SELECTING DAM BREACH INUNDATION SOFTWARE

OBSERVATIONS FROM KENTUCKY

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INTRODUCTION

Dam safety professionals use hydraulic modeling and inundation mapping to estimate the effects of potential dam breaches for dam hazard classification, the development of Emergency Action Plans (EAPs), and assessment of potential risks. FEMA released GeoDam-BREACH in 2012 and a new version on August 27, 2014 to assist dam safety professionals in developing dam breach inundation zones. The Kentucky Division of Water (KDOW) used GeoDam-BREACH in the analysis and flood risk inventory of over 200 dams in 2012-2013. During the inventory process, questions arose as to the appropriate use of GeoDam-BREACH/SMPDBRK relative to the hazard classification of dams and what advantages and disadvantages are presented by alternative breach inundation software. Following KDOW's dam flood risk inventory, FEMA released the *Federal Guidelines for Inundation Mapping of Flood Risks Associated with Dam Incidents and Failures* (FEMA P-946) in July 2013, which provided guidance regarding the appropriate usage of various dam breach software packages. Through a grant funded by FEMA, KDOW performed a side-by-side comparison of various dam breach software packages while incorporating lessons from FEMA. The results of the comparison are used to better understand the applicability of various dam breach inundation software, and provide practical observations and recommendations for evaluating and selecting software that is appropriate to an end user's needs.

DAM BREACH SOFTWARE USED FOR THIS STUDY

FEMA P-946 "presents a variety of information that individual States can incorporate specific to their needs and as allowed by their enabling legislation." The following sections are noted relative to this study:

- Section 10 discusses "Analysis Tools for Dam Failure Modeling" including description of several software packages that can be used for dam breach hydrograph generation and downstream hydraulic routing of a breach hydrograph. Included are recommendations for selecting modeling software based on a tiered approach that considers "type of results needed, the level of effort that can expended, and the potential for loss of life and economic damages that can result from a dam failure."

- Section 11 provides guidance for mapping of dam breaches, including recommendations regarding the format of digital databases for dam breach data and the format of inundation mapping.

In this study, FEMA P-946 is applied to a specific set of dams in Kentucky providing useful insights for modelers to consider at the beginning of an analysis and mapping project. Modeling software packages vary with respect to: the underlying model assumptions, input data requirements, complexity of the computational routine, precision and accuracy of results, the format of model output and software cost. Understanding these differences can assist in selecting software applicable to the purpose and detail required. A brief summary of each model used follows:

- **GeoDam-BREACH,** "Geospatial Dam Break, Emergency Action Planning, Consequences, and Hazards," is an ArcGIS-based toolbar developed by FEMA in coordination with the National Weather Service (NWS) that can be used to create flood risk products (inundation zones, depth, velocity, and arrival time grids) and populate portions of an EAP template. GeoDam-BREACH utilizes NWS' Simplified Dam Break (SMPDBRK) program as the computation engine for breach modeling and downstream routing, but gives the option to import data from other models. GeoDam-BREACH uses either NWS SMPDBRK analysis or user-provided model results as input to a GIS tool that streamlines the creation of flood-risk products and pre-populates portions of an EAP template.

- **DSS-WISE** is a two-dimensional computation engine developed by the National Center for Computational Hydroscience and Engineering (NCCHE) at the University of Mississippi. DSS-WISE Lite is a simplified version of the DSS-WISE program that is accessible via the Dam Sector Analysis Tool (DSAT). It can be used to quickly compute a breach hydrograph, route discharges, and produce dam breach inundation mapping with limited user input through the use of national datasets (such as the National Inventory of Dams (NID) and the National Bridge Inventory (NBI)) and server-based computing (a user submits the input to a server via an internet connection and output data is packaged by the server and sent via electronic mail). DSS-WISE Lite and DSAT were developed by NCCHE through a funding collaboration by the US Department of Homeland Security and the US Army Corps of Engineers.

- The USACE's **Hydrologic Engineering Center River Analysis System (HEC-RAS)** version 4.1 is a one-dimensional hydraulic model. HEC-RAS can be used to compute or import a breach hydrograph and route the hydrograph using an unsteady-state solution. In addition, HEC-RAS 4.1 contains a menu of GIS-based tools known as RAS-Mapper enabling the creation of products such as inundation zones, depth grids, and velocity grids.

- **HEC-RAS 5.0 Beta** is the newest version of HEC-RAS. An official full release of the software is anticipated in winter of 2015. Version 5.0 beta includes new two-dimensional modeling capabilities and enhancements to RAS-Mapper. Although HEC-RAS 5.0 beta has the ability to perform both one-dimensional and two-dimensional computations, in this paper references to "HEC-RAS 2D" are meant to denote the HEC-RAS two-dimensional modeling routine, whereas "HEC-RAS 1D" will be used to refer to HEC-RAS one-dimensional modeling. This study employed the use of a beta version acquired from HEC labs in October 2014.

- **FLO-2D** is a two-dimensional modeling package available from FLO-2D Software, Inc. that can be used to compute or import a breach hydrograph and route discharges using an unsteady-state, two-dimensional computational routine. The program can simulate channel flow, unconfined overland flow, and street flow.

- **HAZUS-MH** uses models for estimating potential losses from earthquakes, floods, and hurricanes. HAZUS uses GIS technology to estimate physical, economic, and social impacts of disasters. The HAZUS Flood Model, which is one component of the HAZUS-MH software, produces loss estimates for vulnerability assessments and plans for flood risk mitigation, emergency preparedness, and response and recovery. The methodology deals with nearly all aspects of the built environment, and a wide range of losses. The user can evaluate losses from a single flood event, or for a range of flood events allowing for annualized estimates of damages.

- **BOSS DAMBRK** is a DOS-based, one-dimensional, steady-state model created by Boss International (now part of Autodesk, Inc.). The model uses the engine from the NWS DAMBRK model that utilizes a one-dimensional, unsteady-state computation engine to route a breach hydrograph, which can be computed within the program.

All of the software used in this study require no license fee and represent a good sampling of the range of options and capabilities available among dam breach software packages.

STUDY METHODS – SELECTED DAMS, AREA OF STUDY, AND COMPARISON CRITERIA

In order to apply FEMA guidance and compare software packages, KDOW used information from previously completed dam breach models and created new model simulations using the selected software. The matrix below denotes which software packages were used for each study dam.

MODEL SETUP

To facilitate a reasonable comparison, the breach was not performed within each model. The breach hydrograph from an existing study was used as a common starting point for each new model. However, some programs cannot import a breach hydrograph, so as an alternative, the existing study breach parameters were applied.

TABLE 1 - STUDY DAMS AND SOFTWARE UTILIZED

Dam Name (NID-KY#)	Height (feet)	Normal Pool Vol. (acre-ft)	Boss-DAMBRK	DSS-WISE Lite	SMPDBK/ GeoDam-BREACH	HEC-RAS 1D	HEC-RAS 2D	FLO-2D	HAZUS
Beech Creek (0043)	67	881.6	X	X	X	X	X	X	X
Willisburg (0103)	77	1610.4	X	X	X	X	X	X	
Big Bone Lick (0307)	65	185		X	X	X		X	
Marion County (0020)	33	218.3		X	X	X		X	
Feltner (0105)	24	40			X	X		X	
Martin County (0109)	40	85			X	X		X	
Campbellsville (0155)	49	949		X	X	X		X	
SF Beargrass (1003)	60	605		X	X	X		X	
Roberson Run (1115)	17	Dry		X	X	X		X	
Game Farm Upper (0372)	20	41.3	X	X	X	X		X	
Woodlake (1130)	29	27.4		X	X			X	
Guist Creek (0040)	60	7944		X	X	X		X	
Whitesburg (0075)	8	13.1		X	X				
Scenic (0012)	25	229.6		X	X			X	

The mapping results for some of these dams are interspaced throughout this paper for comparison.

MODEL OUTPUT

Using GIS and the hydraulic model results for each dam and the associated model runs, dam breach inundation zones were delineated using best available elevation data, noting that DSS-WISE Lite is restricted to National Elevation Dataset topography. HAZUS runs were created to evaluate dam breach analysis results from DSS-WISE Lite, GeoDam-BREACH/SMPDBK, HEC-RAS 1D, HEC-RAS 2D, and FLO-2D at Beech Creek Dam.
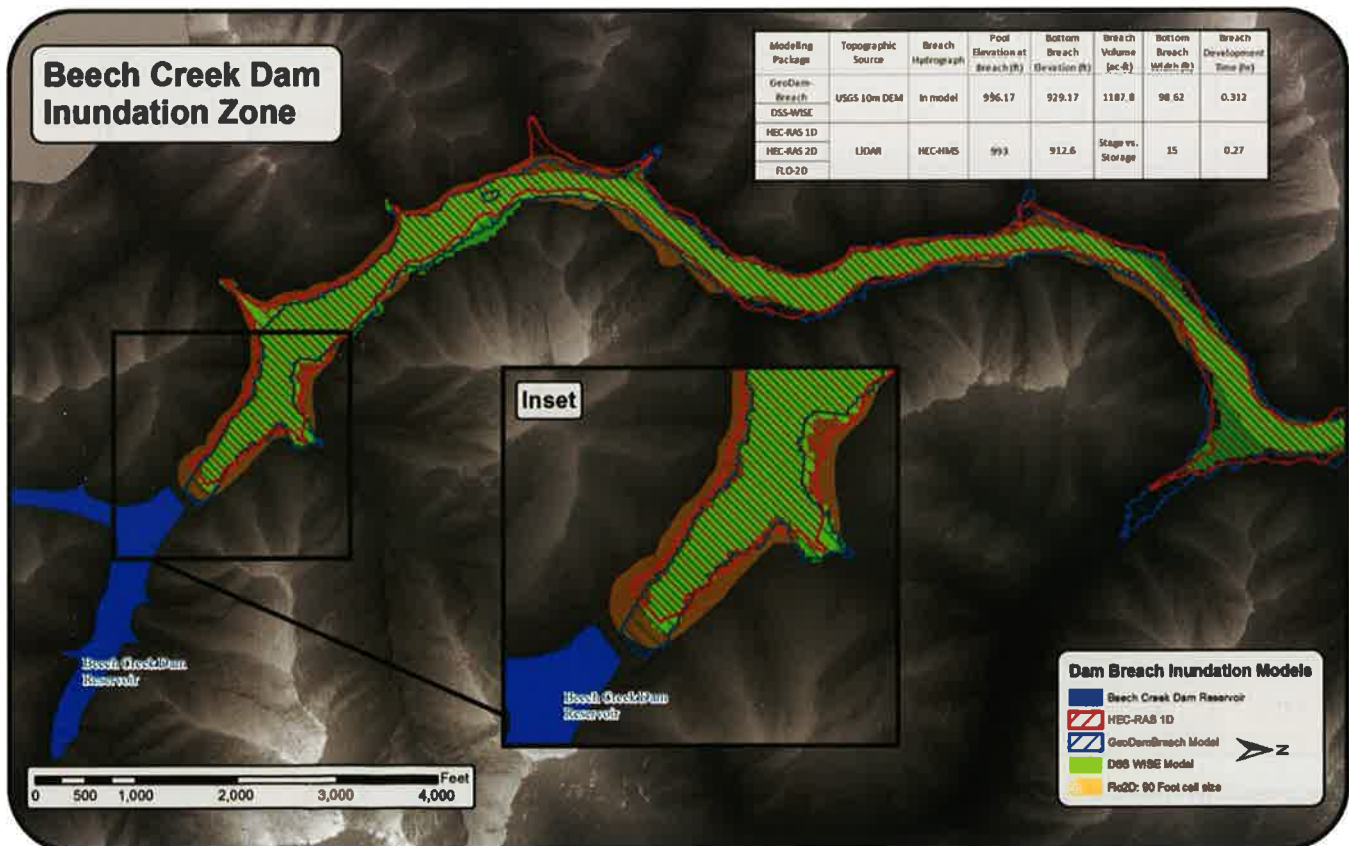
COMPARISONS

In order to make comparisons of the various software programs, the following activities were performed: 1) the evaluation of software usability and features was summarized from questionnaires and interviews given to staff involved in the study; 2) a literature review of dam breach analysis guidance was conducted to incorporate current knowledge with the practical lessons learned; and 3) each model's results are imported to the HAZUS Flood model.

A pragmatic approach tailored to the needs of dam safety professionals yielded a series of questions designed to streamline the process of determining which program to use in a dam breach analysis. These questions are based on considerations discussed in FEMA P-946 and the practical experience of the authors. The questions can serve as a trigger to evaluate project needs, model development costs, and the solutions provided by each software program.

- What is the price of the software or license agreement?

- What is the format of the input data?

  o Does this align well with common data formats with which a typical dam safety professional would be familiar, or is there significant conversion or transformation of data that must occur for proper input into the program?

- Can a breach hydrograph be computed within the program?

  o If so, is it a regression-based parameter model, or a physical model, or can it do either?

  o Can the program compute hydrographs for both non-hydrologic breach events (i.e., "Sunny Day") and hydrologic breach events (i.e., overtopping)?

  o Can a breach hydrograph be imported into the program, and if so, how?

- How much time is involved in the model setup, and if it varies, what are the variables?

- What are the types of products the software can output?

- What are the file formats associated with each of the output types?

  o Can these be readily imported into GeoDam-BREACH?

  o Can these be readily imported into HAZUS?

- Is the software FEMA-approved?

- Is the software still supported? Is there any reason to believe that use of the software may not be a wise long-term solution or that files created in the software may not be accessible a decade from now?

Beech Creek Dam Inundation Zone

Modeling Package	Topographic Source	Breach Hydrograph	Pool Elevation at Breach (ft)	Bottom Breach Elevation (ft)	Breach Volume (ac-ft)	Bottom Breach Width (ft)	Breach Development Time (hr)
GeoDam-Breach	USGS 10m DEM	In model	996.17	929.17	1187.8	98.62	0.312
DSS-WISE							
HEC-RAS 1D							
HEC-RAS 2D	LiDAR	HEC-HMS	993	912.6	Stage vs. Storage	15	0.27
FLO-2D							

Dam Breach Inundation Models
- Beech Creek Dam Reservoir
- HEC-RAS 1D
- GeoDamBreach Model
- DSS WISE Model
- Flo2D: 90 Foot cell size

Feet
0 500 1,000 2,000 3,000 4,000

- If modifications need to be made to the model, what complicating factors may exist? [For example, cost of software is high, learning curve is steep.]

- Does the program require professional expertise to manipulate, or could a relative novice use the program?

- What tools or computational techniques are offered by the software that seems to be uncommon when compared to other software?

- What are potential sources of error inherent to the software package? (For example, DSS-WISE Lite can only use the National Elevation Dataset for its elevation input; some programs cannot account for backwater effects at bridges.)
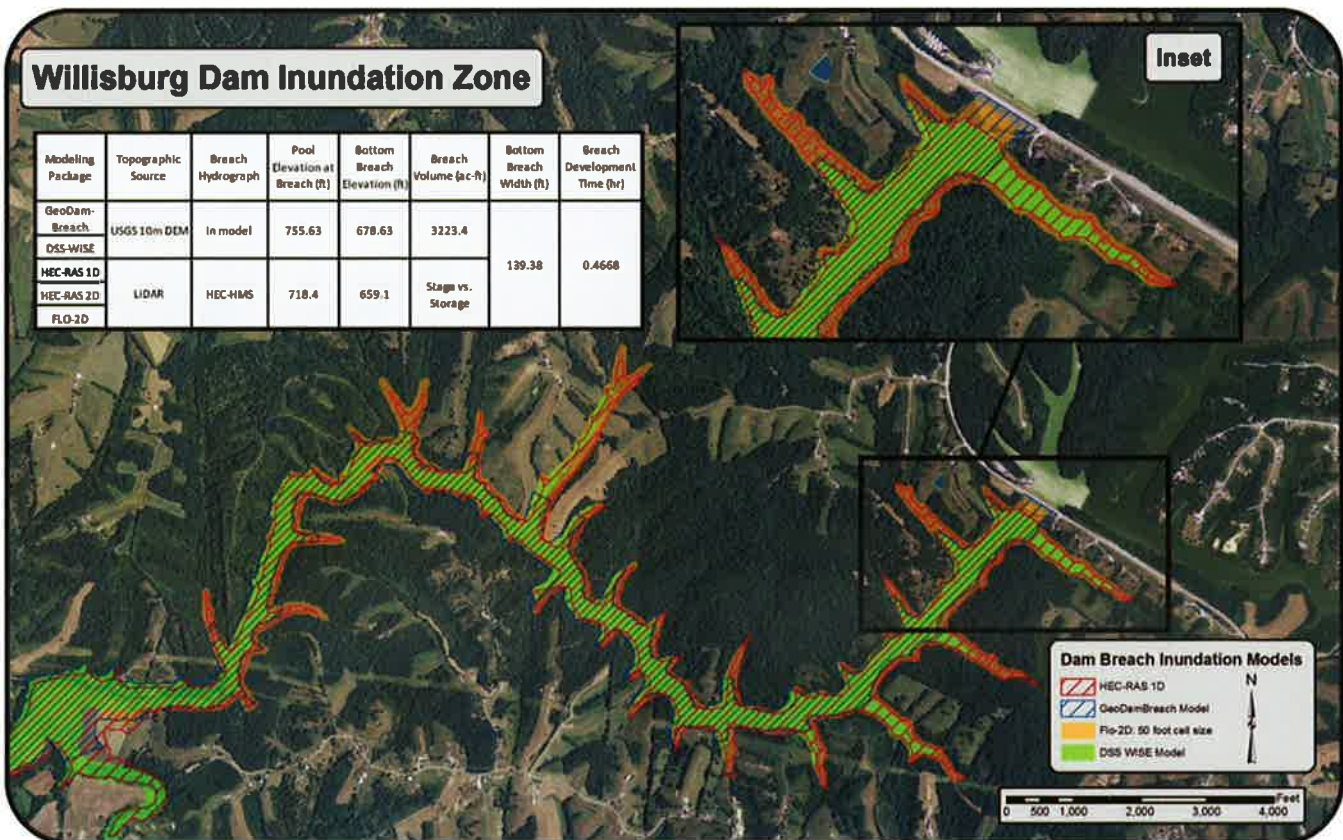
DEVELOPMENT OF LESSONS LEARNED/BEST PRACTICES

Through use of the questionnaire, project staff interviews, review of software manuals, review of model results, and the HAZUS import summary, data was collected with which software comparisons could be made. The results of this process were compiled and sorted to fit topically within the workflow of a typical breach analysis project (i.e., software selection, model setup, model input, computational routine, and output). Conclusions were made regarding the collected information to yield lessons learned and best practices from the study.

Lessons Learned/Best Practices

Initial software assessment: Return on investment

Both short- and long-term costs and benefits should be considered to select a software package. These include licensing and accessibility issues; the long-term software development, support, and viability of a given model; and compatibility with existing studies. Return on investment considerations include:

- The up-front **cost** needed to purchase a software package and learn to use it properly is a key consideration. This should be weighed in light of the immediate users (those who will be performing the project at hand), potential future users (those who may need to modify the model at a later date), and the technical requirements of the project at hand. The software that meets the technical requirements and has a low up-front cost and learning curve may be best suited for use.

- Other than BOSS-DAMBRK, the selected software packages were versions that did not require purchase of a license or a subscription fee. Depending on the particular application, for-purchase software packages may be necessary. FLO-2D Basic and HEC-RAS 2D are both free, but may not be suited for more complex urban environments that require storm water modeling. FLO-2D Pro, for example, includes an interface with EPA SWMM, but entails an annual subscription fee of $1,000.

Willisburg Dam Inundation Zone

Modeling Package	Topographic Source	Breach Hydrograph	Pool Elevation at Breach (ft)	Bottom Breach Elevation (ft)	Breach Volume (ac-ft)	Bottom Breach Width (ft)	Breach Development Time (hr)
GeoDam-Breach	USGS 10m DEM	In model	755.63	678.63	3223.4	139.38	0.4668
DSS-WISE							
HEC-RAS 1D	LiDAR	HEC-HMS	718.4	659.1	Stage vs. Storage		
HEC-RAS 2D							
FLO-2D							

- In terms of a **learning curve**, our reviews of user-friendliness varied depending on the particular tool or feature. The variability in resources that assist a user in learning a particular software package can be illustrated by comparing HEC-RAS and FLO-2D. HEC-RAS has historically had a large user base among dam safety and other water resources professionals, and an experienced HEC-RAS user may easily find another experienced user who can provide guidance, whether in-person or online. HEC-RAS 2D may be easier to learn for those who are HEC-RAS 1D users. For those who are unfamiliar with HEC-RAS 1D, the beginner's access to FLO-2D support requires less industry knowledge due to robust documentation and support, e.g. help menus, tutorials, and webinars. However, customer support and some of the learning material are only available to Pro-subscribers. DSS-WISE Lite is the most user-friendly program, followed by GeoDam-BREACH, because the user has the least amount of input data and most data can be imported from the NID and NBI. They are also laid out in a very intuitive step-by-step method of use.

- The **purpose** of a proposed breach modeling and mapping project should drive the technical and computational requirements for selecting software. Tools like GeoDam-BREACH or DSS-WISE Lite are not intended to define the regulatory hazard classification of a dam. Instead, they were primarily designed to help emergency responders and communities to develop dam breach inundation areas and emergency action plans. This balancing of project purpose and model complexity is addressed in FEMA's P-946 through discussion of model limitations and a matrix that denotes which software packages are appropriate for analyses termed "screening and simple", "intermediate", or "advanced" (FEMA P-946, Page 6-7, Table 6-3).

- One should assess the likelihood of **continued availability and support** of any software considered for use. This is clearly illustrated by the situation in which BOSS-DAMBRK users find themselves. While some states still have users of this software, the model is no longer available for purchase, and the software vendor does not provide support for the product. It is unknown at this time whether there will be federal funding in the future for the DSS-WISE Lite and GeoDam-BREACH programs. Alternatively, the long track record and continued development of USACE products, such as HEC-2 to HEC-RAS, suggests that the HEC will continue to be a solid and reliable option. FLO-2D has continued to improve as well, and with a storm sewer modeling component, it differentiates itself from other modeling packages.

- Regarding **agency needs and preferences**, it should be noted that some state agencies utilize software that addresses both dam
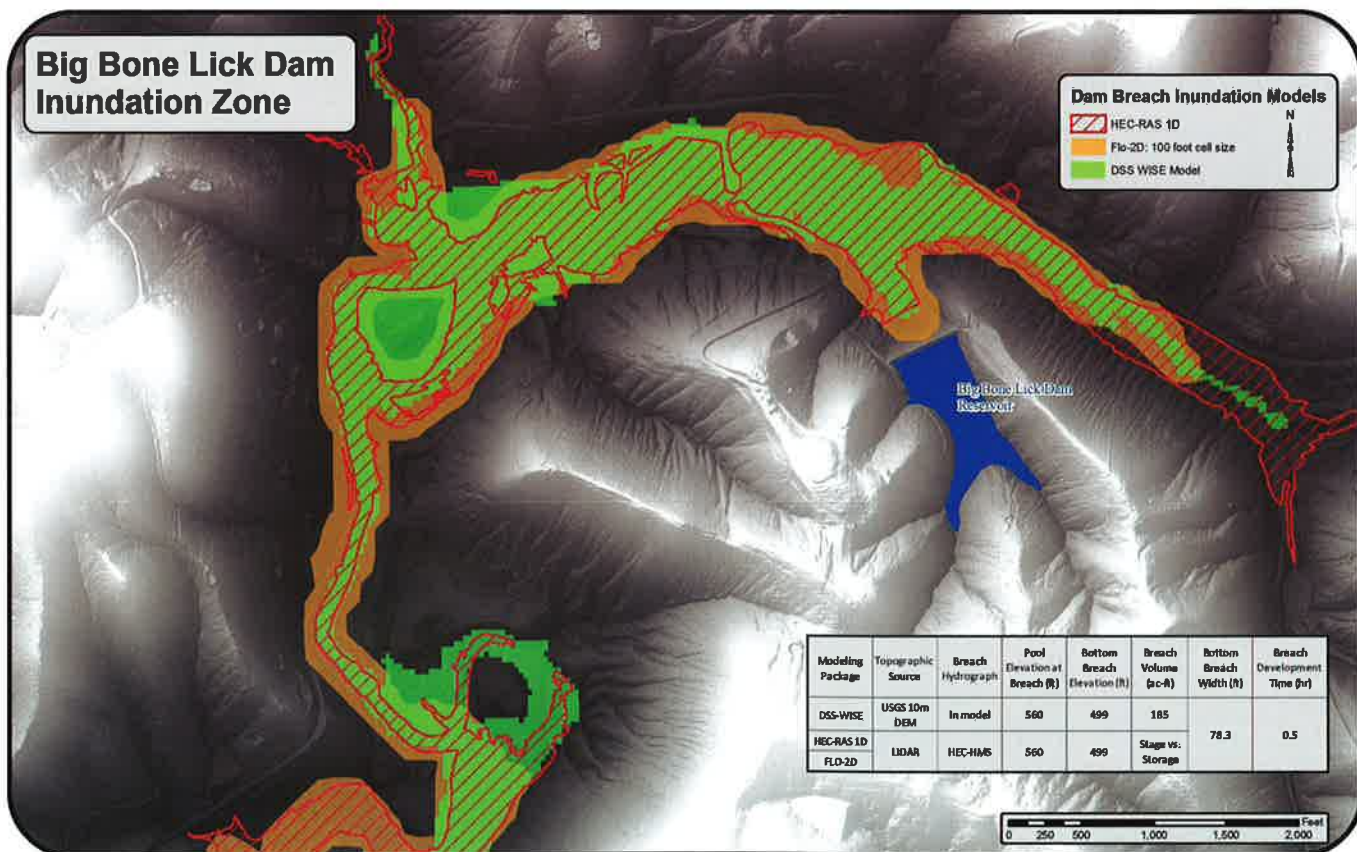
safety and floodplain management. Given the overlap, the ability of GeoDam-BREACH to create flood risk products facilitates a more holistic view of flood risk, enabling the user to create dam safety inundation data that supplements existing FEMA flood study data. Another dam safety and floodplain management area of interaction is the use of two-dimensional modeling software. The availability and use of software with two-dimensional computational options is becoming more prevalent, as evidenced by the Association of State Floodplain Managers' (ASFPM) paper entitled *Unsteady and Two-Dimensional Models: Issues for Regulatory Use.* The software assessed in this study such as DSS-WISE Lite, FLO-2D, and HEC-RAS 5.0 Beta are all two-dimensional hydraulic models. FLO-2D and versions of HEC-RAS up to 4.1 are FEMA approved.

- Consider whether or not an **existing model** is available for study stream of interest, what software package was used, and what modifications may be necessary for a dam breach analysis. Both HEC-RAS and FLO-2D are FEMA-approved models, and the majority of existing FEMA hydraulic models were created in HEC-RAS or its DOS predecessor, HEC-2. In areas where a detailed FEMA study has already been produced, it may be most efficient to modify the existing model. For example, a FEMA HEC-RAS model (typically steady-state) can be converted into an unsteady-state model by importing the dam breach hydrograph and making some adjustments.

MODEL SETUP

The setup of a model can vary considerably depending on the software package and the desired level of precision. The following are best practices and lessons learned that were collected through use of the study software:

- Software such as GeoDam-BREACH/SMPDBK and DSS-WISE Lite require **only basic information** about dam or reservoir geometry and breach parameters. Our experience indicates that a typical model setup and simulation run for GeoDam-BREACH (using SMPDBK) or DSS-WISE Lite is **less than an hour**. For GeoDam-BREACH, a model setup in this timeframe requires basic geometric information about the dam and the breach parameters input by the user. For DSS-WISE Lite, even less data is needed, as breach parameters can be computed, and dam geometric data can be imported with little to no modification from existing national datasets. The speed of setup translates to lower costs making these attractive options for rapid and reasonable assessments where available budget is a driver and/or where answers are needed quickly.

- DSS-WISE Lite can **facilitate the model setup process for other models** that are more detailed (such as HEC-RAS or FLO-2D) by providing a "first-pass" solution that approximates the extents of the inundation zone. The two-dimensional

Big Bone Lick Dam Inundation Zone

Dam Breach Inundation Models
HEC-RAS 1D
Flo-2D: 100 foot cell size
DSS WISE Model

Modeling Package	Topographic Source	Breach Hydrograph	Pool Elevation at Breach (ft)	Bottom Breach Elevation (ft)	Breach Volume (ac-ft)	Bottom Breach Width (ft)	Breach Development Time (hr)
DSS-WISE	USGS 10m DEM	In model	560	499	185	78.3	0.5
HEC-RAS 1D	LIDAR	HEC-HMS	560	499	Stage vs. Storage		
FLO-2D							

computational engine allows flow to travel in multiple directions without the need for cross sections. This benefits the user in understanding items such as the extent of flow up tributary valleys prior to development of a detailed model. Also, the DSS-WISE Lite computational routine is preset to perform analyses for reach lengths of up to 3, 7, and 15 miles, as needed, allowing the user to approximate the downstream extent of input geometry needed. Overall, these approximations of study extents make it less likely that multiple iterations of a detailed model be created to properly capture flow.
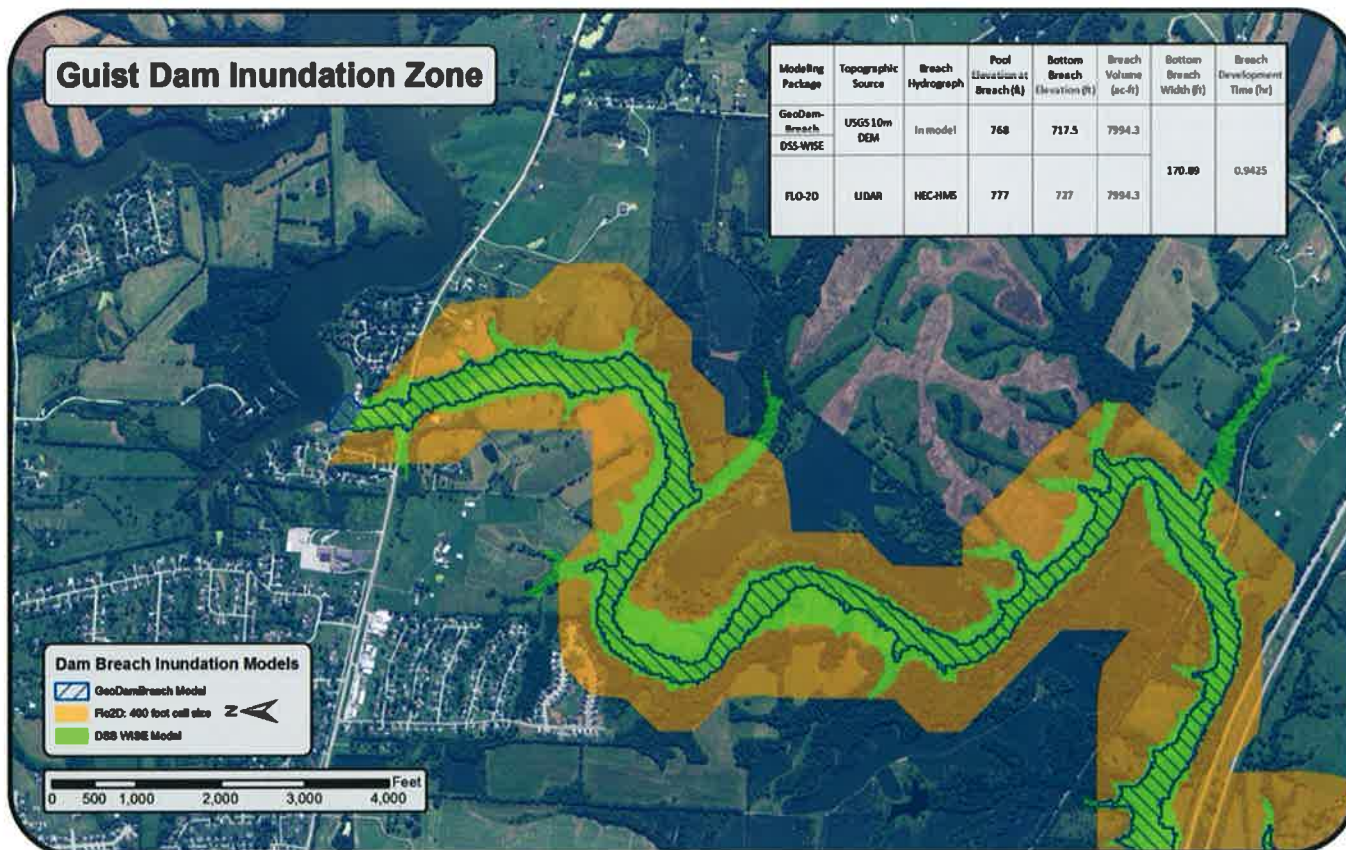
- For software such as BOSS-DAMBRK, HEC-RAS, and FLO-2D that were designed to do more than simple screening level assessments, there is still a **considerable amount of flexibility** in the software options. For example, in HEC-RAS, a steady-state model could be set up to approximate the maximum depth of a breach wave by using simple attenuation techniques to apply the breach peak flow along the stream. This allows the user to more efficiently set up an unsteady-state model (if desired) with geometry in place, initial parameter estimates, and a good indication of the results that should be expected from the unsteady-state model.

- In our experience using HEC-RAS 5.0 beta and FLO-2D, coupling of one-dimensional and two-dimensional areas for a dam breach model may not be as optimal as setting up and running the model for computing all areas as two-dimensional

flow. The editing required to properly model a channel as 1D flow and overbanks as 2D flow can be tedious and may not yield significantly different results than a 2D-only model given that a dam breach will often quickly fill the channel. While some projects may require the inclusion of bridges, culverts, and a detailed representation of the channel in order to provide specific information or more precise answers, other projects may be best suited for 2D-only modeling. In our test cases, models that did not include structures or channel definition and that used simplified assumptions regarding Manning's n roughness values could be set up in half of a day or less. Including all of these elements could cause model set up to be on the order of days.

FLOW INPUT

A given software package may have one or more of the following options to produce a breach hydrograph: entry of user-defined breach parameters, computation of breach parameters within the program using breach regression equations, computation of a breach hydrograph with physically-based methods that use parameters describing the soil characteristics and geometry of the dam, or import of a breach hydrograph. The following summarizes lessons learned during the study regarding breach hydrographs:

- Some software packages include tools that facilitate the computation of a breach hydrograph. DSS-WISE Lite can compute breach parameters using Froehlich's equations, or

Guist Dam Inundation Zone

Modeling Package	Topographic Source	Breach Hydrograph	Pool Elevation at Breach (ft)	Bottom Breach Elevation (ft)	Breach Volume (ac-ft)	Bottom Breach Width (ft)	Breach Development Time (hr)
GeoDam-Breach DSS-WISE	USGS 10m DEM	In model	768	717.5	7994.3		
						170.89	0.9425
FLO-2D	LIDAR	HEC-HMS	777	727	7994.3		

Dam Breach Inundation Models
GeoDamBreach Model
Flo2D: 400 foot cell size Z
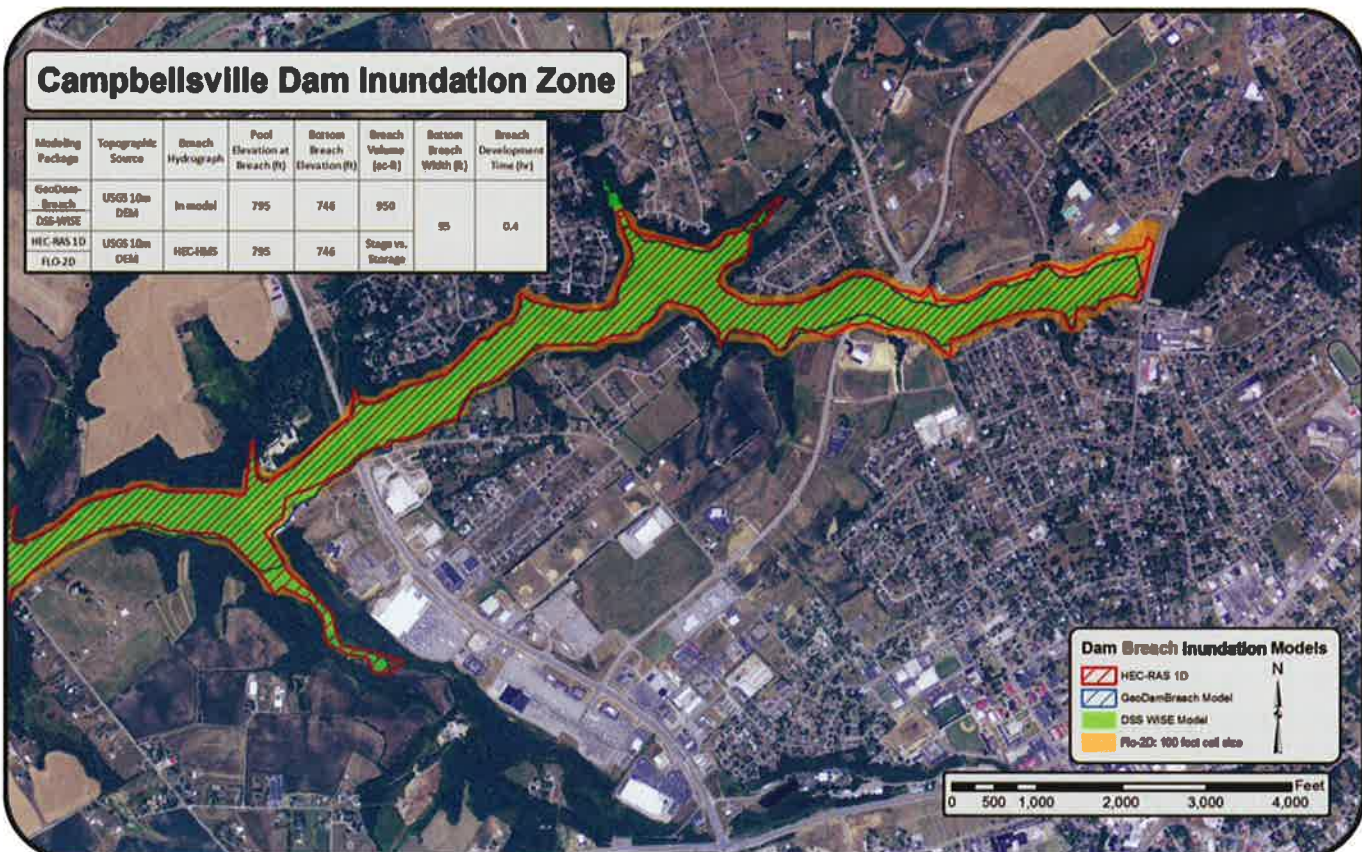DSS WISE Model

Feet
0   500 1,000   2,000   3,000   4,000

alternatively, will accept user-defined values. FLO-2D can compute breach hydrographs using multiple methods, including a physically-based modified version of the NWS-BREACH computational routine.

- One challenge is that software packages vary in their ability to accept hydrograph data from an outside source. Some software allows users to easily link existing hydrograph data to the hydraulic model and some software allows the user to enter a hydrograph in a specific format (e.g., FLO-2D). Other software, like DSS-WISE Lite, does not currently have the capability to import a user-defined hydrograph but will in the next version. The ability to import hydrograph data can be a key consideration for a detailed analysis for which considerable investment has been expended to develop a breach hydrograph in an outside program.

- The user should be aware of the practical and computational limitations of a given software package with regard to breach hydrograph development. DSS-WISE Lite is currently limited to a minimum breach width of 66 feet which may cause over-prediction of the breach hydrograph peak but will have the capability to choose a breach width of 33 feet in the next version. Also, the use of national datasets can sometimes cause issues in DSS-WISE Lite where lake volumes based on NED data and key elevations collected from the NID have discrepancies in elevation values that required editing in order to produce reasonable breach results.

GEOMETRY INPUT

Geometric data import defining the terrain surface, cross sections, bridges, culverts, or other features varies among the studied software packages. The differences in data interoperability affect models' results and ease of use as well as other aspects of software use. Lessons learned include:

- The flexibility to **import data** from one software package to another can be useful when existing models for a given stream reach are available. For example, HEC-RAS geometry data can be imported into FLO-2D, but a significant amount of editing of the imported data is needed in order for it to be used in FLO-2D correctly.

- If high-resolution data is available and used, **be aware of the limitations** of a given model and whether it can fully leverage the benefit of higher resolution data. Some programs limit the number of points in defining a cross section; FLO-2D requires the setting of a computation grid size, which may be much larger than the underlying terrain data; HEC-RAS 5.0 can vary in cell size and leverages much of the geometric data from the underlying terrain to perform computations.

- A key consideration in the creation of model geometry is whether or not **structures such as bridges or culverts** can be included in the model, and if so, how computations through these structures occur. Some of the more significant differences in model results for our study were related to the manner in which computations were performed at bridges and culverts. Some software—such as FLO-2D, HEC-RAS 2D, and BOSS-DAMBRK—relies on

Campbellsville Dam Inundation Zone

Modeling Package	Topographic Source	Breach Hydrograph	Pool Elevation at Breach (ft)	Bottom Breach Elevation (ft)	Breach Volume (ac-ft)	Bottom Breach Width (ft)	Breach Development Time (hr)
GeoDam-Breach / DSS-WISE	USGS 10m DEM	In model	795	746	950	95	0.4
HEC-RAS 1D / FLO-2D	USGS 10m DEM	HEC-HMS	795	746	Stage vs. Storage		

Dam Breach Inundation Models
- HEC-RAS 1D
- GeoDamBreach Model
- DSS WISE Model
- Flo-2D: 100 feet cell size

user-entry of rating curve data. DSS-WISE Lite can omit bridges altogether if the user so chooses; some models allow for explicit definition of bridge or culvert geometry (HEC-RAS 1D), while others do not accurately account for backwater effects at bridges (SMPDBK, in GeoDam-BREACH).

COMPUTATIONAL ROUTINE (ROUTING, MODEL STABILITY, AND OTHER SIMULATION ISSUES)

Each software package contains a mathematical model that is used to compute the routing of a breach hydrograph downstream. The software vary in the manner in which spatial and temporal (time-based) data is input and output, which input parameters are needed, how parameters are applied, which equations or methods are used to compute flow through or at hydraulic structures. Collectively, these items can be referred to as the computational routine of the model, which defines how the model will behave in terms of accuracy, precision, and model stability. Lessons learned include the following:

- Some models are **more stable** than others when running unsteady-state simulations, and may require less adjustment after the initial setup and simulation. FLO-2D was a very stable model, while HEC-RAS (particularly HEC-RAS 1D) exhibited a number of instability issues that must be worked through. This may be due in part to FLO-2D's ability to adjust the computational time step during a model run, while HEC-RAS does not appear to have this option.

- GeoDam-BREACH/SMPDBK uses **simplified flood routing** and does not significantly attenuate flow from the dam breach hydrograph. This can result in overly conservative inundation delineations. Also, backwater effects are not accounted for in GeoDam-BREACH.

- The manner in which a given model utilizes **elevation data** is a key factor in evaluating the model's computational routine. There are two steps in the model routine where elevation data can significantly affect model results: the processing and input of elevation data for model computations, and the use of elevation data to develop inundation boundaries or other output products such as depth grids. Some models are limited to certain datasets, and computational limits (for example, HEC-RAS 2D uses elevations along cell faces and computes volume-elevation data for each cell to better capture the original elevation data, whereas FLO-2D uses a single elevation to represent each grid).

- To the right, model results from **Scenic Lake Dam** are compared to illustrate the effect of elevation data limitations. Downstream of the dam is a very flat floodplain with a small channel. Presented in the map are delineation results from DSS-WISE Lite (two dimensional analysis with low resolution elevation data from the NED), GeoDam-BREACH/SMPDBK (one dimensional analysis with low resolution elevation data from the

Scenic Lake Model Results

NED), and FLO-2D (two dimensional analysis with LiDAR-based DEM sampled to the computation grid size). In this case the models results differ substantially and a user needs to understand the tendencies of the software in use.

MODEL VALIDATION

When a model is being used for purposes such as hazard classification, risk mitigation, or numerous other important applications, the ability to review and validate the model is desirable. Regarding model validation, the following should be considered:

- DSS-WISE Lite does not output the computed breach hydrograph, inhibiting the user from inspecting the hydrograph for model validation purposes.

- Some models do not have validation tools available to the user, while others have very robust tools to assist in this process. FLO-2D reports volume conservation, HEC-RAS reports errors and warnings, both have multiple forms of graphical and tabular data, and BOSS-DAMBRK has a number of output tables. The flexibility to interpret whether or not a model is performing correctly is limited in software packages such as DSS-WISE Lite, which only outputs end-user products, but not interim results.

OUTPUT DATA

Model setup and computations can be rendered of little value if the results are not reported in a format that meets a given project's needs. In addition to the variety of tables and graphs available as model output, the following addresses data formatting for import into HAZUS and GeoDam-BREACH, programs that can communicate and display model results through creation of products such as damage estimates and FEMA flood risk data sets.

- Consider the various means a program can display results and how this fits with project needs. DSS-WISE Lite, FLO-2D, HEC-RAS 2D, and GeoDam-BREACH can produce spatial output that provides the arrival time of a breach wave, supporting emergency planning. Other programs, such as HEC-RAS 1D and BOSS-DAMBRK, provide data in tabular format that requires manipulation in GIS or CAD software.

- In addition to tables and graphs, HEC-RAS and FLO-2D, have animation capabilities that show the fluctuations of a given variable over time. Animations allow for clearer interpretation of model results.

- GeoDam-BREACH facilitates the creation of flood risk products such as a depth grid, velocity grid, arrival time grid, and residual risk polygon, loss-of-life estimates, and an EAP through a series of workflows.

- HAZUS-MH provides a means to estimate potential economic damages due to a breach event. Our study indicated that ESRI grids are the primary breach model output used as input to the HAZUS analysis. Those models with non-grid based outputs, such as cross sections in a HEC-RAS 1D model that have been attributed with water surface elevation can still be utilized, but they require additional processing in order to yield a water surface elevation grid for HAZUS input.

CONCLUSION AND CREDITS

The authors' hope is that this effort provides a general understanding regarding model software selection for those peripherally involved in modeling and able to influence the practice, and practical assistance for the modelers spending hours, weeks and months attempting to select the right approach to get to the right answer for our great nation's dams. We would like to thank ASDSO, FEMA, the software developers, and the numerous professionals who either assisted directly in this study or developed the models that were used, including KDOW Dam Safety staff, AECOM, T&M, Stantec, Arcadis and ICA. We should also note that our comments are meant to be objective and based on personal experience and do not necessarily represent the opinions of our employers.

South Fork Beargrass Creek Dam Inundation Zone
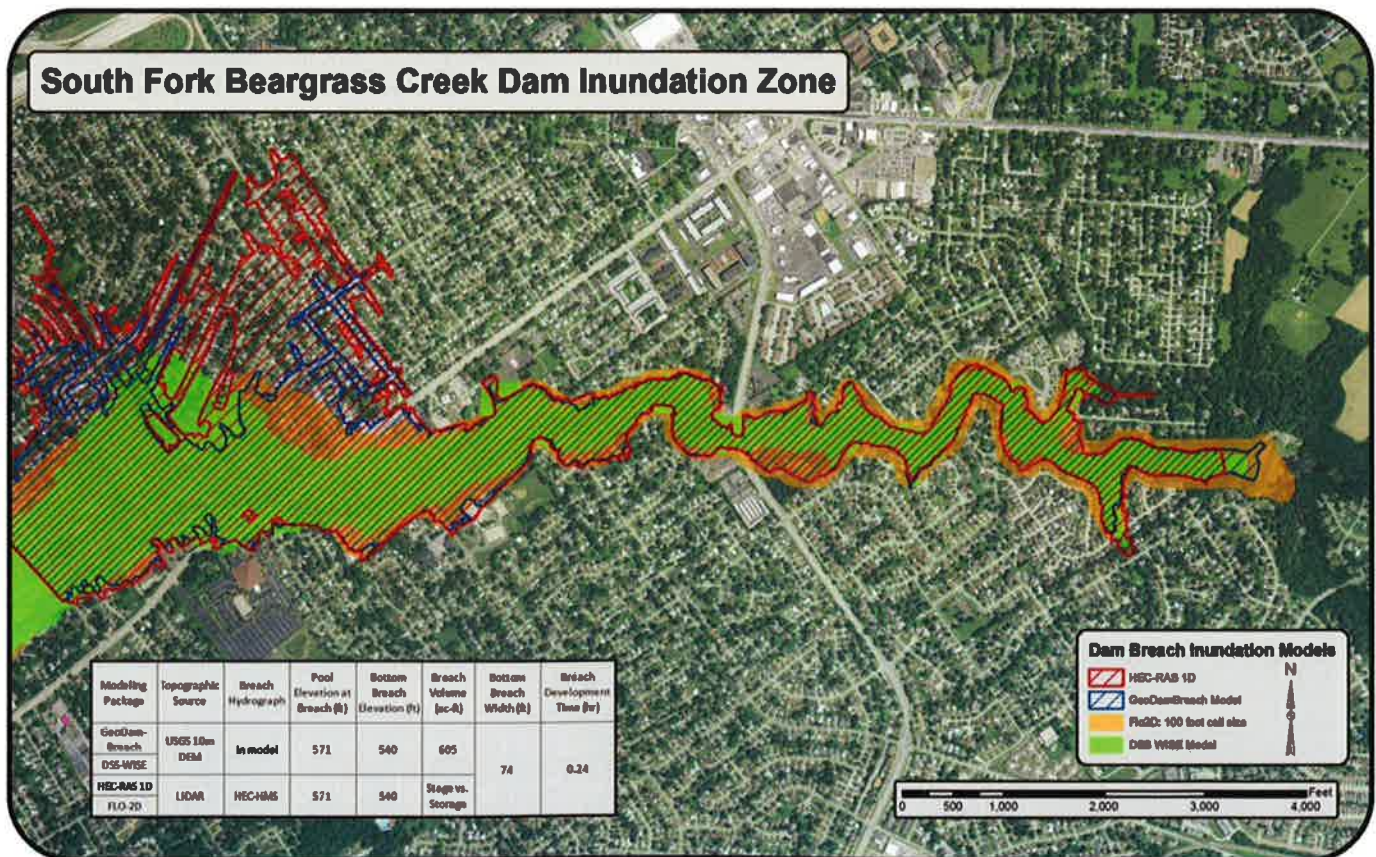
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