VALIDATION OF A NEW GIS TOOL TO RAPIDLY DEVELOP SIMPLIFIED DAM BREAK MODELS

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Abstract

National Weather Service (NWS) forecasters need simple and accurate tools to develop dam failure flood warnings. It is preferable to use a pre-developed engineering model or published Emergency Action Plan (EAP) to produce forecasts. However, easy access to pre-developed models is rare, and many dams in the United States do not have an EAP. Therefore, NWS forecasters commonly use a simple technique known as "Rules of Thumb" and then develop Simplified Dam Break Models (SMPDBK) if time permits. Several NWS offices have independently developed procedures to build SMPDBK models, but these require several time consuming manual steps. To make the process faster, we developed GeoSMPDBK, a GIS-based tool to develop a SMPDBK model in less than 30 minutes. For ease-of-use and consistency, nationally available streamline and 30-meter digital elevation model data are provided as default inputs.

We evaluated GeoSMPDBK by running GeoSMPDBK/SMPDBK hindcasts for six historical dam failures and comparing results to observed data and Rules of Thumb. Unlike many previously published studies, these hindcasts used only input data that would likely be available for real-time forecasting. For two of the dam failures, data from post-event published studies (which used observed breach properties and more detailed geometry data) were also available for comparison.

Rapidly developed GeoSMPDBK models markedly improved upon Rules of Thumb flow hindcasts for 5 out of 6 dams. For the two worst performing GeoSMPDBK models, substantial additional improvement was obtained by adding inactive flow areas to more accurately predict flow attenuation. Seeing this improvement, GeoSMPDBK was enhanced to make defining inactive flow areas easier. For GeoSMPDBK models built using default data, average mean absolute percent flow prediction error for six dams (including the two with refined inactive areas) was 38% compared with 67% for Rules of Thumb.

We compared hindcast elevations and observed high-water marks downstream of two dams (Kelly Barnes and Big Bay). For these dams, we found that replacing the 30-m DEM with a 10-m resolution DEM from NED substantially improved elevation predictions but did not affect flow predictions. Mean absolute errors were 2.0 ft and 2.6 ft for Kelly Barnes and Big Bay respectively. Hindcast errors for Big Bay were higher than errors reported in the literature for post-event models, suggesting additional room for improvement.

Our results confirmed expectations that GeoSMPDBK-based models provide a robust intermediate solution between Rules of Thumb and more complex dynamic models.

Key Words: dam failures, SMPDBK, GIS, flood forecasting

Introduction

The National Weather Service (NWS) must issue accurate and timely forecasts for floods resulting from dam failures to protect lives and property. Although already an important part of the NWS mission, accurate dam break forecasts will become increasingly important during the next 25 years. In 2035, approximately 90 percent of dams in the United States will be more than 50 years old.

Dam failures can be sudden events and the resulting flood waves travel rapidly downstream; therefore, forecasters need tools to rapidly quantify flood characteristics such as peak flow, peak depth, timing, and inundated area. Preferably, forecasters could run detailed dam break models from pre-developed hydraulic engineering studies (e.g. those developed for Emergency Action Plans (EAPs)) with inputs reflecting current hydrologic conditions. Unfortunately, few detailed engineering models are operationally available to NWS forecasters. Forecasters more often use model scenario data published in EAPs to formulate warnings. However, approximately 16,600 significant or high hazard dams in the United States do not have EAPs according to the 2009 National Inventory of Dams (http://nid.usace.army.mil).

In the absence of detailed engineering models or published EAPs, forecasters develop forecasts using simple models and then move on to more sophisticated methods, time permitting. Although very rough, a simple technique known as “Rules of Thumb” (Larson 1998) provides first estimates of peak discharge at the dam and peak discharge, flood depths, and travel times to downstream locations using minimal input data (dam height and reservoir volume). With some additional inputs (geometry for at least two cross sections and Manning’s n estimates), Simplified Dam Break (SMPDBK) models can be built and run (Wetmore et al. 1991). Although substantially simpler than fully dynamic engineering models, both Rules of Thumb and SMPDBK also require specialized training to use properly. In particular, building effective SMPDBK models requires engineering judgment to effectively place cross-sections and determine Manning’s n estimates.

During the past 10-15 years, as GIS tools and digital terrain data have become more universally accessible, several NWS River Forecast Centers (RFCs) independently developed GIS-based procedures to derive SMPDBK inputs. However, these locally developed procedures typically require more manual steps than desirable, have limited documentation, and are not accessible to all RFCs. To address these limitations, we have developed a new GIS-based tool to rapidly develop SMPDBK models referred to as GeoSMPDBK.

GeoSMPDBK is designed to allow forecasters to build a sound SMPDBK model within 30 minutes or less. To facilitate rapid use, the tool is delivered to forecast offices with nationally available DEM (NHDPlus, 30-m) (NHDPlus Team 2010) and river network data sets (NHD), as well as the National Inventory of Dams (NID) in GIS format.

In this paper, we evaluate the accuracy of SMPDBK models developed using GeoSMPDBK and the default data sets. We compare GeoSMPDBK model hindcasts to observed data, to hindcasts from Rules of Thumb, and to simulations from more developed post-event models for a few cases. These experiments are important to (1) quantify the expected accuracy of GeoSMPDBK models using relatively coarse resolution DEMs, (2) confirm that these models with default input data improve upon Rules of Thumb, (3) identify and implement improvements to GeoSMPDBK, and (4) determine potential improvements from more advanced models requiring substantially more resource investment to develop and operationally implement.

This study is unique compared to previous dam break modeling studies because GeoSMPDBK is evaluated in hindcast mode, denying input information (e.g. observed breach properties, observed high water marks for calibration) that will typically not be available in forecast mode. More often, published studies have focused on refining their models with as much data as possible (D.L. Fread and J.M. Lewis 1998; Yochum et al. 2008). Published validation of SMPDBK itself has included model-to-model comparisons and detailed post-event case studies (D.L. Fread 1989), but we have not found previous evaluations of models prepared with limited input data to mimic an operational forecast situation.

Methodology

This section provides a description of the models, the hindcast methodology and the dam failures studied. For this discussion, we divide dam break modeling into two main components: breach modeling and routing. In our hindcasts, we compared two simple routing methods: the NWS Rules of Thumb and SMPDBK models from GeoSMPDBK. Although not used for hindcasts, we also contrasted Hydrologic Engineering Center River Analysis System (HEC-RAS) capabilities with SMPDBK and included results from a HEC-RAS post-event simulation model (from the literature) in our evaluation. The NWS has selected HEC-RAS to replace FLDWAV as the primary tool for one-dimensional hydraulic modeling of rivers (Moreda et al. 2009), and HEC-RAS is included in the NWS Community Hydrologic Prediction System (CHPS) (Roe et al. 2010). In the future, HEC-RAS can also be used for dam break modeling within CHPS.

Breach Model

The ASCE/EWRI Task Committee on Dam/Levee Breaching (2011) provides a detailed review of the science and engineering of earthen embankment breaching, discussing a range of breach models from simple regression to detailed, physically-based. While much is known about breach formation processes, for most dams the only practical method to predict breach parameters in emergency situations is to use empirical equations. Advanced breach models are impractical for widespread operational implementation (e.g. during an imminent dam break) due to difficulty in getting accurate parameter inputs.

Based on uncertainty analysis of empirical breach equations presented by Wahl (2004), we selected the Froehlich (1995) empirical breach equations for use in this study.

$$B_{avg} = 0.1803 K_o V_w^{0.32} H_b^{0.19} \qquad (1)$$

$$t_f = 0.00254 (V_w)^{0.53} H_b^{-0.9} \qquad (2)$$

$$Q_p = 0.607 (V_w^{0.295} H_w^{1.24}) \qquad (3)$$

where:
B_{avg} = average breach width
t_f = time to failure (from breach initiation to final size)
Q_p = Peak flow at breach outlet
K_o = overtopping multiplier, 1.4 for overtopping, 1.0 for piping
V_w = volume of water above breach invert at time of failure (m^3)
H_b = height of the breach (m)

H_w = depth of water above breach invert at time of failure (m)

These equations are applicable to earthen or rockfill dams, which covers all the dams used in this hindcast study and 90% of the dams in the 2009 NID.

Rules of Thumb Routing

The NWS Rules of Thumb were developed to provide quick and easy guidance to forecasters in critical dam break situations. They are intended to be used only as an initial estimate while results from more sophisticated model forecasts are prepared. Quantitative errors associated with using Rules of Thumb as a forecast tool have not been previously documented. Here we use the Rules of Thumb related to peak flow and peak depth estimation, which are defined as follows:

- Maximum flood depth just downstream of the dam is no more than ½ the height of the water behind the dam.
- Flow is reduced by about ½ for each 10 miles of travel downstream of the dam.
- Flood depth is reduced by about ½ for each 10 miles of travel downstream of the dam.

The Rules of Thumb for flow routing were originally derived by plotting observed discharge versus distance downstream on log-log paper for several historical dam failures and visually fitting an approximate curve. Subsequently, a mathematical approximation for that curve was derived, yielding the simple rules described above. The process was repeated using observed wave height versus downstream distance.

SMPDBK

The Simplified Dam Break (SMPDBK) Flood Forecasting Model (Wetmore et al. 1991) predicts peak flow, peak depth, and peak arrival time at selected locations downstream of a dam. Developing a SMPDBK model requires much less user time, data, and technical expertise than implementing a fully dynamic flow routing model using a model such as HEC-RAS.

It takes longer to develop a HEC-RAS model using HEC-GeoRAS (Ackerman 2009) than a SMPDBK model using GeoSMPDBK because:

- SMPDBK requires fewer cross-sections.
- SMPDBK offers guaranteed stability. HEC-RAS will likely require cross-section interpolation and time step adjustments to produce a stable run.
- SMPDBK does not require definition of bank stations.
- GeoSMPDBK/SMPDBK requires fewer mouse clicks overall.
- SMPDBK does not require defining explicit upstream and downstream boundary conditions.

Limitations of SMPDBK are that it only models peak flows and depths and not the full hydrograph, it cannot account for reservoir inflows during event, it cannot account for backwater, and it does not model downstream complexities such as additional dams, levees, and bridges.

GeoSMPDBK

The GeoSMPDBK application eliminates several tedious tasks from the process of developing a SMPDBK model. GeoSMPDBK, built on ArcGIS Desktop technology, provides tools to help a user locate the dam of interest, trace the appropriate section of a river to model, and draw suitable cross-sections with visual reference to topographic background data. GeoSMPDBK automatically generates the SMPDBK input file using information from the DEM, digitized stream line data, the National Inventory of Dams, and the cross-sections drawn by the user. Using the raw cross-section geometry extracted from the DEM, GeoSMPDBK creates topwidth-elevation pairs in the format required by SMPDBK, while preserving the area-elevation curve. When drawing the cross-sections, the user can also use background aerial imagery and topographic data to determine Manning's n values and identify inactive flow portions of the cross-sections.

GeoSMPDBK is delivered to RFCs with default national data sets to provide out-of-the-box functionality. This includes 2009 NID data, 30-meter DEMs from the National Hydrography Dataset Plus (NHDPlus) project, and hydrography from NHDPlus. The required imagery and topographic maps are readily obtained from Web Mapping Services using standard ArcGIS Desktop functionality (http://help.arcgis.com/en/arcgisonline/agolbasemaps.html). More accurate local DEMs can be used if desired. Beta testing and the validation results presented here suggest that, using the provided data, an educated user can create a useful SMPDBK model in less than 30 minutes. Beta testers were able to achieve "educated user" proficiency relatively quickly by practicing with several case studies provided with the default data.

Hindcast Methodology and Dam Failures Studied

To evaluate the serviceability of GeoSMPDBK in a forecasting situation, we generated hindcasts for six historical dam failures using SMPDBK models built with GeoSMPDBK and also using Rules of Thumb. For these hindcast runs, we assume only two known pieces of information in addition to the topographic and hydrographic GIS data: the reservoir volume and water height at the time of the failure. Implementing the Rules of Thumb only requires an estimate of peak flow rate at the dam, estimated using Equation 3. We relied on Equations 1 and 2 to compute breach width and formation time as required by SMPDBK to compute peak flow rate. In keeping with the hindcast philosophy, we did not use observed breach properties from post-event analysis reported in the literature.

Table 1 lists characteristics of the dam failures studied and Figure 1 shows the dam locations. The sample of historical events included in this study includes diverse geographic locations and dam sizes. We were careful to obtain and study primary literature references, extract the appropriate observed data values, and determine the precise geographic locations of the observations to validate our hindcasts.

We used visual inspection of geo-referenced imagery showing vegetation and buildings in the floodplain to estimate Manning's n values. Manning's n values were subjectively assigned based on recommended values from Whetmore et al. (1991) associated with different land-use types in the overbank area: 0.04 – 0.05 for pastureland or cropland; 0.07 for moderately wooded; and 0.1 to 0.15 for heavily wooded areas. These ranges are similar to ranges from Chow (1959). It is important to emphasize that these values are for the floodplain and not the channel, assuming that overbank flow is more important than in-channel flow during dam break floods. Use of these Manning's n assumptions has proven effective in the validation results presented below.

Previous studies we are aware of (D.L. Fread and J.M. Lewis 1998; Yochum et al. 2008) have not taken this hindcasting approach, but have used all post-event data available. For two of the six dams, we compared simulations from post-event models to our hindcast models. This provides information on the potential gains that can be made with improved input data, or more refined models that cannot be created on-the-fly.

Table 1. Historical Dam Failures Studied

Name	State	Year Failed	Dam Height (ft)	Water Level at Time of Failure (ft)	Volume in Reservoir prior to flood (acre-ft)	Primary Reference
Little Deer	Utah	1963	86.0	75.1	1000	Rostvedt et al. (1968)
Swift Dam	Montana	1964	189.0	157.0	30004	Boner and Stermitz (1964)
Hell Hole	California	1964	220.0	115.2	24811	Scott and Gravlee (1968)
Buffalo Creek	West Virginia	1972	46.0	46.0	392	Davies et al. (1972)
Kelly Barnes	Georgia	1977	38.0	37.1	630	Sanders and Sauer (1979)
Big Bay	Mississippi	2004	51.3	44.5	14200	Yochum et al. (2008)

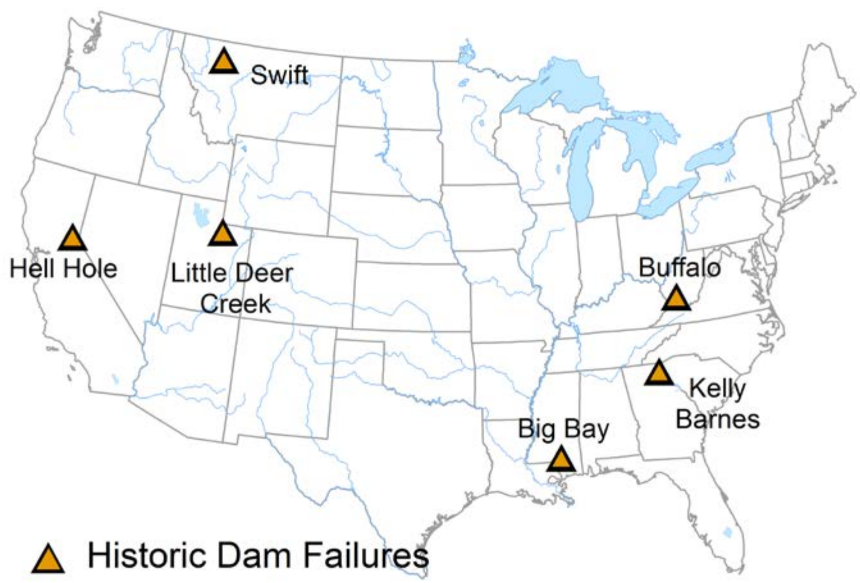

Figure 1. Locations of dam failures studied.

Table 2 and 3 report all observed flow and elevation values used for validation. Observed flow data were extracted from the original references. Some references only reported “indirect” or “estimate” as the measurement technique, however, many reported using the slope-area computation procedure (Benson and Dalrymple 1967). We suspected that “indirect” and “estimates” are also references to the slope-area technique. The uncertainty in these observed flow estimates is not known but Benson and Dalrymple (1967) provided some information on possible errors from the slope-area technique. They reported a maximum error of 25 percent from the worst of 22 observations on the Columbia River and an average error of 6.7 percent for the remaining 21 observations (omitting the worst observation). ‘Observed’ flows for Big Bay dam were derived from the detailed, post-event HEC-RAS model developed by Yochum et al. (2008).

In many cases where latitude and longitude of observations were not available, the geographic locations were estimated from the reported downstream distance measured along the centerline of the NHDPlus flowline data set. Actual stream distance will vary with the source map scale and flow depth for sinuous streams. For the observation locations corresponding to USGS gauging stations, the USGS reported latitude-longitude coordinates of the gauge were taken as the observation location.

In addition to flow comparisons, we also compared predicted elevations to high water mark elevations for some locations. Unfortunately, high water mark data are not reported as often as flow. In addition, we found that elevation prediction errors are more sensitive to knowing the precise location of the high water marks. Therefore, we only report comparisons to high water mark elevations for the Big Bay and Kelly Barnes dam where we could most confidently identify the high water mark locations from the literature (see Table 3). For Big Bay Dam, Yochum et al. (2008) reported the locations of high water mark data in latitude-longitude coordinates. From the Kelly Barnes publication (Sanders and Sauer 1979), we extracted high water mark elevations from the profile plot provided and estimated locations using both the map provided and distances along the profile.

We were also able to make a flow depth comparison 33.1 miles downstream of Hell Hole Dam on the Middle Fork of the American River near Foresthill. At this USGS gauging station location, a plot of flow measurement data reveals an obvious break in the stage–flow relationship, suggesting a bankfull elevation of 11.5 ft. By subtracting this value from the observed stage of 69 ft, we estimated the observed flood depth as 57.5 ft. We assumed that the channel conveys only a small portion of the flow in this dam break flood such that the depth above bankfull is the best number to compare to the flood depth predicted by either SMPDBK or Rules of Thumb. Although many of the flow observations downstream of Little Deer and Swift dams also correspond to USGS gauging stations, the flow measurement records available for these locations were not adequate to infer bankfull stages and, hence, dam break flood depth.

Table 2. Observed flows from the literature.

Dam Name	River Station	Distance from Dam (mi)	Obs Flow (ft3/s)	Technique Used to Estimate Observed Flow
Little Deer	Damsite	0.02	47000	"Estimate"
	Duchesne nr Hanna	9.25	17500	Gauging station
	Duchesne nr Tabonia	36.1	5260	Gauging station
	Duchesne at Duchesne	57.93	2980	Gauging station
Swift	Birch Creek nr Dupuyer	14.26	881000	Indirect
	Two Medicine R. Below Birch Creek nr Ethridge	65.19	204000	Slope-area
Hell Hole	Mid. fork of the Amer. Near Foresthill	33.13	310000	Slope-area
	Mid. fork of the Amer. Near Auburn	54.59	253000	Gauging station
Buffalo	Buffalo Ck below Saunders	1.39	50000	Indirect
	Buffalo Ck below Stowe	7.05	13000	Indirect
	Buffalo Ck above Accoville	12.34	8800	Indirect
	Buffalo Ck at Man	15.25	7500	Indirect
Kelly	D	0.23	23000	Slope-area
	E	0.84	24000	Slope-area
	F	2.09	14300	Slope-area
	G	4.56	6380	Contracted-opening
	H	6.25	3660	Contracted-opening
Big Bay	500000	0	146931	HEC-RAS
	495418	0.38	141986	HEC-RAS
	489003	1.73	106666	HEC-RAS
	480714	3.09	80882	HEC-RAS
	471891	4.64	69580	HEC-RAS
	461552	6.57	51920	HEC-RAS
	435769	11.39	34543	HEC-RAS
	406278	16.77	27691	HEC-RAS
	398757	18.31	26914	HEC-RAS

Table 3. Observed elevations or depth from the literature.

Dam Name	River Station	Longitude (Decimal Degrees	Latitude NAD 83)	HWM Elevation (ft NAVD 88)
Hell Hole	Mid. fork of the Amer. Near Foresthill	-120.4089	39.0581	(57.5)*
Kelly	D	-83.3618	34.5996	1064.6
	E	-83.3595	34.5922	845.5
	F	-83.3420	34.5944	804.7
	G	-83.3235	34.6171	715.8
	H	-83.2975	34.6191	
Big Bay	495418	-89.5741	31.1732	245.8
	489003	-89.5898	31.1619	227.0
	480714	-89.6093	31.1633	218.0
	471891	-89.6271	31.1583	204.6
	461552	-89.6452	31.1473	193.7
	435769	-89.7022	31.1359	166.7
	406278	-89.7572	31.1422	139.2
	398757	-89.7741	31.1300	127.7

* Value reported for Hell Hole is flood elevation above bankfull.

Results and Discussion

Rules of Thumb

Figure 2 compares the routing Rules of Thumb curve with observed data from the six dams, plotting the reduction in peak flow against distance from the dam. This highlights observed attenuation compared to the Rules of Thumb attenuation. Note that for most dams, the first observed flow is not right at the dam. Therefore to construct Figure 2, flows at the dam were estimated by extrapolating backwards from the nearest observation by using the decay ratio predicted by our best SMPDBK model. The Rules of Thumb method tends to predict flow attenuation in the middle of the range of observed values.

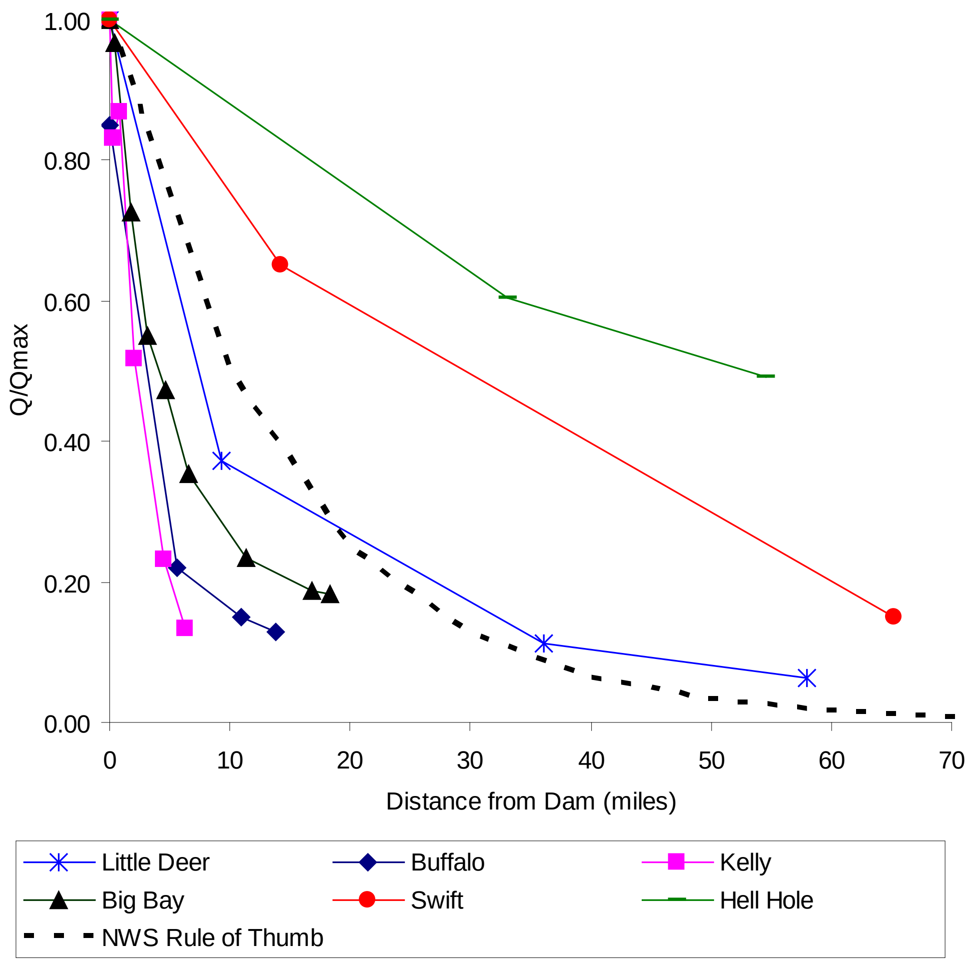

Figure 2. Peak flow attenuation from NWS Rules of Thumb compared to observed flow attenuation. Q = flow; Q_{max} = flow at the dam.

Cross-section Spacing

For GeoSMPDBK hindcasts, cross-sections were drawn so that there is one cross-section intersecting each observation location. Additional cross-sections were drawn to properly represent changes in the width of the flood plain along the river. Table 4 lists the number of cross-sections, the total model length for each dam, and the average cross-section spacing. For this study, the number of cross-sections in each GeoSMPDBK model was kept relatively low, consistent with a forecast situation in which there is not a lot of time to draw cross-sections. We observed that wise placement of a few cross-sections gives optimal performance and adding interspersed cross-sections generally does not improve performance. When placing cross sections, an educated user will use visual inspection with GIS imagery to avoid drawing cross-sections intersecting elevation anomalies. For example, in the initial Big Bay model, we found anomalous DEM data causing unexpectedly high elevation values at the bottom of a single cross-section. Inspection of the DEM along with imagery data suggested that this DEM error was caused by a bridge deck being evaluated as the terrain height at this location. Obtaining a more accurate DEM (as discussed below) may be a useful alternative.

Table 4. Cross-section spacing information.

Dam Name	No. of cross-sections	Model Length (mi)	Avg. cross-section spacing (mi)
Little Deer, UT	13	57.9	4.5
Swift Dam, MT	11	65.2	5.9
Hell Hole, CA	6	54.6	9.1
Buffalo Creek, WV	5	15.3	3.1
Kelly Barnes, GA	8	6.3	0.8
Big Bay, MS	9	18.6	2.1

Flow Comparisons

To test the simplest possible hindcasts, initially no effort was made to incorporate inactive flow areas into the GeoSMPDBK cross-sections. We later modified two of the models to include inactive flow areas. In this section we analyze the results of the simulations without inactive flow area considerations. The next section provides the analysis of results for the simulations with inactive flow areas. Table 5 summarizes the results for predicted flows from GeoSMPDBK (with and without the inactive areas) and Rules of Thumb downstream from the six dams studied. Table 6 provides further details on simulation results compared with observations for each location.

For each of the Rules of Thumb and GeoSMPDBK simulations, the predicted peak flows are compared to observed peaks at each cross section to produce a mean absolute error of flow prediction. For all but Little Deer, GeoSMPDBK yields a substantially lower mean absolute percent error than Rules of Thumb as expected. Excluding Little Deer, the relative error is reduced, on average, to 40% of the Rules of Thumb hindcast error (second to last column).

Table 5. Mean absolute percent flow prediction errors.

	No. of Sections with Obs. Flow	Mean absolute percent error for flow prediction relative to observed			GeoSMPDBK Pct. Error/ Rules of Thumb Pct. Error	
		Rules of Thumb	GeoSMPDBK Initial	GeoSMPDBK w/ Inactive	Initial	w/ Inactive
Little Deer	*3*	49	274	127	5.59	1.51
Swift Dam	*2*	89	20		0.22	-
Hell Hole	*2*	94	13		0.14	-
Buffalo Creek	*4*	33	14		0.42	-
Kelly Barnes	*5*	109	67	39	0.62	0.54
Big Bay	*5*	29	16		0.60	-

Average Mean Absolute Percent Flow Error for Rules of Thumb over six dams = 67%
Average Mean Absolute Percent Flow Error for Best GeoSMPDBK models (using the results with inactive where available) over six dams= 38%

Table 6. Flow observations and hindcast predictions.

Dam Name	River Station	Distance from Dam (mi)	Obs Flow (ft3/s)	Predicted Flows (cfs) Rules of Thumb	GeoSMP DBK	GeoSMPDB K – w/ inactive
Little Deer	Damsite	0.02	47000	65203	72273	72273
Little Deer	Duchesne nr Hanna	9.25	17500	34417	39849	29169
Little Deer	Duchesne nr Tabonia	36.10	5260	5386	22139	16868
Little Deer	Duchesne at Duchesne	57.93	2980	1192	20707	7893
Swift	Birch Creek nr Dupuyer	14.26	881000	165629	569967	
Swift	Two Medicine R. Below Birch Creek nr Ethridge	65.19	204000	4912	215435	
Hell Hole	Mid. fork of the Amer. Near Foresthill	33.13	310000	29240	354803	
Hell Hole	Mid. fork of the Amer. Near Auburn	54.59	253000	6576	283183	
Buffalo	Buffalo Ck below Suanders	1.39	50000	24456	26043	
Buffalo	Buffalo Ck below Stowe	7.05	13000	16542	13480	
Buffalo	Buffalo Ck above Accoville	12.34	8800	11478	9165	
Buffalo	Buffalo Ck at Man	15.25	7500	9388	7550	
Kelly	D	0.23	23000	23324	21347	21347
Kelly	E	0.84	24000	22361	21134	20740
Kelly	F	2.09	14300	20512	18001	16169
Kelly	G	4.56	6380	17294	13107	9625
Kelly	H	6.25	3660	15389	10371	7749
Big Bay	500000	0.00	146931	74596	121919	
Big Bay	495418	0.38	141986	70245	83146	
Big Bay	489003	1.73	106666	64478	79508	
Big Bay	480714	3.09	80882	57891	72387	
Big Bay	471891	4.64	69580	51584	60663	
Big Bay	461552	6.57	51920	45145	50987	
Big Bay	435769	11.39	34543	32160	33788	
Big Bay	406278	16.77	27691	21843	23496	
Big Bay	398757	18.31	26914	19802	21620	

Flow attenuation relative to peak flow at the dam is plotted in Figure 3, which shows that GeoSMPDBK models were able to correctly discriminate the relative flow attenuation among different dams. With the exception of Little Deer, there was obvious improvement when compared to the Rules of Thumb model, which predicts the same attenuation rate for all dams. With the exception of Hell Hole, where the flow attenuation was modeled almost perfectly, our initial GeoSMPDBK models consistently underestimated flow attenuation (i.e. the model predicts too great a flow at large distances from the dam). This situation was most severe in the case of the Little Deer simulation creating large flow prediction errors far downstream of the dam, ultimately leading to a large mean absolute error.

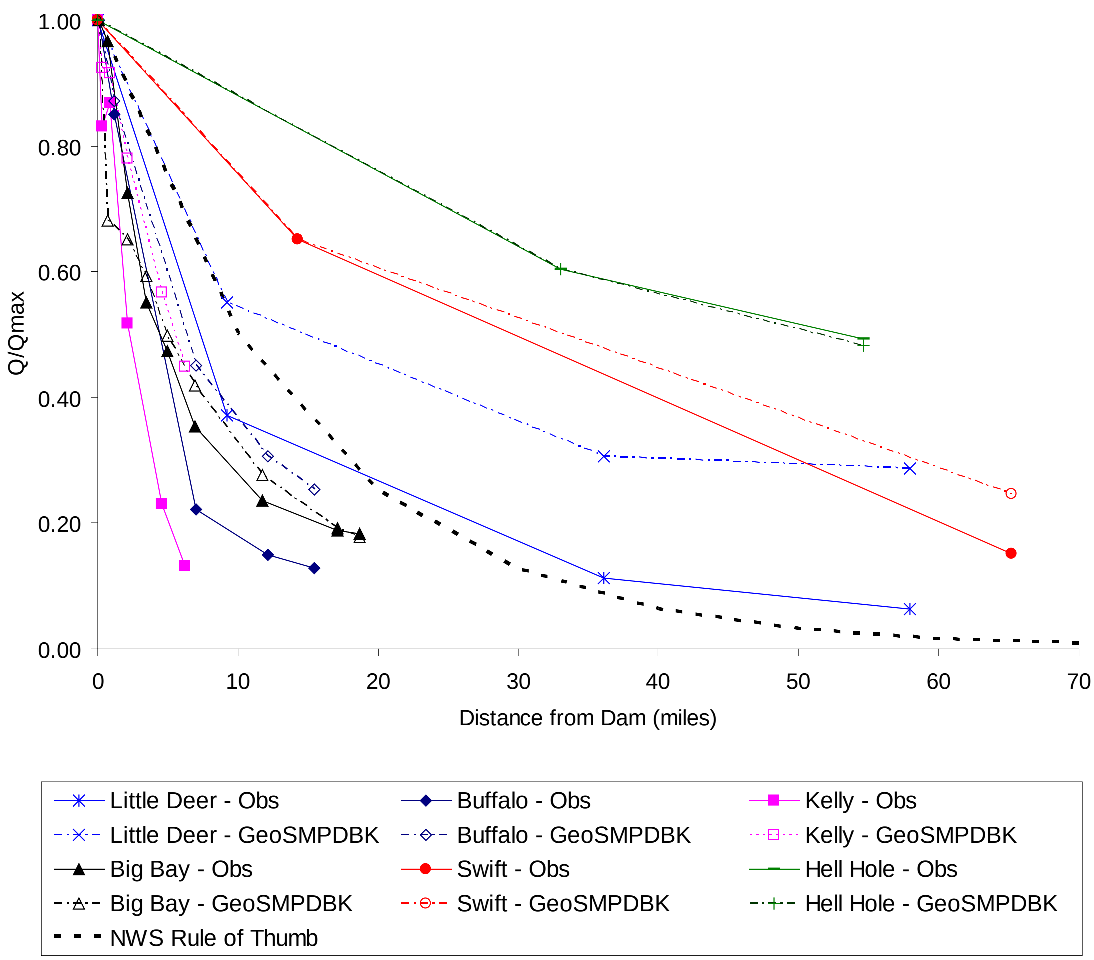

Figure 3. Peak flow attenuation predicted by GeoSMPDBK models compared with observations and Rules of Thumb predictions.

Inactive Flow Areas

We hypothesized that a big reason these initial GeoSMDBK models did not predict enough flow attenuation is because they ignore inactive flow or storage areas. To test this hypothesis, we re-developed models for Little Deer Creek and Kelly Barnes Dam (the worst performing models in terms of percent flow error) to explicitly account for inactive flow areas. In the process, the GeoSMPDBK codes were enhanced to provide functionality enabling the user to easily assign portions of cross-sections as inactive areas. To assign inactive flow areas, topographic maps were examined to identify wide areas of the floodplain where water would likely spread out and slow down (often near tributary junctions). Cross-sections were added at the beginning, end, and middle of these inactive areas and a portion of the middle cross-section was then assigned as inactive area. Figure 4 shows an example of how sets of three cross-sections were used to approximate inactive areas for SMPDBK. The bounding cross-sections are necessary so that the model does not assume that the inactive area extends beyond the bounding locations.

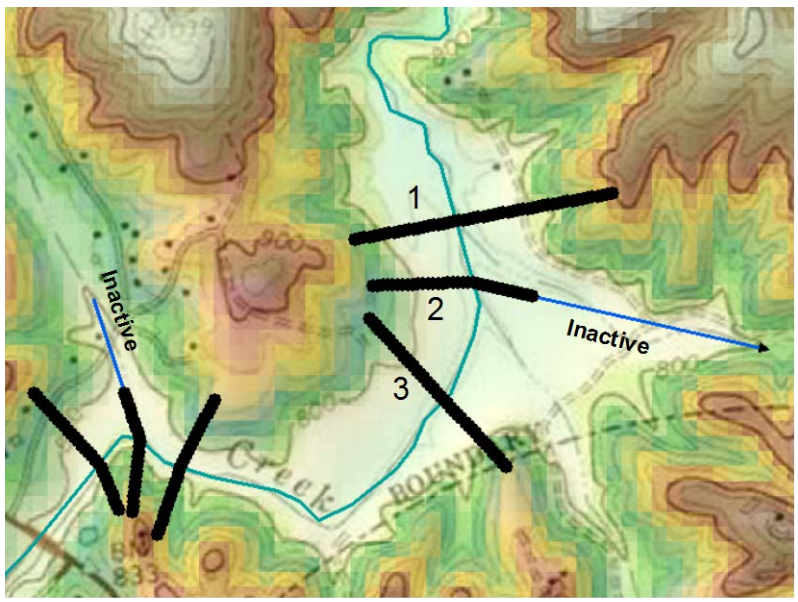

Figure 4. Example of cross-section placement to approximate inactive areas.. Cross-sections 1 and 3 bound a cross-section with inactive area. The blue(thinner) portion of cross-section 2 is assigned as inactive flow area.

Figure 5 shows improvements in the attenuation curves obtained when inactive areas were explicitly modeled. No calibration was done to achieve these results, so similar improvements could be expected in prediction mode. Table 5 (in previous section) includes the mean absolute error for these two models with inactive areas. For the best six GeoSMPDBK models (including two with refined inactive areas), average mean absolute percent flow prediction error over six dams was 38% compared with 67% for Rules of Thumb.

Despite substantial improvements with explicit inactive areas, GeoSMPDBK Little Deer hindcast errors are still relatively high. Both errors in the breach parameters used to compute peak flow at the dam and errors in the routing/attenuation model contribute to the high error. The Little Deer dam break occurred in June when there was “little inflow to the Duchesne River from other tributaries" (Rostvedt and Others 1968). Thus, one hypothesis to explain the over-simulation of downstream flows is that substantial re-infiltration of water into the relatively dry riverbanks and floodplain soils down stream of the dam may have occurred. Additional model development to reduce these errors is beyond the scope of this study. We believe that the relatively good performance of the Rules of Thumb for Little Deer is by chance.

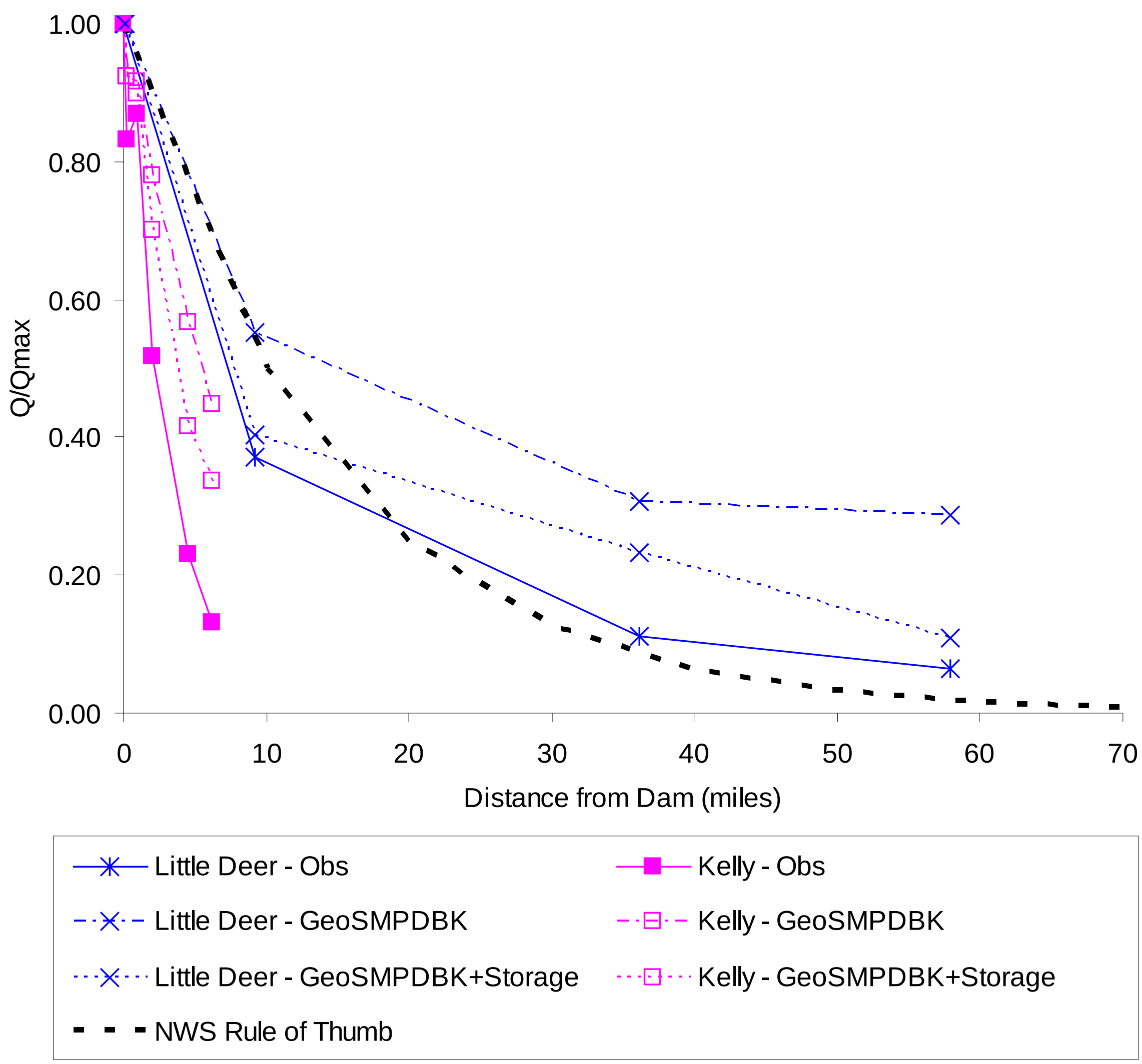

Figure 5. Attenuation curves showing improvements for Little Deer and Kelly Barnes after adding inactive areas to the models.

Elevation Prediction Results

With judiciously placed cross-sections, we compared simulated elevations from SMPDBK with observed high water mark elevations. Table 7 summarizes elevation prediction errors.

Table 7. Summary of elevation prediction errors.

Dam Name	River Station	HWM Elevation (ft)	Predicted Elevation (ft): GeoSMPDBK model with NHDPlus 30-m DEM	Predicted Elevation (ft): GeoSMPDBK Model with NED 10-m DEM	Abs. Error using 30-m DEM (ft)	Abs. Error using 10-m DEM (ft)
Kelly	D	1064.6	1074.6	1066.3	10.0	1.7
	E	845.5	853.8	847.1	8.3	1.6
	F	804.7	800.6	805.0	4.0	0.29
	G	715.8	717.5	720.1	1.7	4.3
Mean absolute error (ft)					**6.0**	**2.0**
Big Bay	495418	245.8	246.0	243.0	0.1	2.8
	489003	227.0	220.1	221.7	6.9	5.3
	480714	218.0	220.1	214.5	2.1	3.6
	471891	204.6	197.4	206.5	7.2	1.9
	461552	193.7	180.5	195.5	13.2	1.8
	435769	166.7	161.4	166.1	5.3	0.6
	406278	139.2	137.8	138.6	1.4	0.7
	398757	127.7	124.3	123.6	3.4	4.1
Mean absolute error (ft)					**4.9**	**2.6**

Note:All elevations are feet above NAVD 88.

Initial simulations using cross-sections derived from the NHDPlus 30-m DEM yielded errors at individual points ranging from 0.1 to 13 ft while mean absolute elevation errors were 6 ft and 4.9 ft respectively for Kelly Barnes and Big Bay locations. Because these errors are substantially larger than model errors reported in the literature (see next section), we also generated simulations using the same section lines but using the latest 10-m DEM from the National Elevation Dataset (NED) as input. Results with the 10-m DEM show substantially lower elevation prediction errors. Mean absolute error for Kelly Barnes was 2.0 ft with point errors ranging from 0.29 to 4.3 ft. For Big Bay, mean absolute error was 2.6 ft with point errors ranging from 0.6 ft to 5.3 ft. Interestingly, the flow prediction errors did not change much moving to the 10-m DEM. Mean absolute flow error for Big Bay actually increased to 20% from 16% and the error for Kelly Barnes only changed from 39% to 38% when using the 10-m DEM.

The depth estimate at the Foresthill site downstream of Hell Hole dam was used for additional validation. As explained above, the observed flood depth estimate at this location was 57.5 ft. Our GeoSMPDBK model predicted a flood depth of 60.2 ft at this location, yielding an error of 2.7 ft (less than 5% error). This demonstrates the ability of a GeoSMPDBK developed model to predict a reasonable depth/elevation 33 miles from a dam. The most distant elevation validation point in Table 7 is 18.3 miles from Big Bay dam.

Comparison to Results from Post-event Models in the Literature

Consistent with our findings, Fread (1981) indicates that the state-of-the-art dam break models in 1981 (SMPDBK being one of them) usually had errors of 1 to 2 ft or more, even in post-event mode when actual breach geometry is provided to the models.

Yochum et al. (2008) used final bottom breach width, bottom elevation, and breach formation time observations to develop a detailed HEC-RAS model for the Big Bay Dam failure. Yochum et al. (2008) developed basic, non-bridge cross-sections using a 10-m DEM. In addition, they altered basic cross-sections to include an approximate channel section below the DEM cross-section, and added ineffective areas through visual inspection and engineering judgment. The final model included 105 cross-sections with a spacing of about 200 ft, in contrast to our GeoSMPDBK model with only 9 cross-sections with a spacing of about 2.1 miles. Yochum et al. (2008) used both site visits and aerial photographs to estimate Manning's n values. We used flows from their Big Bay HEC-RAS model as the 'truth' for validation above. The post-event HEC-RAS mean absolute error in depth prediction was 0.9 ft compared to 2.6 ft for our best GeoSMPDBK model (Table 7). This shows the potential for improvement with more advanced models, but additional research is necessary to determine if this level of improvement is fully achievable in forecast mode.

Fread and Lewis (1998) report on a post-analysis simulation of the Buffalo Creek failure using FLDWAV. They used observed data from Davies et al. (1972) to build the model including observed breach size, breach formation time, and reservoir area-elevation data. Fread and Lewis (1998) do not report the source of information for cross-section geometry. We also have a SMPDBK model of Buffalo Creek used by the NWS for training and developed based on the same input data. Mean absolute percent flow error from this post-event SMPDBK model is 10% compared with 14% for our hindcast GeoSMPDBK using modeled breach parameters (Table 5). Fread and Lewis (1998) report 11% flow errors from FLDWAV with comparisons at the same four points, a very similar result to the post-even SMPDBK model.

Summary and Conclusions

For thousands of dams in the United States, NWS forecasters lack access to pre-developed engineering dam break models. Therefore, simple methods to rapidly derive quantitative forecasts for floods from dam failures are still needed in parallel with efforts to make existing engineering models more accessible. This paper describes the validation of GeoSMPDBK, a new tool to rapidly derive inputs for SMPDBK models. GeoSMPDBK is a relatively simple tool designed to build a dam break model in less than 30 minutes. To facilitate rapid model development, GeoSMPDBK is delivered to forecast offices with default national GIS datasets.

We validated GeoSMPDBK by developing hindcasts for failed dams. The hindcasting approach only allowed use of information likely to be available at the time of the failure, to mimic a realistic forecasting situation. We evaluated GeoSMPDBK hindcasts by comparison to observed data, Rules of Thumb, and where possible, to post-event analyses from the literature. Rules of Thumb serve as an important reference point that any viable forecast model must outperform. We have not found previously published work evaluating Rules of Thumb or SMPDBK in hindcast mode.

Initial GeoSMPDBK models built using NHDPlus 30-m DEMs and approximate Manning's n estimates from online imagery markedly outperform Rules of Thumb in five out of six dams for flow predictions. The two worst performing GeoSMPDBK models were refined to include inactive flow areas, substantially improving results without using any post-event data for calibration. Using the best GeoSMPDBK models, mean absolute percent flow errors ranged from 13% to 127% over the 6 dams studied, with an average of 38%. We were able to compare hindcast elevations and observed high water marks only downstream of Kelly Barnes and Big Bay dams. For these dams, we found that replacing the NHDPlus 30-m DEM with a 10-m resolution DEM from NED substantially improved elevation predictions but did not affect flow predictions. Errors at individual validation points ranged from 0.29 ft to 5.3 ft while mean absolute errors were 2.0 ft for Kelly Barnes and 2.6 ft for Big Bay. These hindcast errors are only slightly higher than errors reported for post-event models where more information such as observed breach geometry were used (D.L. Fread 1981). However, a detailed post-event HEC-RAS model for the Big Bay Dam achieved a mean absolute elevation error of 0.9 ft for the same validation points, suggesting room for improvement. While our elevation comparisons were not comprehensive, they do provide GeoSMPDBK users information on the possible magnitudes of elevation errors to expect in forecasting situations.

Dam break forecasting is an iterative process. A preliminary forecast may be developed using a very fast and simple approach such as Rules of Thumb. With more time, a forecaster could run a pre-developed dam failure model or GeoSMPDBK could be used to develop a new SMPDBK model. Validation results from hindcasts runs confirm expectations that GeoSMPDBK-based models do provide a robust solution with an intermediate level of accuracy between Rules of Thumb and more complex dynamic models. Validation also highlighted the benefits of explicitly defining inactive areas and using a more accurate DEM for water elevation predictions.

Beyond GeoSMPDBK, the NWS is working towards integrating more advanced pre-developed models into NWS operations, specifically existing HEC-RAS models for US Army Corps of Engineers owned dams. Future enhancements to dynamic models and model building tools in the community may also make rapid development of dynamic dam break models more feasible. Limitations associated with SMPDBK itself (e.g. no backwater, no dams in series, one-dimensional) can only be overcome by implementing more complex dynamic models. However, due to its ease of use and current availability, GeoSMPDBK is an effective tool likely to be needed for years to come.

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