

DAM FAILURE ANALYSIS USING HEC-RAS AND HEC-GeoRAS

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Abstract An analysis of dam failure models provides a scenario generating tool for identifying the resulting hazards. Floodplain managers and emergency management personnel may then utilize the resulting contingencies to protect against the loss of life and property damage. The Hydrologic Engineering Center's River Analysis System (HEC-RAS) can be used in concert with HEC-GeoRAS to develop a dam failure model. HEC-GeoRAS is used to extract geometric information from a digital terrain model and then imported into HEC-RAS. Unsteady-flow simulation of the dam break is performed using HEC-RAS and results are mapped using the GIS. Inundation mapping of water surface profile results from dam failure models provides a preliminary assessment of the flood hazard and provides insight for emergency preparedness. The process for gathering and preparing data, creating an unsteady-flow model in HEC-RAS, entry of dam breach parameters, performing a dam failure analysis, and mapping of the flood progression is discussed.

INTRODUCTION

There are more than 79,000 dams listed in the National Inventory of Dams (NID) for the United States and territories. According to the U.S. Geological Survey, more than 7,700 of these dams are categorized as major dams. Major dams include dams 50 feet or more in height, dams with normal storage capacity of 5,000 acre-feet or more, and dams with a maximum storage capacity of 25,000 acre-feet or more (USGS, 2005a). The potential failure of these dams places property and human life at risk. In fact, almost 12,000 of the dams listed in the NID are categorized as "high risk" where the failure of the dam would likely result in the loss of human life, significant property damage, and environmental damage.

The catastrophic results of dam failures have been realized in the United States dating back to the failure of the South Fork Dam, Pennsylvania, in 1889. Other notable dam failures have included the St. Francis Dam (California, 1928), Buffalo Creek Dam (West Virginia, 1972), Canyon Lake Dam (South Dakota, 1972), Teton Dam (Idaho, 1976), Kelly Barnes Dam (Georgia, 1977), and Lawn Lake Dam (Colorado, 1982). Each of these dam failures resulted in the damage of property and human death.

Public concern for the safety of dams, resulted in the adoption of the National Dam Inspection Act in 1972 which authorized the U.S. Army Corps of Engineers to inventory and inspect all non-Federal dams. Continued interest in dam safety was evidenced in the passing of the Water Resources and Development Act of 1996 and the Dam Safety and Security Act of 2002. Despite efforts to improve the safety of the dams, we must still address the concerns of what may happen should a dam fail. The potential loss of life and property damage likely to occur during a catastrophic dam failure may be mitigated through an understanding of the resulting flood wave characteristics and inundated area. The flood results may then be applied to develop emergency response plans and future land use planning.

The use of geographic information systems (GIS) and has become more mainstream and data have become more readily available. In particular, the availability of terrain data has improved the proficiency with which skilled engineers can develop hydraulic models capable of simulating a dam breach scenario and evaluating the resultant flood wave. The use of HEC-RAS in modeling dam failure scenarios and HEC-GeoRAS in model development and analysis of the flooded area using a GIS is discussed.

BUILDING THE RIVER HYDRAULICS MODEL

A river hydraulics model is only going to be as good as the data and personnel used to develop it. Detailed terrain information for the main channel and overbank floodplain areas are the principal data required for creating a river hydraulics model. Land use data (used for estimating Manning's roughness coefficients) and hydraulic structure information (bridge crossings and inline structures) are also essential to building a

complete river hydraulics model. For modeling dam failures, further information describing the failure mode, breach size, and breach timing are necessary. This section of the paper will discuss data considerations for developing a river hydraulics model to perform dam failure analysis.

Terrain Collection/Preparation A detailed description of the land surface is imperative to developing a quality river hydraulics model. Terrain data is used to establish the area available to convey flow downstream. The computed water surface profile is then mapped on the land surface to identify the floodplain. Traditionally, a detailed description of the land surface is recorded by taking transects of the floodplain in the field or reading elevations off of topographic maps to develop cross sections. If a digital terrain model (DTM) exists for the study area, however, GIS tools can be used to extract elevation data along user-specified locations.

The land surface can be represented in the GIS using two different model types: vector or raster. The vector model stores data as a series of triangulated points forming a continuous network of triangles. This vector format is referred to as triangulated irregular network (TIN). In raster form, the terrain is described by a grid of evenly-spaced data. Computations done on a gridded basis are much faster than computations on vector data.

The TIN format, however, is the preferred method of data storage as a basis for river hydraulics because the land surface can be more accurately described by a minimum of data. Elevation data can be surveyed in more detail in areas of high relief (such as at the banks of rivers or levees) and in less detailed where the terrain changes very little (such as an open field). Linear features that direct the flow of water (such as roads, levees, or ridges lines) are easily added to the TIN to force the surface to specific elevations. A comparable raster dataset, on the other hand, requires a very fine grid spacing. This, in turn, can result in an enormous data file that is awkward to manage and increases data processing.

High Resolution Data Access to high resolution digital terrain data appropriate for river hydraulics is limited. Gathering enough data points to create an accurate DTM is a costly endeavor. Two methods for large-scale data collection of terrain data are LiDAR and photogrammetry.

LiDAR (Light Detection and Ranging) is the latest in technology being used to gather elevation data. Light is transmitted to a target and some of the light is reflected back to the source. The time for the light to travel to the target and back is used to compute the range to the target. Airborne LiDAR units can gather geo-referenced elevation data with a vertical accuracy better than 15 centimeters at 5-meter horizontal spacing.

Another airborne-based method for building digital terrain models is photogrammetry. The photogrammetric process requires the acquisition and registration of aerial photos. Elevation points are then identified from the aerial photos using stereo-compilation. Because this is an intensive process, the end product is costly. However, the terrain model is ideal for hydraulic modeling because human judgment has determined the most important points for creating the terrain surface. A consequence of this screening process is that the size of the resultant data files is minimal. The end product of the process is an accurate terrain model in the form of a TIN with aerial photographs for reference.

LiDAR is competing with the time-tested methods of surveying and photogrammetry. However, the advertised costs often don't reflect the time required to process the data into an accurate description of the bare-earth terrain. Unlike the data generated from the rigors of photogrammetry, LiDAR returns a "shotgun" of data that will include extraneous data such as tree tops, fence lines, and cows out to pasture. An enormous dataset results from the LiDAR data collection that must be processed to remove the elevation artifacts. These data can be unmanageable for the non-expert GIS user. Automated algorithms for the processing of digital terrain data are currently in place to process large datasets, however, advances are needed.

Low Resolution Data Low resolution raster data are availability to the general public for the entire United States (and a lot of the world) in various formats and resolutions. The U.S. Geologic Survey currently provides a seamless National Elevation Dataset (NED) for the United States at 1 arc-second (30m) and 1/3

arc-second (10m) elevation postings (USGS, 2005b). For the contiguous US, the NED data is provided in a geographic projection with the NAD83 horizontal datum and the NAVD88 vertical datum. The NED data are based on the highest quality USGS 7.5-minute Digital Elevation Models (DEMs) available that were previously developed from 1:24,000-scale topographic quadrangle maps. Because the NED are based on the USGS DEMs, the most accurate data have a vertical accuracy (root mean square error) of ± 7 meters, with a maximum tolerable error of 15 meters (USGS, 1998).

Shuttle Radar Topography Mission (SRTM) data are also available at the 1 arc-second (30m) data in the United States and 3 arc-second (90m) data around the world (USGS, 2005c). Gathered in 1990, the SRTM data is more current than the NED; however, the data have a lower vertical accuracy specification of ± 10 meters.

Even the highest resolution data that is widely available is not appropriate for most river hydraulic applications, but may be suitable for dam failure scenarios. The use of low resolution terrain models, such as the raster data available from the USGS, will preclude their use in evaluating low flows. Further, the data will need to be adjusted to reflect the properties of the main channel.

Merging of Channel Data The large-scale data collection methods previously discussed do not account for describing the shape of the land surface in the river channel below the water. An accurate river hydraulics model must account for the in-channel area. Channel data may come from traditional survey transects of the river or from one of many bathymetric survey methods. The channel data must then be merged with the overbank terrain data to give a full description of the floodplain cross section.

Channel data may be merged in the GIS to complete the DTM or within the river hydraulics model at specific cross section locations. The method for merging channel data will be dictated by the type of data available. Regardless of the method, careful consideration of the coordinate system for each piece of data is warranted so as to not mix data with different vertical datums.

HEC-GeoRAS Development HEC-GeoRAS is a set of tools specifically designed to process geospatial data to support hydraulic model development and analysis of water surface profile results (HEC, 2005). GeoRAS assists engineers in creating datasets (referred to collectively as RAS Layers) in ArcGIS to extract information essential for hydraulic modeling. The latest release of HEC-GeoRAS supports the extraction of elevation data from DTMs in either the TIN or grid format.

GeoRAS requires that the user have a DTM. The DTM must be projected into a coordinate system – the coordinate system of the DTM is used as the basis for developing each of the RAS Layers. GeoRAS also requires that the Stream Centerline layer and Cross-Sectional Cut Line layer be created. The development of all other RAS Layers is optional based on the data needs for the river hydraulics model. A summary of RAS Layers and their use in building a hydraulic model is provided in Table 1.

The Stream Centerline layer is used to identify the connectivity of the river system. It is created in the downstream direction and is used to assign river stations to the cross sections, bridges, and other structures to order computational nodes in the HEC-RAS model.

The Cross-Sectional Cut Lines layer is the principal data constructed using HEC-GeoRAS. Cut lines are digitized across the floodplain area to capture the profile of the land surface. Cross sections should be digitized perpendicular to the path of flow in the channel and overbank areas to be consistent with one-dimensional flow characteristics. Having created the bank lines and flow path centerlines prior to laying out cut line locations is advantageous.

Once the RAS Layers have been created, GeoRAS tools and menus are available to assign and populate attribute data. Lastly, the data are written out to the HEC-RAS geospatial data exchange format and can be imported into HEC-RAS.

Table 1. Summary of HEC-GeoRAS layers and corresponding output for HEC-RAS.

RAS Layer	Description
Stream Centerline	Used to identify the connectivity of the river network and assign river stations to computation points.
Cross-Sectional Cut Lines	Used to extract elevation transects from the DTM at specified locations and other cross-sectional properties.
Bank Lines	Used in conjunction with the cut lines to identify the main channel from overbank areas.
Flow Path Centerlines	Used to identify the center of mass of flow in the main channel and overbanks to compute the downstream reach lengths between cross sections.
Land Use	Used to assign flow roughness factors (Manning's n values) to the cross sections.
Levee Alignment	Used to identify the location and elevation of high ground on a cross section that limits flow from going out into the floodplain.
Ineffective Flow Areas	Used to identify the location of non-conveyance areas.
Blocked Obstructions	Used to identify obstructions to flow.
Bridges/Culverts	Used to extract the top-of-road data from the DTM at specified locations.
Inline Structures	Used to extract the weir profile from the DTM for inline structures (dams).
Lateral Structures	Used to extract the weir profile from the DTM for structures the pass flow perpendicular from the main channel.
Storage Areas	Used to define the extent of detention areas and develop the elevation-volume relationship from the DTM.
Storage Area Connections	Used to extract the weir profile from the DTM for connections between storage areas.

HEC-RAS Model Development HEC-RAS is a one-dimensional river hydraulics model used for steady-flow and unsteady-flow water surface profile computations through a network of open channels (HEC, 2002). Because HEC-RAS solves the full Saint-Venant equations, it is well suited for computing the flood wave propagation resulting from a dam failure scenario.

Initial model development may be performed using HEC-GeoRAS and using an HEC-RAS option to import the GIS data. At a minimum, the data import should establish the river/reach schematic and the description of cross sections. The river hydraulics model will need additional cross section information, hydraulic structures data, flow data, and boundary conditions prior to simulation. This section will focus on just a few of the more important data considerations.

Channel Data If the cross-sectional data came from a low resolution terrain model the channel data will not be represented in the cross section. For a large flood wave resulting from a dam break, the channel data may not be significant. The importance of the channel portion of the total cross-sectional conveyance will need to be evaluated: if the channel conveyance is rather small compared with the total conveyance, for instance, the peak stage of the flood wave may not be significantly affected. To perform the dam breach analysis, however, RAS will need a channel for the low-flow portion of the simulation.

If channel data are available from previous hydraulic studies, HEC-RAS provides the capability to merge data from two different geometry files. Using the channel merge capabilities in RAS, channel data or overbank data can be merged with an existing dataset. The merging of channel data taken from field surveys with data extracted from a DTM is shown in Figure 1. The vertical datum must be identified and data adjusted for consistency.

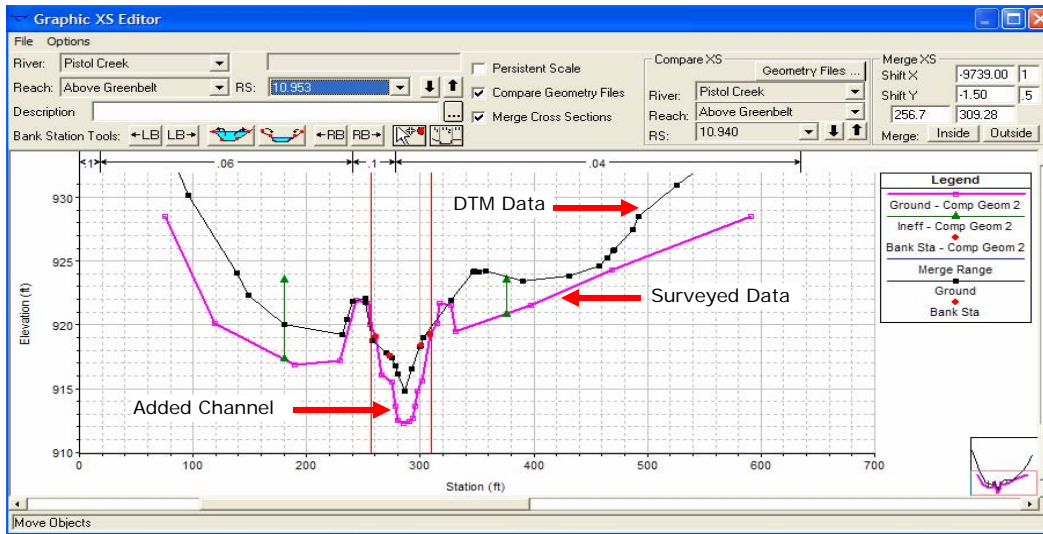


Figure 1. Merging channel data using the graphical cross section editor in HEC-RAS.

If channel data is not available, it can be estimated from field surveys and topographic maps. A shape may be estimated for uniform sections of channel and added to the overbank data. HEC-RAS provides channel modification tools for quickly adding a trapezoidal channel to cross sections along a given river reach. As shown in Figure 2, the data extracted from the terrain model are horizontal in the main channel reflecting the elevation of the water surface during data capture. A trapezoidal channel is added based on an approximation or survey of water depth, top width, and side slopes.

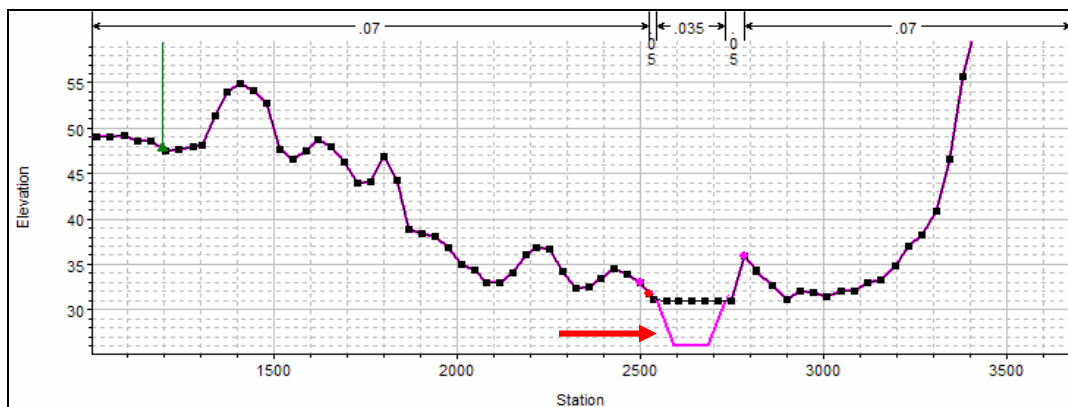


Figure 2. Adding a channel is necessary for model stability.

Modeling the Dam A dam is modeled in HEC-RAS as an inline structure. An inline structure is represented with a weir profile (that includes the spillway) and gates for normal low-flow operation. An example of an inline structure is shown in Figure 3.

There are two different ways to model the volume of water stored behind the dam in HEC-RAS. Ideally, the storage volume behind the dam would be computed from cross sections taken from surveyed bathymetric data of the reservoir. Alternatively, a storage area could be used with an elevation-volume relationship representing the storage volume behind the dam. The method with the cross sections is preferred because it allows for a sloping water surface behind the dam during the failure, rather than the flat water surface represented with a storage area. A sloped water surface results in higher discharge at the beginning of the failure because the upstream pressure force is considered. The resultant downstream peak stage, however, will be dependant on the breach size, breach timing, storage volume, and geometry of the downstream floodplain.

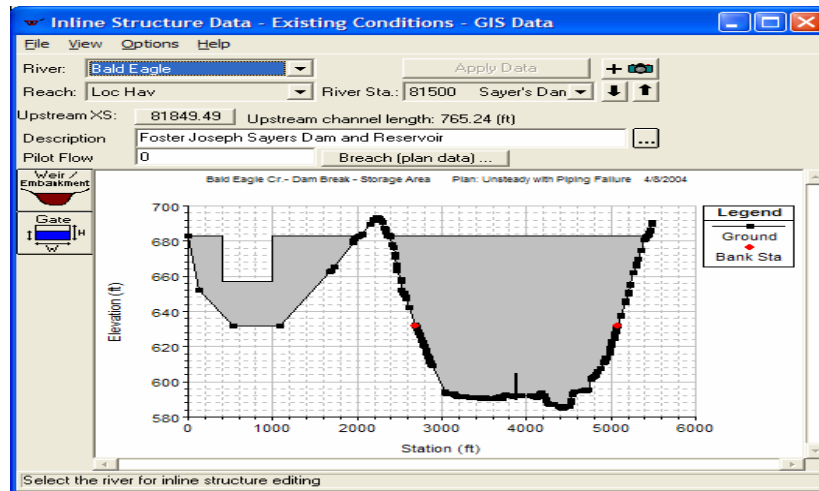


Figure 3. A dam is represented as an inline structure in HEC-RAS.

Dam Breach Data To model a dam failure in RAS, you must enter the failure mode, breach size, and breach time. HEC-RAS supports both overtopping and piping failure modes with the failure trigger being a target water surface, water surface and duration, or specific time. The breach size is defined by a trapezoid and the duration over which the breach occurs. Lastly, RAS allows the user to customize the progression of the breach over the full formation time. Data entry in HEC-RAS of breach information is shown in Figure 4.

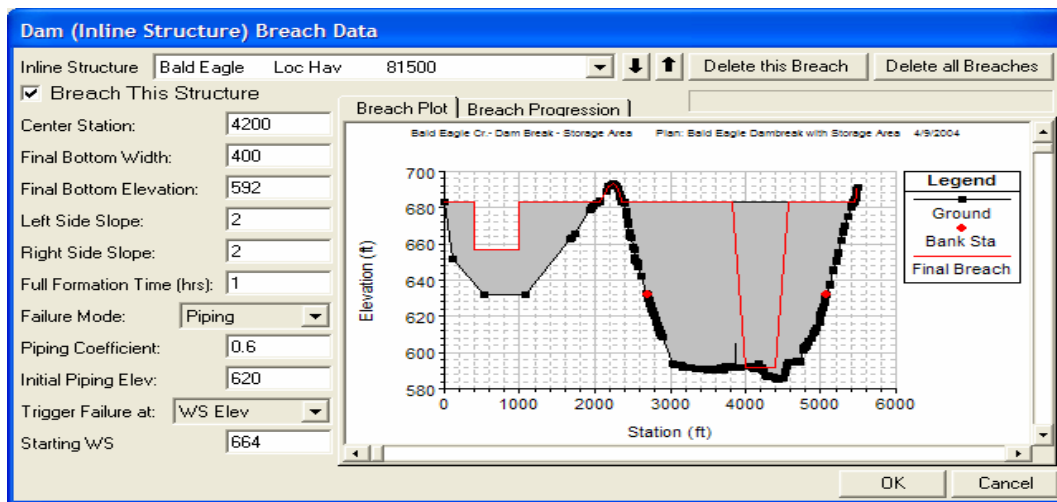


Figure 4. Dam breach information entered in HEC-RAS.

When performing dam breach analysis of historic dam failures, breach information may be available. When simulating a hypothetical dam failure, breach size and formation time must be estimated. Breach parameters can be estimated based on historic dam breach data using regression equations or numerical models based on sediment transport. The uncertainty associated with any one method for predicting dam breach properties favors estimating several breach sizes and formation times to form a matrix of possibilities. The sensitivity of the resulting flood wave may then be analyzed prior to adopting a set of breach parameters. The U.S. Bureau of Reclamation Dam Safety Office has summarized the bulk of research on historic dam failures and methods used for predicting dam breach properties (USBR, 1998).

Estimation of breach parameters using regression equations is based on dam height, dam material, water surface elevation, and storage volume. If a physically-based numerical model is used, such as the BREACH program (Fread, 1988), more detailed information describing the soil properties is required. Each method will predict a final bottom width, side slope, and formation time for the failure in addition to a

peak outflow. For large reservoirs, the peak discharge is less sensitive to the time of failure and more dependent on the breach width. However, the inundation of areas in close proximity to the dam is sensitive to both breach time and width.

HYDRAULIC ANALYSIS

Using a matrix of breach parameters, multiple breach scenarios may be simulated. The resultant travel time and magnitude of peak discharge can be evaluated to identify the set of breach parameters to adopt. The hydrographs from each scenario will tend to converge as they are routed downstream. Therefore, the proximity of the location of interest will govern the set of breach parameters adopted for the dam failure model. If the location of interest is in close proximity to the dam, the breach width and formation time will be critical and a conservative estimate of the parameters is prudent. The importance of the breach parameters will become less significant as the location of interest moves farther downstream.

An example of the affect of model input is illustrated in the HEC-RAS profile plot shown in Figure 5. The comparison of modeling the reservoir as a series of cross sections versus a storage area results in very significant rise in stage near the dam; however, the affects are less pronounced farther downstream. Animations of the dam failure and water surface elevations in profile and at cross sections are also supported in HEC-RAS.

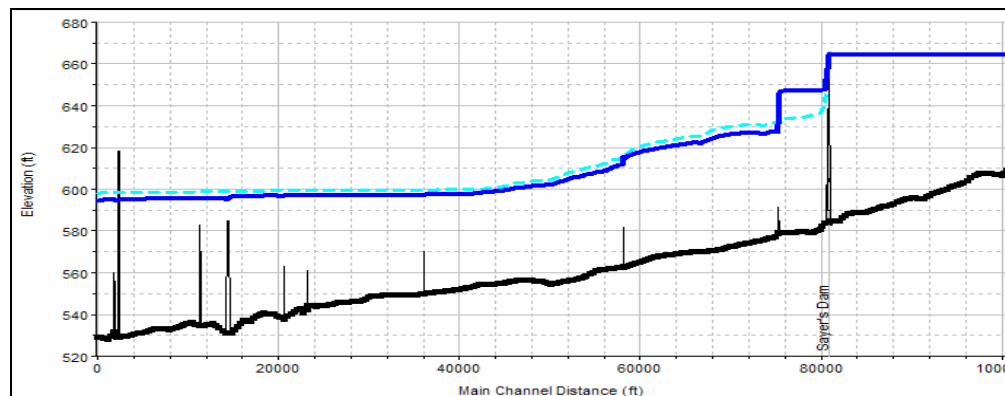


Figure 5. Example profile comparison of dam failure scenarios in HEC-RAS.

Perhaps the most critical output from dam failures simulations is predicting the flood wave travel time to populated areas. Given flood warning, the loss of human life may be mitigated. Hydrograph output from HEC-RAS can be used to estimate the arrival time of the waters to flood levels, as shown in Figure 6.

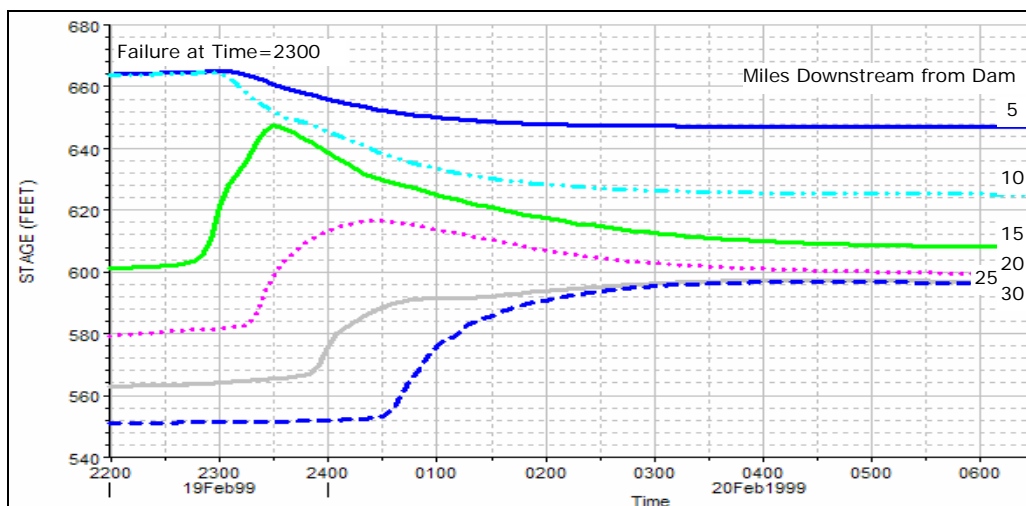


Figure 6. Stage hydrographs at river mile locations downstream of the dam.

FLOODPLAIN MAPPING

Floodplain mapping is accomplished in the GIS using HEC-GeoRAS. GIS information is exported from HEC-RAS and read into the GIS with GeoRAS. The geo-referenced cross sections are imported and water surface elevations attached to the cross sections are used to create a continuous water surface. The water surface is then compared with the terrain model and the floodplain is identified where the water surface is higher than the terrain. HEC-GeoRAS produces inundation maps for flood extent and depth and, as shown in Figure 7, when displayed with aerial photographs can be used to identify the area impacted during a dam failure scenario.

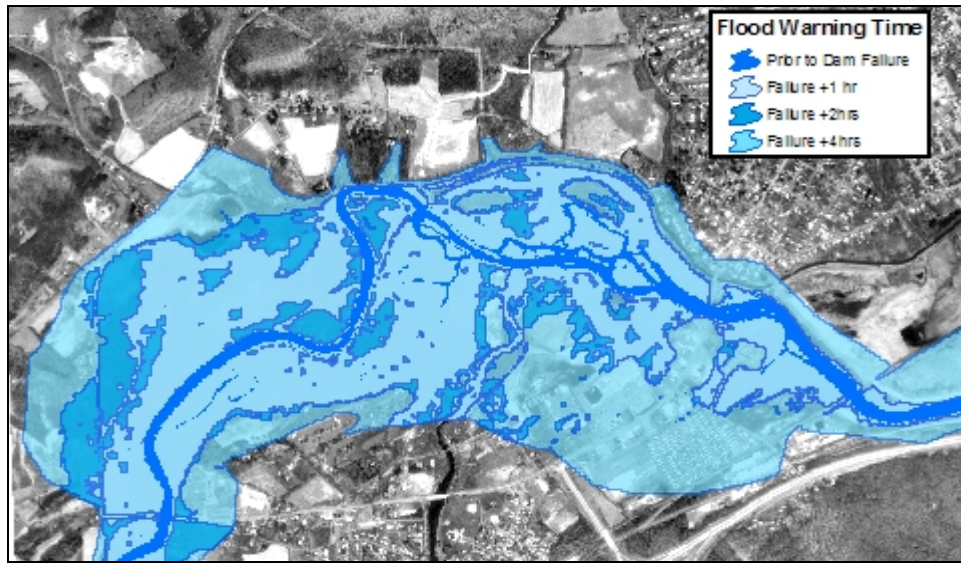


Figure 7. Inundation maps displaying flood warning times after dam failure.

CONCLUSIONS

Dam failure places populations at risk; however, tools exist to evaluate the contingencies. HEC-RAS used in concert with HEC-GeoRAS provide the capabilities to create a river hydraulics model, simulate a dam failure, and map the resulting flood wave. Because of the availability of digital terrain data and processing capabilities, GIS is well suited to assist in performing dam failure analysis. The proper analysis of the hazards associated with dam failure will assist in land use planning and in developing emergency response plans to help mitigate catastrophic loss to human life and property.

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