Impact of spatial resolution on downstream flood hazard due to dam break events using probabilistic flood modeling

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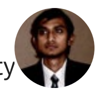

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IMPACT OF SPATIAL RESOLUTION ON DOWNSTREAM FLOOD HAZARD DUE TO DAM BREAK EVENTS USING PROBABILISTIC FLOOD MODELING

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Abstract

With up to 14,000 high-hazard potential dams in the US, a dam break is a serious safety hazard for downstream locations and an operational concern for dam managers. Dam break simulation using computer-based flood models require topography, generally represented using digital elevation models (DEM) as a significant input which may affect the model accuracy. Until recently, most flood model simulations were conducted deterministically without incorporating uncertainties from model parameters. A clear understanding on the spatial resolution in a probabilistic context by incorporating uncertainties in model parameters such as dam break hydrographs, is needed for comprehensive dam break modeling analysis. The objective of this study is to *address the impact of spatial resolution on the relative accuracy of downstream flood hazard after a dam break event*. It is hypothesized that higher spatial resolution will significantly increase the model predictive ability and the accuracy of flood hazard maps. The current study employs a two-dimensional (2D) flood model, Flood2D-GPU in a probabilistic framework to investigate these spatial resolution impacts by applying dam break simulations on Burnett Dam near Asheville, NC. The dam break hydrograph is chosen as the uncertain parameter as it adds greater source of uncertainties in most situations. Using GoldSim®, Monte Carlo modeling software, 99 stochastic dam break hydrographs representing various possible scenarios are generated. These hydrographs are input into Flood2D-GPU to produce probability weighted flood hazard maps. The probabilistic simulations are carried out for 9m, 31m, 46m, 62m and 93m spatial resolutions. The results indicate that increasing the resolution from 93m to 9m causes a slight 0.8% increase in overall flood hazard extent. Although, resolution improvement from 93m to 31m leads to increase in high-danger zone by 8.4% agreeing with the hypothesis. Analysis of relative hazard underestimation reveals that 31m grid resolution minimizes this parameter and thus is recommended for the study area. However, the results cannot be replicated to other areas and further analyses are required to confirm the findings of current study. The outcomes of this study will assist dam break modelers to enhance their Emergency Action Plans by providing recommendations for suitable spatial resolution and to avoid increased modeling time.

Key Words: Spatial resolution, Flood2D-GPU, Monte Carlo Simulation, GoldSim®, Probabilistic flood modeling, Flood hazard.

Introduction

Dam break event is a serious concern for floodplain managers all over the world. According to US Army Corps of Engineers' (USACE) National Dam Inventory, there are up to 14000 high-

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hazard-potential dams in the US (USACE, 2013). The failure of these dams may result in a high amount of social, environmental and economic damages. According to the Association of State Dam Safety Officials (ASDSO), repair costs of nation's dams are estimated to be $50 billion and $16 billion investment is needed to repair high hazard potential dams (American Society of Civil Engineers (ASCE), 2009). With the ASCE rating the current conditions in the nation's dams with a "D" grade, it is very crucial to evaluate the consequences of dam hazards such as dam breaks.

Flood models are important tools in simulating a dam failure event. Available flood models can be generally categorized into one-dimensional (1D), two-dimensional (2D) and coupled 1D-2D models. Dam break modeling using these computer-based flood models require terrain data which are generally represented using digital elevation models (DEM). 1D models cannot provide sufficiently accurate inundation mapping results due to inaccuracies in cross-section discretization and thus disabilities in flow representation in the floodplain such as lateral flow diffusion (Kalyanapu et al., 2011; Qi and Altinakar, 2012). 2D models have addressed this drawback by a higher order of topographic representation, desirable flood pathways in the simulations as well as existing and planned structures (Kalyanapu et al., 2011).

Multiple sources of uncertainty are involved in dam break flood hazard mapping problem. Previous studies generally indicate that the spatial resolution affects the model accuracy. There have been some efforts on exploring the scaling impacts on flood modeling results. Hardy et al. (1999) showed that spatial resolution causes a wide variation in model performance and inundation extent predicted by 2D TELEMAC-2D model (Hervoeut and Van Haren, 1996; Bates et al., 1995). Horritt and Bates (2001) investigated the effects of scaling properties on a 1D LISFLOOD-FP model (Bates and De Roo, 2000) performance in inundation mapping. Resolutions of 1000m to 10m were analyzed and the results showed that the maximum model performance is at 100m spatial resolution and 500m resolution proved to be sufficient for water level prediction. Cook and Merwade (2009) indicated that higher spatial resolution and vertical accuracy of terrain model reduces the predicted inundation area using 1D HEC-RAS model (USACE, 2006) and 2D FESWMS model (Federal Highway Administration (FHWA), 2002). Nevertheless, most of the flood simulations were conducted based on single parameter set for a single flood simulation or limited number of simulations without incorporating uncertainties from model inputs. Hence, a clear understanding on the spatial resolution in a probabilistic context by incorporating the model parameter uncertainties such as dam break hydrographs is needed for comprehensive dam break analysis. This is because, as spatial resolution changes, it will affect the inundation extent and bulk flow characteristics which accordingly influence the floods hazard extent. In this study the flood hazard is defined as the potential adverse impact on human life and any downstream developments if a dam fails (ACER, 1988). For any location, flood hazard is characterized as low hazard, judgment and high hazard zones, depending the velocities and flood depths simulated at that location.

The objective of this study is to *address the impact of spatial resolution on the relative accuracy of downstream flood hazard after a dam break event*. It is hypothesized that higher spatial resolution will significantly increase the model predictive ability and the accuracy of flood hazard maps. Supported with a probabilistic dam break hydrograph simulator, numerous dam failure scenarios are generated to incorporate various uncertainties such as time to failure, breach width, breach side slope and final elevation of breach. The hydrographs are employed as inputs to the 2D flood model to simulate dam break events. The general procedure of the study by Kalyanapu et al. (2012) is followed here for probabilistic flood hazard estimation and extended to dam break simulation. Downstream of the dam is classified into different hazard zones for each spatial resolution based on the flood modeling results. This investigation is performed on the Burnett Dam located in Swannanoa River watershed near Asheville, North Carolina. The presented framework is flexible and can also be performed for similar studies at different locations.

Methodology

A probabilistic dam break modeling framework is used in this study which contains the following three modules: 1) Monte Carlo Simulation (MCS); 2) Geospatial flood modeling; and 3) Flood hazard analysis. The framework is used to model dam break for five different DEM spatial resolutions and relative accuracy of various categories of flood hazard extent at these spatial resolutions is analyzed. Figure 1 visualizes the schematic of framework used in this study.

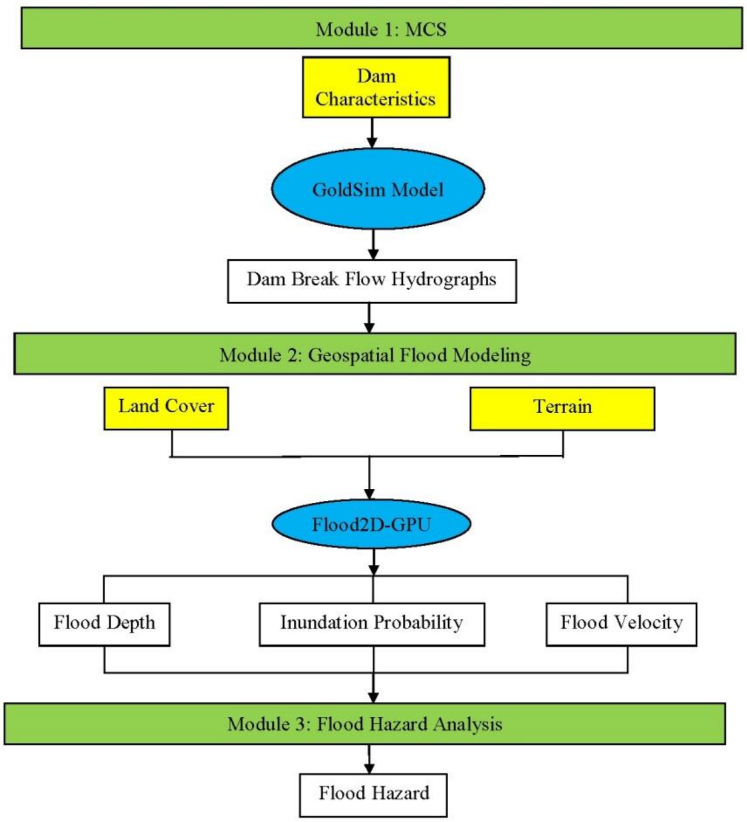


Figure 1. Probabilistic flood hazard framework schematic

In the MCS module, a dynamic simulation software GoldSim® is used to produce stochastic dam break hydrographs based on dam break features in which each parameter is characterized by a stochastic variable. Normal Probability Density Function (PDF) is applied for time to total failure, breach width and final elevation of breach, and Discrete PDF is used for breach side slope. The PDFs are visualized in Figure 2 (a) to (d). The methodology presented by Fread (1988) is adopted herein to generate flow hydrographs which are presented in the equations 1 to 3:

$$Q_b = C_v K_v (3.1 b_t (h_w - h_{bt})^{\frac{3}{2}} + 2.45 m (h_w - h_{bt})^{\frac{5}{2}}) \quad (1)$$

$$h_{bt} = h_d - (h_w - h_{bt}) (\frac{t}{\tau})^{\rho}; \quad 0 \le t \le \tau \quad (2)$$

$$b_t = b_f\left(\frac{t}{\tau}\right)^{\rho} \qquad (3)$$

In which Q_b is breach outflow, C_v is approach velocity correction factor, K_s is weir submergence correction factor, b_t is instantaneous bottom width of the breach, h_w is water surface elevation, h_{bt} is instantaneous elevation of the breach bottom, b_f is final bottom width of the breach, h_d is elevation of the top of the dam, t is time from beginning of the breach, τ is total failure time and ρ is a constant between 1 and 4. It is to be noted that the units should be in US Customary System. The resulting hydrographs are used as randomly varying inputs to a 2D flood model since they generally add most uncertainties into dam break modeling.

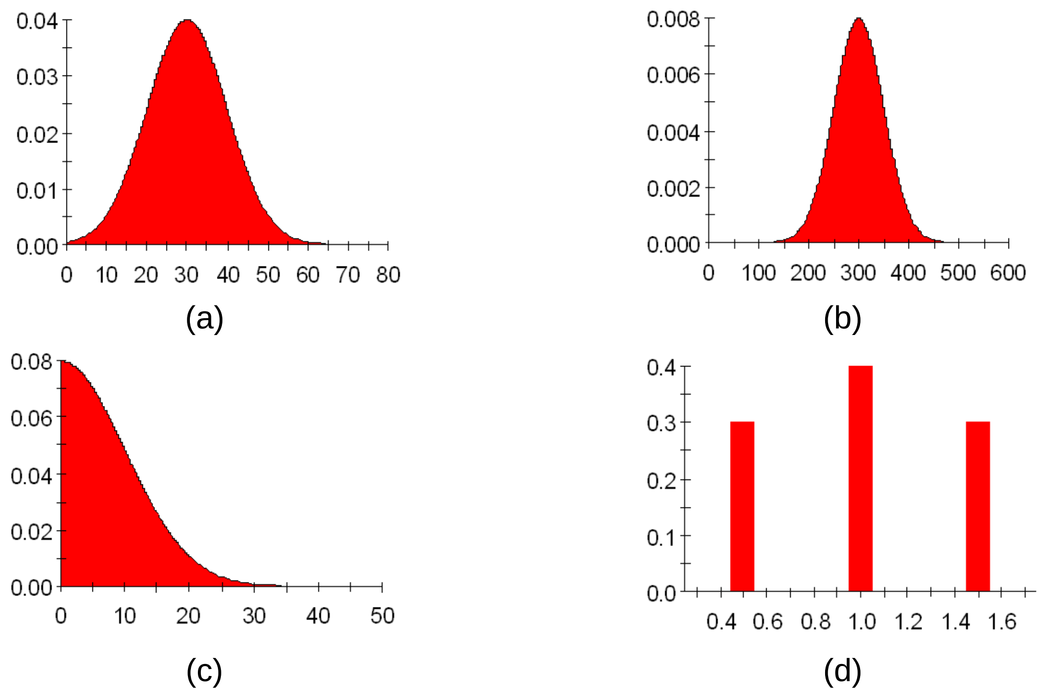


Figure 2. Probability distribution curves of: a) time to total failure; b) final bottom width of the breach; c) final elevation of breach bottom; and d) side slope of breach width

In the geospatial flood modeling module, a 2D unsteady numerical flood model, Flood2D-GPU (Kalyanapu et al., 2011) is employed. The model was coded in NVIDIA's CUDA programming environment and solves the non-linear shallow water equations using a first-order accurate upwind difference scheme to generate flood depths and velocities. Primary datasets needed are topography, surface roughness and flow hydrograph.

A flood model realization is generated for each randomly sampled hydrograph. The flood inundation boundary is delineated by calculating the water depth at each grid cell and identifying inundated cells (i.e. non-zero floodwater depth) using a GIS-based post-processing framework. Inundation probability is determined as the number of times a grid cell is flooded divided by the total number of flood simulations (Kalyanapu et al., 2012). The outputs of this module are GIS raster flood probability map as well as flood depth and velocity for each stochastic hydrograph.

In the flood hazard analysis module, probabilistic spatial flood hazard maps are generated. The maximum flood depth and velocity are estimated from flood modeling module and are multiplied with the flood probability to create probability weighted flood hazard maps (Kalyanapu et al., 2012). Depth-velocity curves (Figure 3), derived from Assistant

Commissioner – Engineering and Research (ACER) (1988) are used to determine the hazard intensity. The flood hazard level is classified into three different groups of low-danger, judgment and high-danger zones. In the low-danger zone, the possible lives-in-jeopardy is assumed to be zero. In the high-danger zone, it is assumed that all lives are in threat. The judgment zone represents a zone where the lives-in-jeopardy is considered to be uncertain and may vary between zero to total lives in threat.

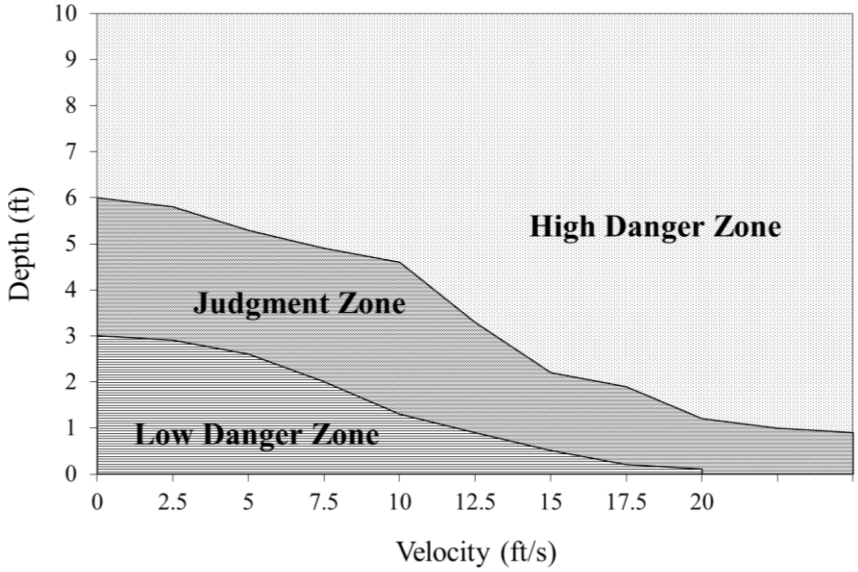


Figure 3. Floodwater depth – velocity hazard classification. Source: ACER (1988)

Case Study

The impact of spatial resolution on dam break is investigated on Burnett Dam in Swannanoa River Watershed located in Buncombe County, NC. Burnett dam is a part of Asheville municipal water supply, has reservoir area of 7 mi^2, and a drainage area of 22 mi^2. The total capacity at crest of spillway is 11,600 ft^3/s-day and the sea-level altitude is 2601 ft. It is selected in this study because of its proximity to urban areas including cities of Swannanoa, Black Mountain, and Asheville along the Swannanoa River.

There was no prior information on PMF studies on Burnett Dam to compare the performance of Flood2D-GPU to previous studies. To address this issue, Taum Sauk Dam break event of 2005 was used to calibrate the Flood2D-GPU. Taum Sauk dam is a hydroelectric plant located in Reynolds County, MO. It failed on December 14th 2005 due to prolonged minor leaks. This failure event was simulated by Flood2D-GPU using 9m DEM spatial resolution and calibrated (Kalyanapu et al., 2011). The calibration revealed the model's accuracy and potential applicability to other case studies. Thus it is applied for the Burnett Dam break probabilistic simulations in this study.

DEM of 9.43m spatial resolution for the area was generated from the National Map website (http://nationalmap.gov/). Furthermore, 31.03m, 46.56m, 62.07m and 93.11m DEMs were synthesized based on 9.43m spatial resolutions using nearest-neighbor resampling method. Hence, total of five DEMs were produced for the analysis. These resolutions will be henceforth referred to as 9m, 31m, 46m, 62m and 93m in the remaining of the paper. Topographic slopes of each DEM were generated using GIS Slope Function. Range of slope variation is represented in Figure 5. The minimum slope is zero in each resolution and the maximum changes from 88.1% at 93m resolution to 342.5% at 9m spacing with an increasing trend. A Manning's roughness value of 0.11 is used to represent the vegetation and short grass in the study region (McCuen, 1998).

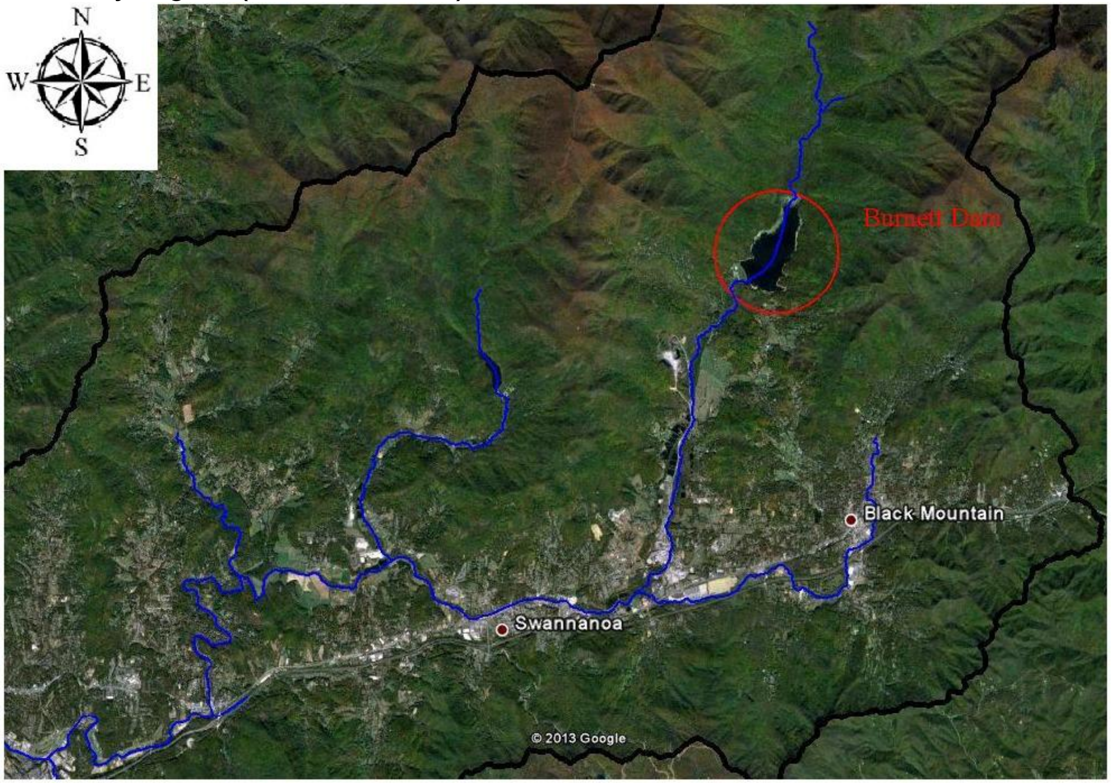


Figure 4. Location of Burnett Dam in Swannanoa River

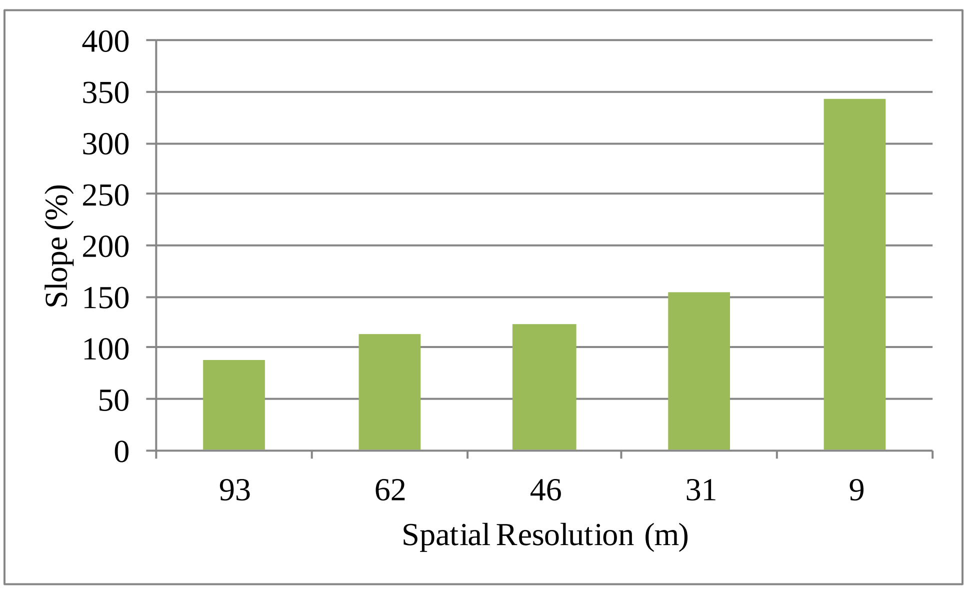


Figure 5. Maximum ground slope variation in different spatial resolutions

Results and Discussion

As discussed in the methodology section, using 99 randomly produced hydrographs by GoldSim model along with DEM and Manning's roughness coefficient as inputs to Flood2D-GPU, probabilistic dam break simulations were performed. Raw outputs from the model were processed within GIS environment for 9m, 31m, 46m, 62m and 93m spatial resolutions. Figure

6 shows change in the run time with respect to number of computational cells. Higher number of computational cells obviously represents finer spatial resolution. Total run time remarkably increases by resolution refinement as expected (Kalyanapu et al., 2011). The increase in the run time can be well represented by a linear equation where correlation coefficient (R^2) is 99.96%. Regression analysis reveals that average of 0.4 second computational time is required for each cell. In addition, computational times show a significant improvement compared to a regular CPU-based 2D flood model. Same simulation would require approximately up to 979, 147, 70, 53 and 43 days for 9m, 31m, 46m, 62m and 93m spatial resolutions, respectively when implemented in the CPU-based version of the flood model (rough CPU estimates based on Kalyanapu et al., 2011).

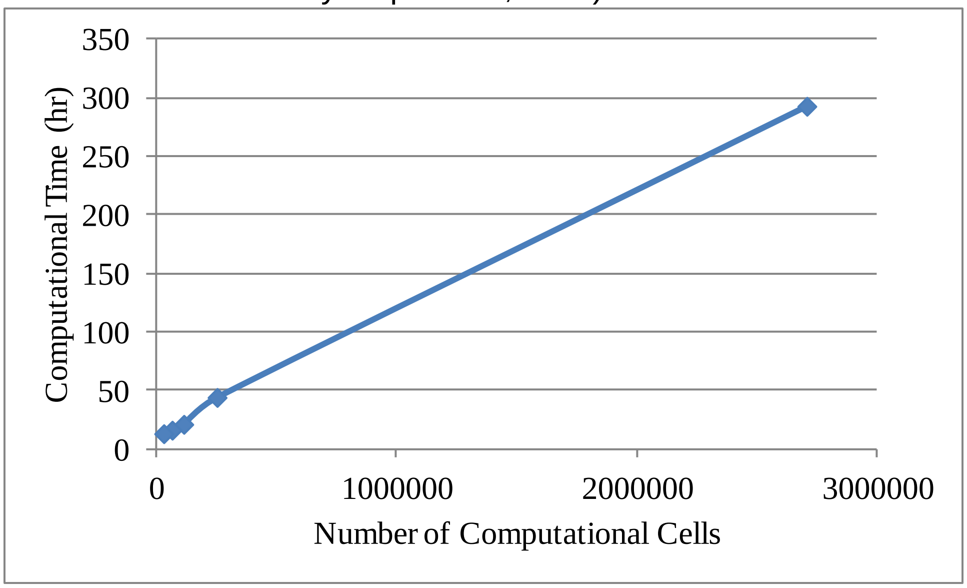


Figure 6. Maximum ground slope variation in different spatial resolutions

Preliminary outputs of Flood2D-GPU including inundation depth and velocity are discussed here. Maximum inundation depth ranges between of 18.4 m to 31.5 m by varying grid resolution. Flood depth of higher than 21.5 m is only observed at 9m resolution, immediately downstream of the Burnett Dam where steep slopes are existed. This hilly area has average slope of 9.9% and the higher the slope, the greater depth will occur. The lowest maximum flood depth is 18.4 m and occurs at 31m resolution. Higher inundation depths than this value often occur at steep slopes at all of the other resolutions. An interesting point that can be concluded is that with steeper slopes, the difference between estimated flood parameters (depth and velocity) by different DEM resolutions intensifies. Therefore, significance of selecting a suitable DEM is highlighted in the regions with steep slopes.

Figure 7 presents the inundation area within the simulation domain. The predicted inundation area decreases from 18.4% to 7.8% with grid resolution refinement from 93m to 9m. This is in agreement with the results of Cook and Merwade (2009) for the deterministic simulations by both 1D HEC-RAS and 2D FESWMS models. The main reason of reduction in inundation area is due to better terrain representation by higher resolution and loss of topography in lower grid spacing. To give a better insight about relative change in the inundation maps at different spatial resolutions, F statistic (Bates and De Roo, 2000) is used as measure of fit. The parameter F can be computed by Equation 4:

$$F_{i/j} = \frac{A_i \cap A_j}{A_i \cup A_j} = \frac{A_i \cap A_j}{A_i + A_j - A_i \cap A_j} \qquad (4)$$

Where A_i and A_j are inundated area at spatial resolutions of i and j, $A_i \cap A_j$ is the inundation area predicted by both resolutions i and j, and $F_{i/j}$ is the relative accuracy of resolution i in respect with resolution j. The parameter was generally employed to determine the inundation prediction discrepancy from observed data. However, it can be applied to determine the discrepancy between the base map and other inundation maps attained from different simulation scenarios in the absence of observed data (Cook and Merwade, 2009). Here it is used to compare the inundation areas estimated by two different DEM resolutions. Finer resolution is considered as the base map and the discrepancy of the coarser resolution from this is quantified. Table 1 presents this parameter along with the percentage of inundation area for different grid resolutions. Based on the table, the F statistic varies in the range of 65.5%–84.6% from 93m to 31m DEMs. The parameter is 100% for 9m apparently since it is compared with itself.

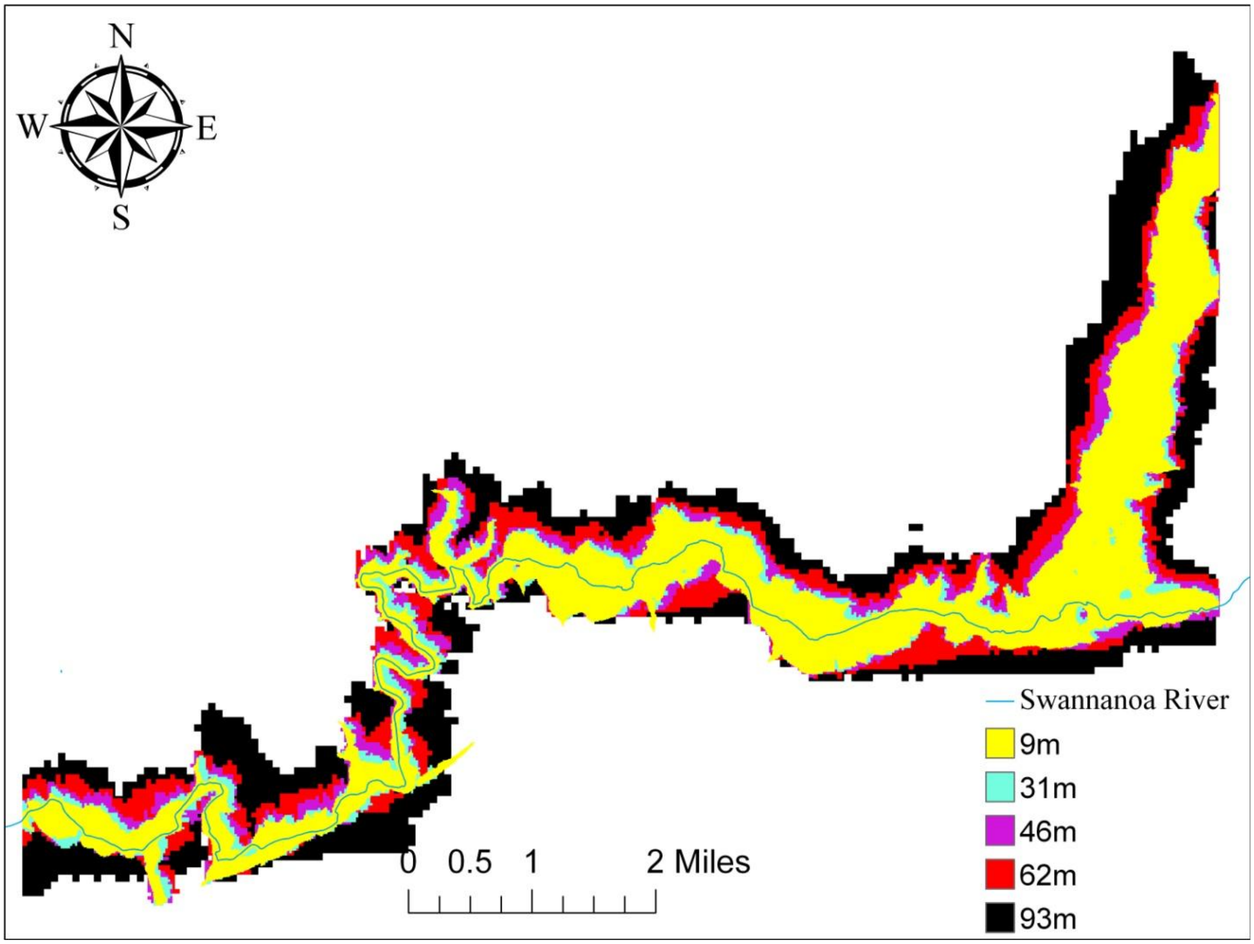


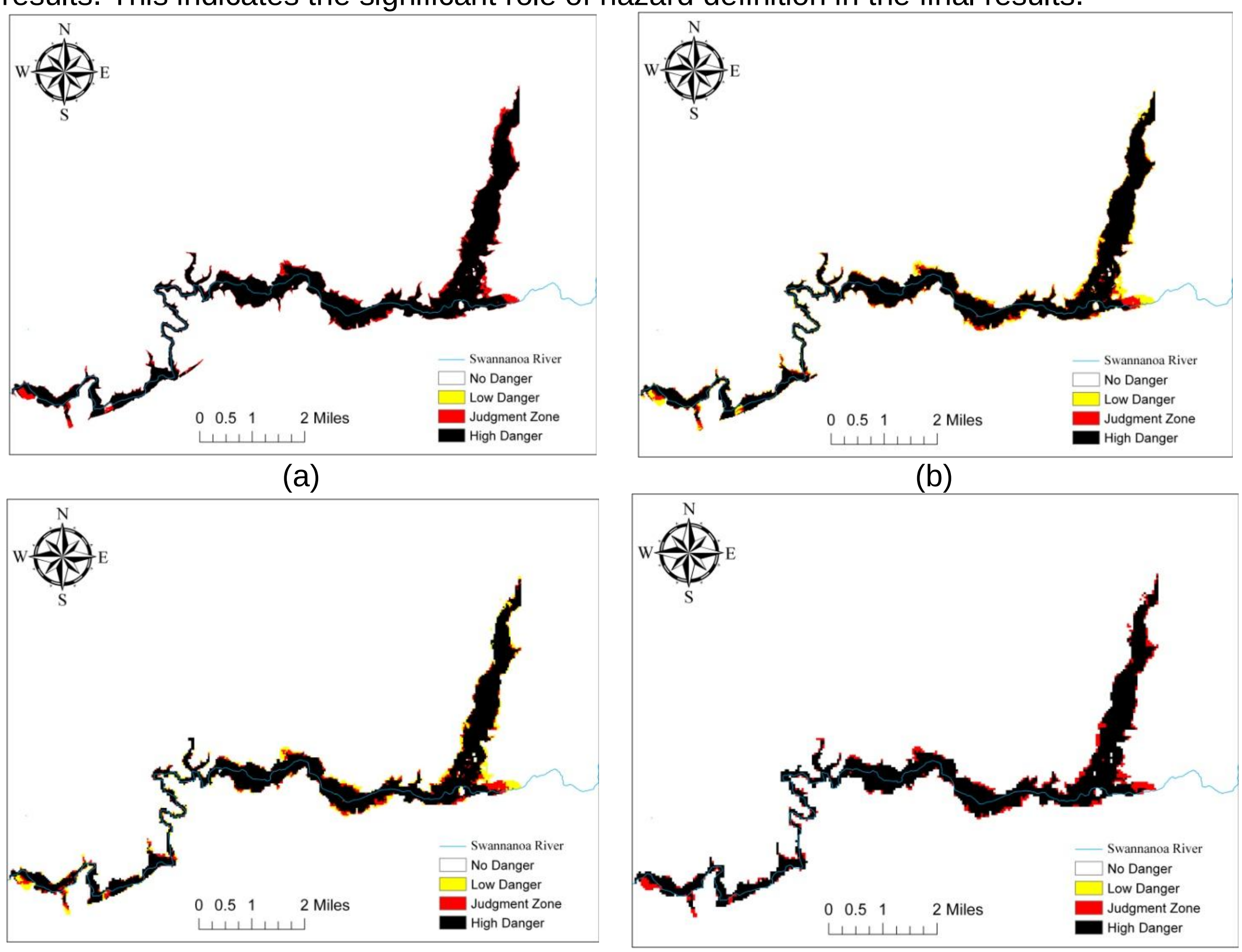
Figure 7. Spatial variation of maximum inundation area for different spatial resolutions

Table 1. Comparison relative accuracy of inundation area predicted at different spatial resolutions

Spatial Resolution (m)	Inundation Area (%)	F Statistic (%)
93	12.6	65.5
62	8.6	77.1
46	6.9	78.8
31	5.8	84.6
9	5.3	100.0

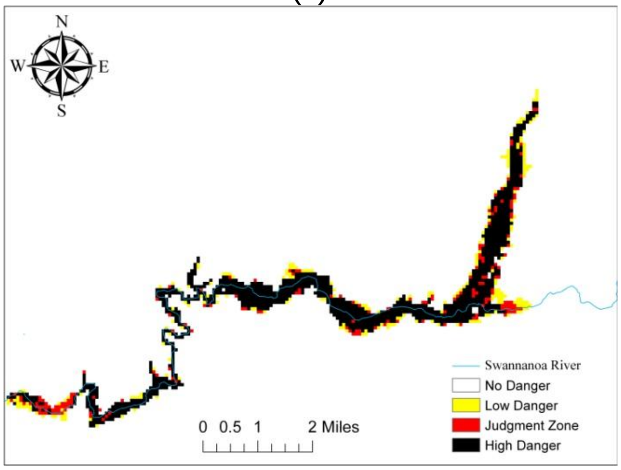
The resulting probability weighted flood hazard maps are presented in Figure 8. Histogram plot of each flood hazard class at different spatial resolutions are shown in Figure 9. Increasing the resolution from 93m to 9m leads to a minor 0.4% increase in overall flood hazard and also a slight 0.7% increase in “high danger” class extent. With improving the resolution from 93m to 31m, percentage of “high danger” zone by overall hazard has been increased by 6.8% agreeing with the hypothesis. It can be concluded that as the spatial resolution increases, more locations are classified to a higher danger level. This could be because, with improved spatial resolution, the grid cells that were classified as judgment and/or low hazard are converted to high hazard zone. However, after refining the resolution from 31m to 9m, 0.7% reduction occurs in percentage of “high danger” class by overall hazard.

To give a better understanding of hazard variation with DEM resolution, trend of each danger class and overall hazard with spatial resolution was also analyzed. Figure 10 presents the variation of different danger classes and overall hazard with grid scale. An increasing trend in “high danger” class and overall hazard can be seen by increasing the resolution which is in accordance with the expectations. Whereas “low danger” and judgment zones show a decreasing trend by increase in resolution from 93m and reaches a minimum and then increasing with grid refinement. Minimum area occurs at 46m and 31m for “low danger” and judgment classes. It is to be noted that these results can be because of definition of danger classes by the reference curves applied here and other hazard classifications may change the results. This indicates the significant role of hazard definition in the final results.



(a) (b)

(c) (d)



(e)

Figure 8. Flood hazard maps for spatial resolutions of: a) 9m; b) 31m; c) 46m; d) 62m; and e) 93m

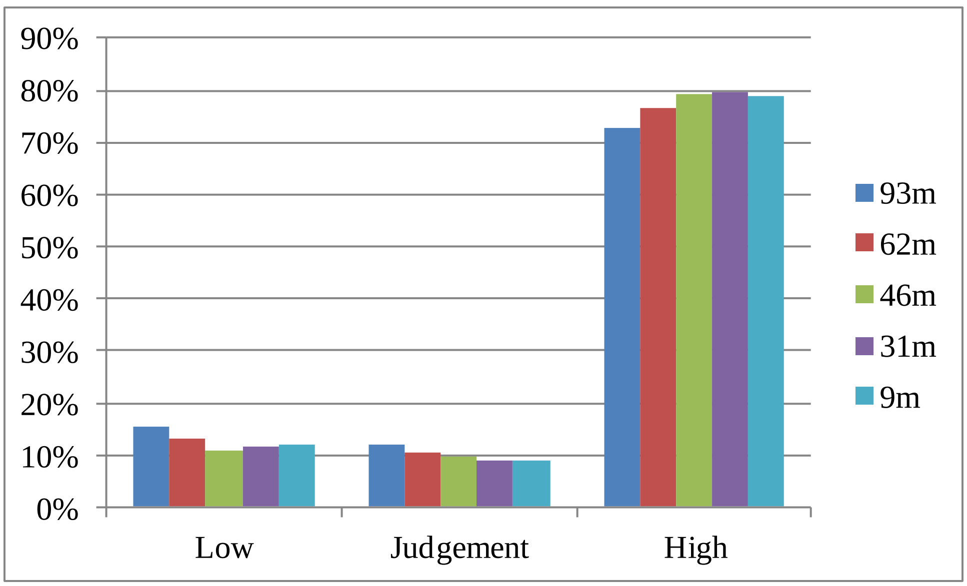


Figure 9. Area of different hazard classes for 9m, 31m, 46m, 62m and 93m grid resolutions

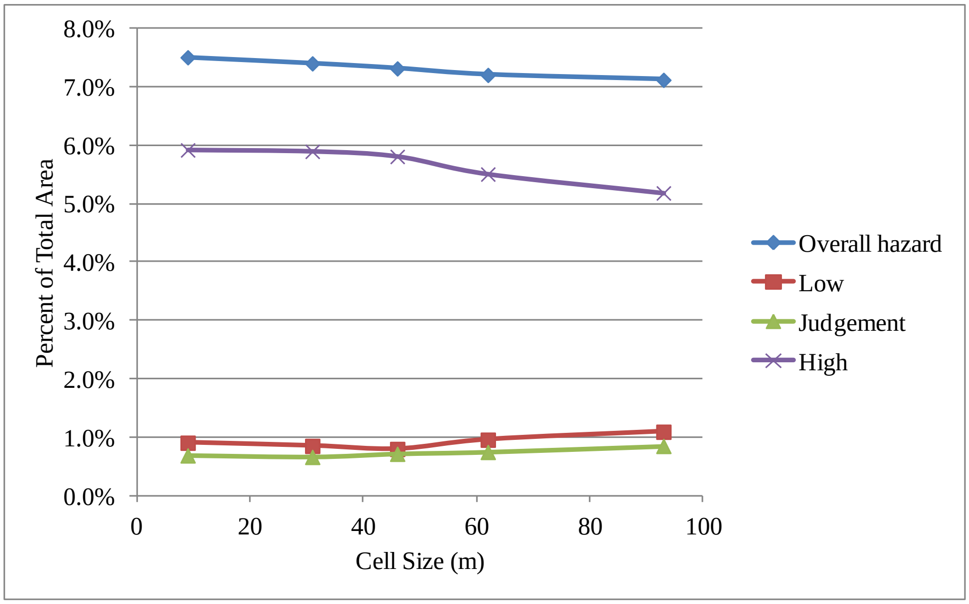


Figure 10. Trend of different hazard classes with spatial resolutions

Another analysis was to investigate the hazard intensity change with respect to spatial resolution. Spatial distribution of relative bias (underestimation/overestimation) was obtained between each two different grid resolutions. Relative bias is considered as the change from a lower to higher danger class. For doing so, hazard rasters were resampled to the higher resolution cell size using nearest-neighbor approach. Relative underpredicted area for different resolutions is presented in Figure 11. From this figure, relative underestimation does not show any specific trend is not minimum anywhere. Therefore, an optimal grid resolution cannot be suggested for the study area.

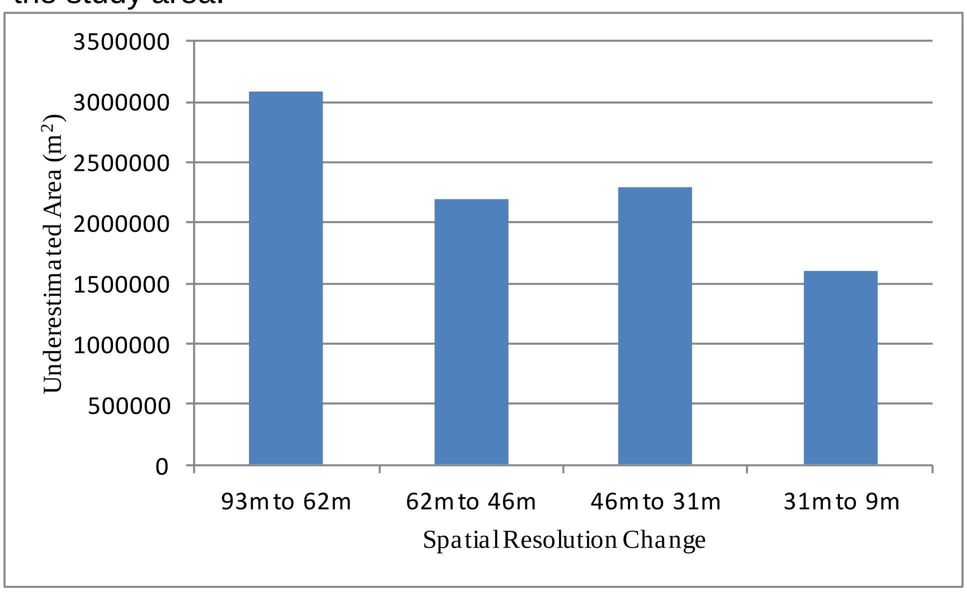


Figure 11. Relative underestimated area for different spatial resolutions

To investigate the effects of topography on the underestimated locations, ground slope was generated for each resolution based on the DEMs. Relative underestimation layers were overlaid with the topographic slope to explore the characteristics of the underpredicted cells. Figure 12 shows the percentage of relative underestimated area for different slope ranges. The results indicate that 81.9% to 91.9% of the underestimated cells are located in the slopes of greater than 2.5% in which 56.7% to 78.5% of them are in the slopes of greater than 5% varying with spatial resolution. This means that more than a half of underestimations occur in the areas with slopes greater than 5%. This highlights key role of topographic resolution in the hilly areas. Moreover, it implies that the selection of an appropriate spatial resolution depends on the topographic characteristics of the case study. In other words, a general advice about the sufficient spatial resolution cannot be given based on the results of this study. Further studies should be performed in other areas with different topographic characteristics to verify the results of this study and to determine an adequate topographic scale for dam break simulations. This will be useful to reach the highest model performance and also to avoid the redundant computational time simultaneously.

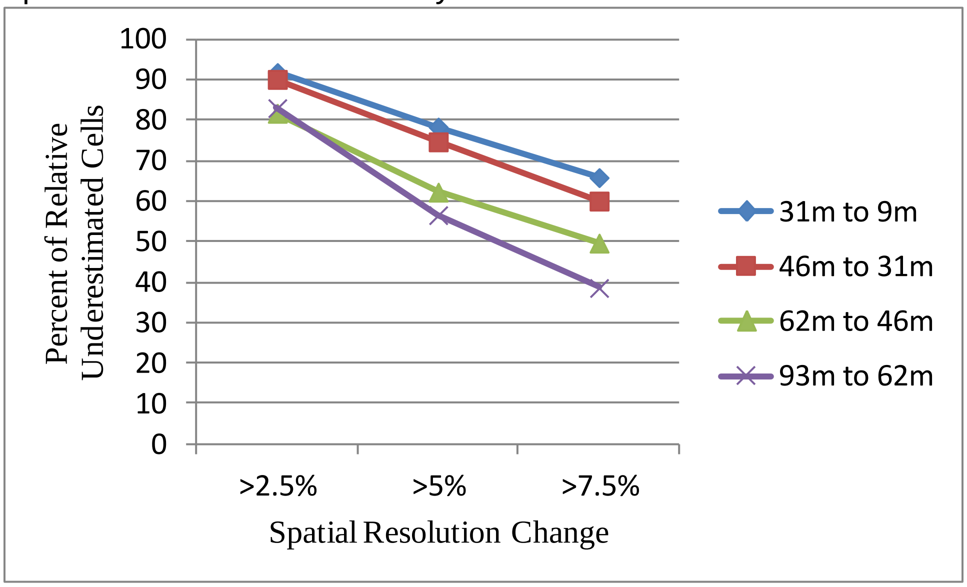


Figure 12. Percent of relative underestimated cells for different slope ranges

Finally, it is to be noted that the hazard was estimated based on flood depth and velocity here. Other parameters such as warning time which have been suggested in the previous studies (e.g. Graham, 1999) are not taken into account which incorporates another uncertainty to the results. This can affect the number of cells in each hazard class and accordingly the conclusions about the trend of hazard variation with spatial resolution. Thus, it is suggested that the same procedure being repeated in the future by using other hazard estimation methods to verify findings of this study.

Summary and Conclusion

A probabilistic dam break simulation was carried out in order to investigate the spatial resolution effects on downstream flood hazard. Five different spatial resolutions including 93m, 62m, 46m, 31m and 9m were used to generate spatial flood hazard maps. A 2D flood model, Flood2D-GPU is employed in a probabilistic framework to investigate these spatial resolution impacts by applying dam break simulations on Burnett Dam located in Buncombe County, NC. The dam break hydrograph is chosen as the uncertain parameter as it adds greater source of uncertainties in most situations. 99 stochastic dam break hydrographs representing various possible dam failure scenarios are generated by GoldSim® MCS software. These hydrographs are input into Flood2D-GPU to produce probabilistic flood hazard maps. The probabilistic simulations were carried out for 9m, 31m, 46m, 62m and 93m spatial resolutions. The most important findings for this study can be summarized as:

- ✓ The inundation area extent predicted through Flood2d-GPU decreases with finer spatial resolution. This is mainly due to difference in terrain description by different resolutions of DEM.
- ✓ Increasing the resolution from 93m to 9m will lead to a slight change in overall flood hazard and “high danger” class extent.
- ✓ “High danger” area generally increased with improving the DEM spatial resolution. It can be concluded that as the spatial resolution increases, more locations are classified to a higher danger level. This could be because, with improved spatial resolution, the grid cells that were classified as judgment and/or low hazard are converted to high hazard zone.
- ✓ More than a half of relative underestimated cells are located in the areas with slopes greater than 5%. This emphasizes the significance of topographic resolution in the hilly environments. Therefore, a coarse terrain model is not suggested for the areas mostly covered by steep slopes.

To provide general recommendations to dam safety officers and floodplain managers, studies similar to the current studies need to be performed. This will be useful to reach the highest model performance and also to avoid the redundant computational time simultaneously.

Acknowledgment

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