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Modeling potential impacts of a breach for a high hazard dam, Elizabethtown, Kentucky, USA

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ABSTRACT

The USA contains over 87,000 dams of which 17% are classified as being of high hazard potential. Many of these high hazard dams do not have an Emergency Action Plan (EAP) in place, a key part of which includes an inundation map to identify the downstream areas impacted by a potential dam breach. The objective of this study was to conduct a hypothetical dam breach analysis for such a high hazard dam located in Elizabethtown, Kentucky. A hypothetical dam breach was modeled using the Simplified Dam Break model (SMPDBK) that incorporates actual dam measurements and hypothetical breach information based on previous studies of similar dams. Post-processing in ArcGIS produced an inundation map in which flood impacted areas were delineated based on the progression of the peak flood discharge over time. Results indicated that a peak breach discharge of 1034 m^3/sec would reach the city limits 2.87 h after the initial breach impacting 388 structures and 1725 people. Key evacuation points and locations of greatest vulnerability were identified based on flood arrival timing and access to evacuation points. This research demonstrates how a combination of dam breach modeling procedures and GIS post-processing can produce an accurate peak outflow breach and subsequent flood inundation map, both key features of an Emergency Action Plan.

1. Introduction

According to the Association of State Dam Safety Officials (2015), dam safety programs across the US reported 173 instances of dam failures and an additional 587 incidents where intervention likely prevented a dam failure between 2005 and 2013. The first recorded instance of a dam failure in the US occurred in January 1869 in Danbury, CT when ice from the Kohanza reservoir breached the Upper and Lower Kohanza dams resulting in 11 fatalities (ASDSO, 2015). The costliest dam failure in US history occurred at the Teton Dam, ID in June 1976 during the first filling of the reservoir, resulting in 11 deaths and damages totaling over one billion dollars (Seed & Duncan, 1987; Stene, 1996). The following year two dam failures, the Laurel Run Dam, PA and Kelly Barnes Dam, GA caused a combined 79 deaths. These failure events led to the establishment of the National Dam Safety Program under the stewardship of FEMA (ASDSO, 2015).

The USA contains over 87,000 recorded dams, mainly earthen in structure, approximately 17% of which are classified as being a high hazard potential, that is “structures for which failure would cause loss of life or serious damage to homes, commercial buildings, utilities, highways or railroads” (US ACE, 2015). At the national level, 40% of these high hazard dams do not have an Emergency Action Plan (EAP) in place which aims to identify “potential emergency conditions at a dam and specifies preplanned actions to be followed to minimize property damage and loss of life” (FEMA, 2004). A central part of these EAPs is the inclusion of an inundation map that identifies the downstream areas impacted by a potential dam breach, and which locations/populations are most vulnerable from flooding. FEMA defines hazard vulnerability as the “degree to which people, property, the environment, or social and economic activity – in short, all elements at risk – are susceptible to injury, damage, disruption, or loss” (FEMA, 1983). In Kentucky there are 1114 dams of which 164 are classified as state regulated high hazard dams (US ACE, 2013a). Although not required by state or federal law, despite the high hazard classification, 63% of these high hazard dams have an EAP in place with inundation maps, (DamSafetyAction.org, 2015). Furthermore, the American Society of Civil Engineers (ASCE) downgraded Kentucky's overall dam safety from a “C−” received in 2003 to a “D+” in 2011 because of the reduction in investment afforded to the dams in the intervening

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period (ASCE, 2011). Between 2004 and 2013 the state dam safety budget reduced from approximately $1.6 to $0.58 million, which caused the funding per regulated high hazard potential dam to drop below the national average by $1000 per dam (ASDSO, 2013). The ASCE (2011) also recommended that Kentucky develop EAPs with inundation maps for all high hazard dams.

In order to better assess the potential hazard a dam poses and identify areas that may be impacted, a dam breach/break analysis can be conducted. This procedure typically involves three key components: estimation of the dam breach peak flow, routing the hydrograph downstream, and estimating inundation levels (Water Resources Program, 2007). Various dam breach models have been developed mainly by the National Weather Service (NWS). Physical models, including the NWS BREACH program, incorporate a full suite of dam/reservoir breach components, including initial failure mode and breach progression, and allow for integration of soil properties and tailwater effects. Parametric-based models (e.g. DAMBRK/FLDWAV) allow users to model peak discharge and breach hydrographs that result from a dam breach (Colorado Division of Water Resources, 2010; Fread, 1988, 1998). Empirical models such as the NWS Simplified Dam Break Model (SMPDBK – a simplified version of the DAMBRK version) are deterministic in nature driven by statistical relationships that are derived from observed dam failures; however, they still allow the calculation of peak discharges and inundation depths (Shahraki, Zadbar, Motevalli, & Aghajani, 2012; Wetmore & Fread, 1991).

The US Soil Conservation Service and Bureau of Reclamation have developed empirical relationships between peak breach discharge and the height of the dam examined based on prior analysis (Kentucky Department for Environmental Protection, 1979). Determining the size and rate of breach development is also crucial. As a result, dam breach models often allow users to evaluate a range of breach parameters for comparison (Gee, 2008). Froehlich (1995) and Wahl (1998; 2004) successfully developed empirical relationships between various breach parameters including breach width, failure time and peak outflow. These studies generally apply a series of linear and non-linear multiple regression analyses between the significant dam breach parameters and resultant outflow (Pierce, Thornton, & Abt, 2010). Once developed, these empirical relationships may be used to calibrate future dam breach model parameters towards generating accurate inundation maps. When integrated with elevation and landcover data within a Geographic Information System (GIS), these inundation maps indicate the potential damage and vulnerability to flooding for downstream areas (Lodhi & Agrawal, 2012; Reed & Halgren, 2011; Seker, Kadbasli, & Rudvan, 2003; Qi & Altinakar, 2012).

The purpose of this study is to conduct a hypothetical dam breach analysis for a high hazard dam that does not have an EAP. The research will demonstrate how a combination of dam breach modeling procedures and GIS post-processing may produce an accurate peak outflow breach and subsequent flood inundation map, to assist with developing an EAP.

2. Materials and methods

2.1. Study area

The dam selected for this study is the Valley Creek Mps #4 dam located on Freeman Creek which drains through the city of Elizabethtown, KY into the Nolin River (Fig. 1). This particular dam was chosen for the study because it is an earthen dam rated as a high hazard potential and does not have an EAP. Constructed in 1966, the 13.4 m high dam created Freeman Lake, a reservoir with a normal storage volume of 2.257×10^6 m^3 to supply water to Elizabethtown (US ACE 2013b). The dam and reservoir are situated immediately upstream of the city, which, according to the 2010 census, has a population of 28,531.

2.2. Data

Modeling and mapping the impacts of a potential dam breach of this nature involves 6 digital datasets: dam inventory, elevation, land cover, orthoimagery, census block population, and transportation infrastructure data. The National Inventory of Dams (NID) provided the necessary dam inventory data for the Valley Creek Mps #4 dam (US ACE 2013b). The US Geological Survey (USGS) provided the elevation and land cover data. A 10 m resolution digital elevation model (DEM) covering the study area from 2013 was obtained from the USGS National Elevation Dataset (Gesch et al., 2002) and imported into the Watershed Modeling System (WMS) software. To analyze the flood impacts from the dam breach, a 30 m resolution land cover raster from 2011 was obtained from the Multi-Resolution Land Characteristics Consortium (MLRC) (Homer et al., 2015), along with 1 m orthoimagery (2014) from the USGS (Mauck, Brown, & Carswell, 2009) for the area downstream of the modeled dam breach. Finally, the Kentucky Geography Network GeoPortal provided 2010 census block data (US Census Bureau, 2013) and major transportation infrastructure (Kentucky Transportation Cabinet, 2002) data for Elizabethtown in the form of a vector polygon/line shapefiles.

2.3. Dam break model

Although empirical in nature and therefore requiring less data, the SMPDBK model was comparable to more complex models for several observed and hypothetical dam failures (Wetmore & Fread, 1991). Studies in the US (Gindy, Thomas, & Madsen, 2007; Sutko, 1987), China (Yongxing, 1995), Turkey (Bozkuş & Kasap, 1998) and Iran (Shahraki et al., 2012) successfully simulated dam breach impacts by applying the SMPDBK model. While SMPDBK can produce reliable results, these studies also highlighted that care must be taken in selecting the appropriate input data, in particular the physical characteristics of the downstream environment in which the floodwater travels. The bottom friction of the surface over which the water flows can be particularly sensitive to small changes, although the overall model error is relatively small at less than 10% compared to physical models (Bozkuş & Kasap, 1998; Shahraki et al., 2012).

The inundation maps generated by the model can also be exported into ArcGIS for additional spatial analysis, an option that is not readily available for other dam break models. First, SMPDBK computes the peak outflow from the breach based on the reservoir size, breach size, and length of time for the breach to form (Equation (1)):

$$Qp = 3.1WHw^{1.5}\left[\frac{A}{A+\tau\sqrt{Hw}}\right]^3 \tag{1}$$

where Q_p = *dam breach peak discharge (cfs)*, W = *Mean breach width (ft)*, H_w = *initial height of water over base elevation of breach (ft)*, τ = *elapsed time for breach development (hours)*, $A = 23.4S_a/W$, *and* S_a = *surface area of reservoir at level corresponding to depth* H_w *(acres)* (Water Resources Program, 2007). Dam breach parameters were acquired from Wetmore and Fread (1991) for the initial model simulation. The peak breach discharge produced was then compared to discharges produced by the aforementioned empirical methods.

Once the peak flow had been calculated, the flow was routed