on the breach geometry itself. The default used in HEC-RAS for the breach weir coefficient is 1.44 (2.6 for English Units). The default for the piping coefficient for use in the orifice equation is 0.5.

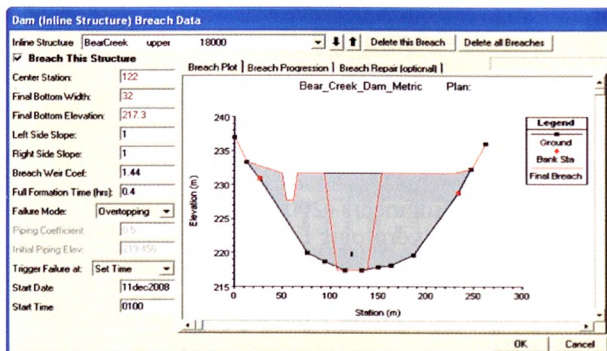


Figure 3. Bear Creek Dam and assumed Breach Geometry

Breach parameters are used to define the shape of the breach and the time it takes to fully develop. An analysis of the breach parameters is conducted external to HEC-RAS and involves consultation with available regression equations, numerical models, and envelop curves. Wahl (2004) demonstrates a comparison of many different dam breach parameters, most of which were evaluated for the Bear Creek model. Typically, a sensitivity analysis is conducted with the range of breach parameter results (most importantly breach width and breach development time) to determine the uncertainty of the breach outflow hydrograph. Because of the high degree of uncertainty in both the timing and geometry of the breach, the most conservative set of breach parameters is often used.

HYDROLOGY

Dam Failure is most appropriately modeled in HEC-RAS using unsteady flow. Flow Hydrographs are entered as upstream boundary conditions under the Unsteady Flow Data Editor. For a flood induced dam failure, a flood hydrograph must be developed external to HEC-RAS. Typically the flood that is analyzed is the Probable Maximum Flood, as is the case with the Bear Creek simulation. However, it is common to check other hypothetical floods such as the 100-year return interval flood. A Sunny Day breach simulation will use an upstream hydrograph with only baseflow contributions. Sunny Day dam failures are assumed to occur under “normal” conditions.

SIMULATION ANIMATION

The output animation capabilities in HEC-RAS are excellent. This is especially interesting when animating an unsteady model such as a Dam Breach. The output data from an HEC-RAS model can be checked in plan view, profile view and as individual cross-sections including all upstream and downstream faces of structures. In any of the above mentioned output graphics it is possible to view the flood wave as an animation. The animation controls allow the user to animate the simulation results, control the animation speed, and stop the animation to view at any desired time. This feature proves to be especially helpful in understanding the travel time and general movement of flood waves.

POST PROCESSING

With the HEC-RAS model complete the output data

can be exported to a GIS ready format. Using HEC-GeoRAS for a dam breach model, the maximum water surface profile can be brought into GIS, although any output profile in the simulation can be exported. A graphical output is created to represent the max water surface. The shapefile representing the max water surface is generally rough and requires some adjustment to accurately represent the true flood inundation extents. This is best done using a combination of aerial photography, generated contour lines, and on-site knowledge obtained during field visits.

With the Max Water Surface shapefile completed, important data can be added to the map at corresponding cross-sections such as flood wave arrival time, time of maximum water depth, elevation of maximum water depth, *etc.* This information is easily obtained from the HEC-RAS model using the flow and stage hydrograph output. Figures 4 and 5 show the maximum water surface inundation for the PMF flood event with relevant information included. In the hydrograph output, the HEC-RAS default setting only provides hydrographs for the internal and external boundary cross-sections. A specific cross-section can be chosen in the Stage and Flow Output Locations option in the Unsteady Flow Analysis Window.

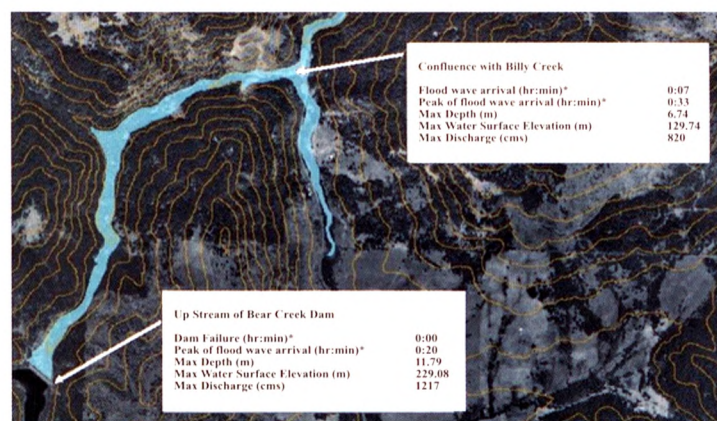


Figure 4: Dam Breach Flood Inundation downstream of Bear Creek Dam and the Confluence with Billy Creek.

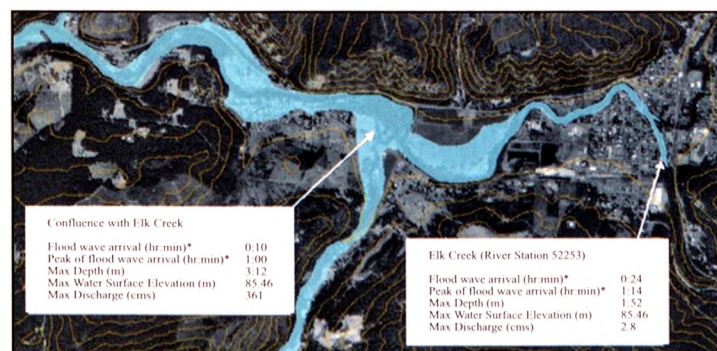


Figure 5: Dam Breach Flood Inundation at the Confluence of Elk Creek and the City of Drain.

CONCLUDING REMARKS

Together the GIS extension program HEC-GeoRAS and the HEC-RAS program are useful tools in computing flood inundation maps from dam breach simulations. These programs offer a lot of flexibility with the definition of structures and the breach development, which allows for an increase in confidence in the output results.

Because this is a dam breach simulation, full calibration of the model is not possible. The hydraulic modeler must rely on good practice and sound judgment to maximize the confidence in the results. In some streams, historical flood data may exist, in which case it would be prudent to calibrate the model to at least some lesser flood event. However, HEC-RAS has shown to be a very reliable tool in simulating a dam breach event, when good modeling techniques and sound judgment is used (Brunner, 2003). Still, to fully understand the results presented by HEC-RAS for a dam breach model, a sensitivity study on the uncertain parameters is warranted.

In an area such as Bear Creek where a dam failure would endanger lives, running a dam breach simulation provides valuable information about the areas most likely to be affected. The HEC-RAS output from the simulation also allows the user to make estimates of when flood waves will first arrive and when flows will be at a maximum at desired locations downstream of the dam after a failure. This information could prove to be of great importance when creating an emergency plan for the unfortunate event of a dam breach.

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