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Impacts of Elevation Data Spatial Resolution on Two-Dimensional Dam Break Flood Simulation and Consequence Assessment

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CHAPTER 4

IMPACTS OF ELEVATION DATA SPATIAL RESOLUTION ON TWO-DIMENSIONAL DAM BREAK FLOOD SIMULATION AND CONSEQUENCE ASSESSMENT

4.1 Introduction

The National Inventory of Dams (NID) reports that there are approximately 79,500 dams in United States, including approximately 11,800 dams that are considered high-hazard. High-hazard dams are defined as those in which failure would likely result in loss of life (at least one person) and significant downstream damage (FEMA 2007). Considering only high-hazard dams in the United States, approximately 40 percent do not have an emergency action plan (EAP) to be used in the event of a dam failure resulting from a natural event, such as a large storm or earthquake, or from a manmade event, such as a terrorist attack (FEMA 2007). The purpose of an EAP is to mitigate the loss of life and property by (1) identification of potential flood zones downstream of the dam structure and (2) predict the timing of the dam break flood wave. Fig. 4.1 below shows all high-hazard dams in the United States and designates whether an EAP exists for the dam.

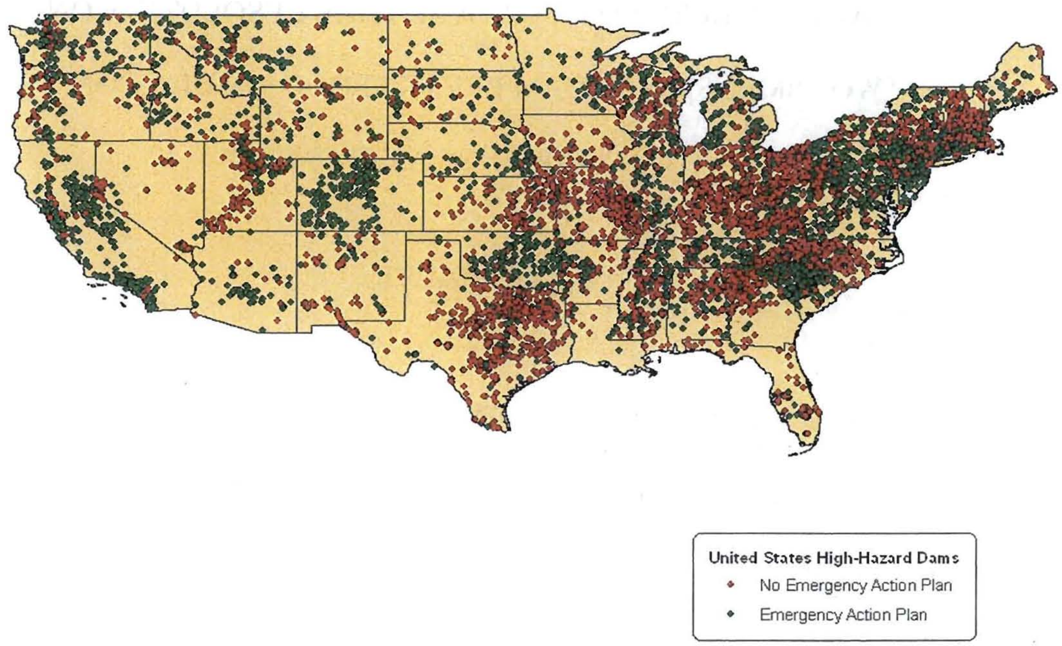

Fig. 4.1. High-hazard dams located in the United States (source data from NID).

The urgency for high-hazard dams to have an EAP has been increased since it has been found that ~3,500 dams in the United States are considered unsafe or deficient (ASCE 2005; FEMA 2008).

In January, 2006, the Task Group on Emergency Action Planning and Response, consisting of state and federal dam safety professional and engineers, the emergency management community, the security and protection community, and emergency response organizations, was formed to develop recommendations and strategies to increase the number of EAP's for designated high-hazard dams (FEMA 2007). The Task Group found that all non-federal high-hazard classification dams must be mapped for dam breach in order to save lives and reduce casualties from dam failure and that regardless of state law or regulation, dam owners should prepare an EAP. However, the Task Group also found that there is limited funding available to develop these plans and has, therefore, been identified as a primary constraint in developing EAPs for all high-hazard dams. Given the importance of identifying flood wave impacts to save lives and protect property downstream of high-hazard dams, a cost-effective method is needed to develop EAP's for all dams, and at a minimum, develop methodology for high-hazard dam prioritization.

Undoubtedly, the greatest cost in developing an EAP is determining area of potential inundation downstream of the dam. Similar to the procedures used to develop flood insurance rate maps (FIRMs) for the Federal Emergency Management Agency (FEMA), dam breach inundation is typically determined by developing cross sections for one-dimensional flow modeling and using either steady or unsteady modeling approaches (Hudock 2006). The area of inundation is subsequently determined by connecting water surface elevations at each cross section and creating the flood area by interpolation (Bates and De Roo, 2000). However, two-dimensional models are becoming more widely used (Beffa and Connell, 2001; Bradford and Sanders, 2002; Lin et al., 2003; Zhou et al., 2004, Judi et al., 2009) since these models have significantly greater ability to determine flow velocity and direction, and thus inundation area when compared to one-dimensional models (TRB 2006). For this reason, the National Research Council (NRC 2009) has recommended that two-dimensional models be used in floodplain delineation studies.

The major limitation of two-dimensional models has been the associated computational cost. To alleviate some of the computational cost, two-dimensional models have recently taken advantage of increased computing power now standard in desktop computers. These advancements include the use of OpenMP (Neal et al. 2009) and Java multithreading (Judi et al., 2009) for parallel computing on multi-core, multi-processor computers, as well as parallel computing on graphics processing units (GPU) (Lamb et al. 2009). These models have shown that computation time using two-dimensional models can be greatly reduced which can lead to more analyses completed at a faster rate.

However, when utilizing high resolution digital elevation data (e.g. LiDAR) and simulating regional-scale events (e.g. dam failures), the simulation still may be infeasible for flood analysis despite increased computing power (Neelz et al. 2007). High resolution digital elevation data is typically preferred for flood studies since these are better able to represent complex topographic features and the associated complex flow characteristics, which may be diffused when using lower resolution digital elevation model (DEM) data (Sanders 2007, Marks and Bates 2000). The consequence of using coarse resolution DEM data has been investigated in raster-based two-dimensional models in urban areas with resolutions of 2, 4, 8, 16, and 32 meters (Yu and Lane 2006). It was found that the model was sensitive to resolution with respect to both inundation extent (greater with coarser resolution) and flood wave time (faster with coarser resolution). A similar study was conducted using a raster-based two-dimensional method in a rural area at DEM resolutions of 10, 20, 50, 100, 250, 500, and 1000 meters (Horrit and Bates 2001). All simulations were compared to observed satellite radar data, and found that the total inundation area was similar for resolutions up to 100 meter, indicating that simulations using resolutions finer than 100 meters did not yield significantly better results in terms of inundation area. Clearly coarsening resolution has effects on the area and timing of the flood wave, but the resolution necessary depends on many factors, such as the purpose of the study and the scale at which the model operates. While these grid resolution studies have stated the performance of raster-based models in terms of inundation extent, depths, and velocities, they do not indicate the impacts grid resolution on the consequences of flooding in terms of socio-economic factors, important considerations when developing an EAP.

This study examines the impact of elevation data spatial resolution on two-dimensional dam break flood simulation results and population and economic consequences. Unique to this study is the inclusion of the socio-economic metrics of population at risk (PAR) and economic cost of damages, both relevant to developing EAPs. While most grid resolution studies focus on one specific geographic location, this study includes case studies from six randomly selected locations in the U.S. to determine if the results from the study are independent of site-specific conditions.

4.2 Methodology

A two-dimensional hydraulic model based on the complete shallow water equations developed using Java is the basis for this study (Judi et al. 2009a).The non-conservative form of the equations are shown in Equations 4.1, 4.2, and 4.3, which consist of a continuity equation and momentum in the x and y direction, respectively.

$$\frac{\partial h}{\partial t}+\frac{\partial uh}{\partial x}+\frac{\partial vh}{\partial y}=0 \tag{4.1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial H}{\partial x}+gS_{fx}=0 \tag{4.2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial H}{\partial y}+gS_{fy}=0 \tag{4.3}$$

where h is the water depth, H is the water surface elevation, u is the velocity in the x-direction, v is the velocity in the y-direction, t is time, g is the gravitational constant, S_{fx} is the friction slope in the x-direction, and S_{fy} is the friction slope in the y-direction. The friction slope terms are estimated based on the Manning formula.

An explicit finite difference scheme was used to solve the partial differential equations with an upwind-differencing method used for numerical stability. The variables are placed on a staggered grid with the velocity vectors located at the cell face and the scalar quantity, h, located at the cell center. This helps provide some stability to the model as well as reduce computations needed during each time step. The model uses a structured grid which makes it possible to easily ingest readily available DEM data without requiring a mesh generation tool. The model has been shown to accurately represent both depths and timing of the flood wave in both laboratory experiments as well as a real-world dam break (Judi et al. 2009a). To decrease computation time, the two-dimensional model implements Java multithreading to provide desktop parallel computing on multi-core computers, coupled with an effective domain-tracking algorithm, which together has shown to cut computation time by as much as 220 times (Judi et al. 2009b).

This model has developed for the National Infrastructure Simulation and Analysis Center (NISAC). NISAC is a recognized source of expertise on issues germane to critical infrastructure protection, preparedness, and continuity of operations. NISAC draws on the modeling, simulation, and analysis expertise at Los Alamos and Sandia National Laboratories to systematically quantify the potential consequences of damage to critical infrastructure from natural and manmade disasters. These analyses help decision makers understand infrastructure protection, mitigation, response, and recovery options. They also help decision makers prepare for and respond to the physical, economic, and security implications to our nation if these infrastructures are disrupted.

For this study, six dams randomly located in the United States were selected to determine the impacts of grid resolution on dam breach simulations. The randomly selected dams are located in a variety of topographical regions, as shown by the variation in both longitudinal (along the main flow path) and area average slope (taken as the average maximum slope, defined by the maximum downhill decent between a cell and its neighbors, in the flooded region). The longitudinal slope characterizes the slope, thus the ability of water to flow in the direction parallel to the flood wave. The area average slope characterizes the slopes transverse from main channel or in the direction of the floodplain, thus the ability of water to flow into the direction of the floodplain. These slopes are shown in Fig. 4.2. The longitudinal slopes of the dams range from near 0% to 1.5%. Based on the comparison of area average slope to longitudinal slope, it would appear the most of the dams are characterized by a downstream channel with some ability to contain flow, with the exception of Breach 3.

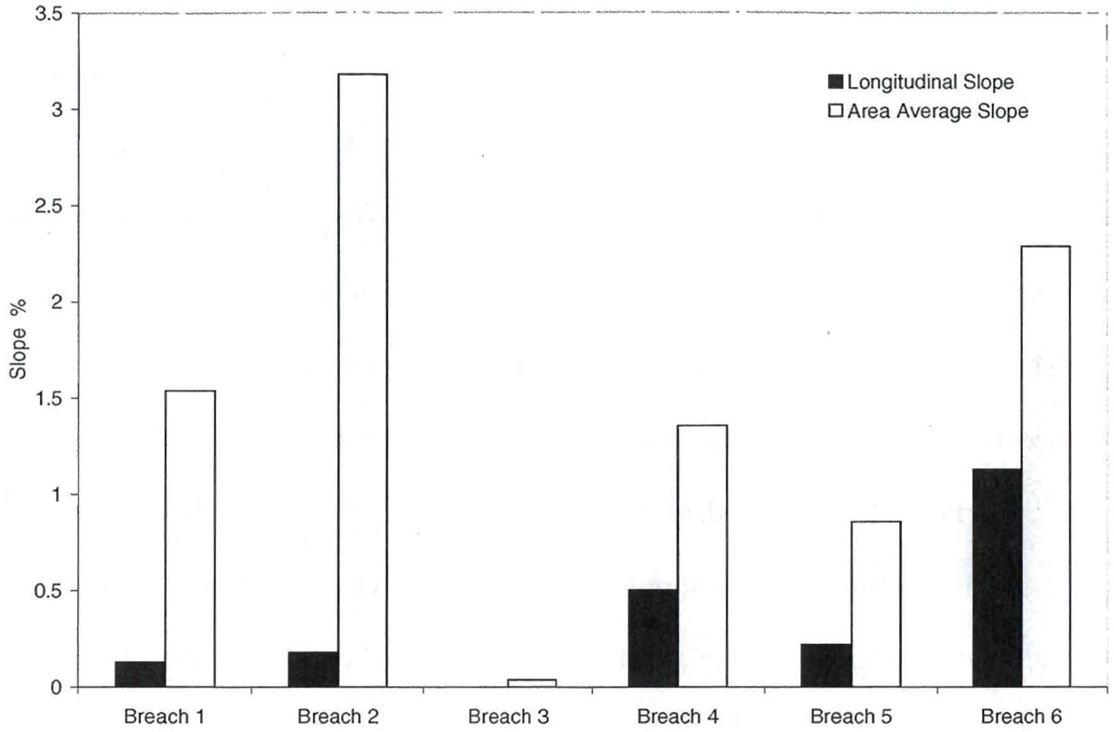

Fig. 4.2. Dam breach longitudinal slopes (slopes along the main flow path) and average area slopes.

The DEM data used in this study is the National Elevation Dataset (NED) available at 1/3 (10-meter) arc-second for much of the United States, distributed by the United States Geological Survey (USGS). The stated accuracy of the DEM data is 7 meters (RMSE). The grid resolution study presented here examines DEM resolutions of 10, 30, 60, 90, and 120 meters. The 10 meter DEM data obtained from the USGS was used as the base elevation dataset, and all other resolutions were re-sampled from the 10 meter resolution to the necessary resolution using the nearest neighbor method (Wu et al. 2008). Each breach simulation consisted of a discharge hydrograph developed using the approach implemented in the National Weather Service DAMBRK model (Fread 1991).

The hydrographs used in the dam breach simulations are shown in Fig. 4.3 below. The hydrographs developed for the breaches were used for each of the resolutions.

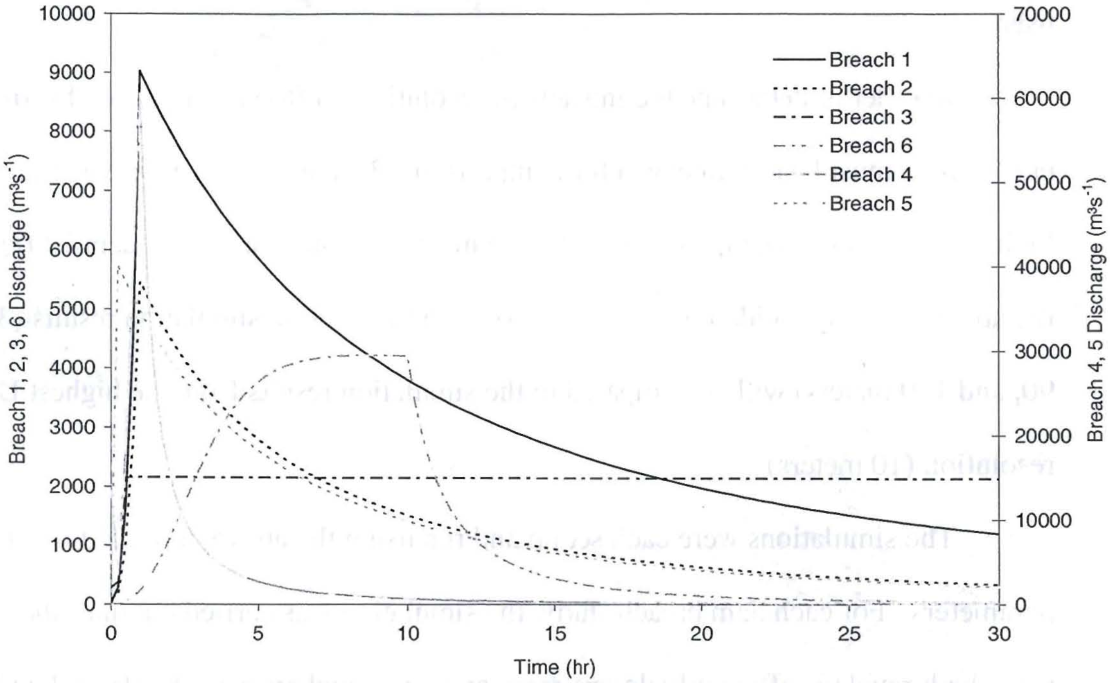

Fig. 4.2. Breach discharge hydrographs developed for each of the 6 dam breach study areas.

The final input parameter for the simulation is the Manning's roughness value. For dam breach modeling, it has been common practice to use a constant roughness value due to lack of data to develop distributed roughness values (Begnudelli and Sanders 2007, Baliani et al. 2002). For these simulations, a constant roughness value of .035 is used.

In order to determine the impacts of resolution on flooded area, depths, timing, etc…, there must be baseline data for comparison. Because it is generally believed that higher resolution topographic data will give more accurate results (Sanders 2007) and in the absence of any validation data, all coarser grid resolution simulation results (30, 60, 90, and 120 meters) will be compared to the simulation results from the highest DEM resolution (10 meters).

The simulations were each set up and run using the above described input parameters. For each dam breach study, the simulation was carried out until the flood wave had traveled sufficiently downstream and inundated areas of the floodplain began to recede. The computation time for each of the simulations are shown in Table 4.1. Most simulations were run using a Mac Pro computer with 2 dual-core Intel Xeon processors with a clock speed of 3.0 GHz and 4 GB of RAM, while a few of the larger simulations were run using a Linux quad quad-core (16) AMD Opteron™ 8354 processors with a clock speed of 2.21 GHz and 32 GB of RAM.

Table 4.1. Model computation time for 10, 30, 60, 90, and 120 meter resolutions.

	Computation Time (hr)				
Study	10 Meter	30 Meter	60 Meter	90 Meter	120 Meter
Breach 1	44.02*	2.4	0.37	0.133	0.08
Breach 2	8.65	0.37	0.083	0.03	0.05

Breach 3	131.35*	20.05	1.33	0.9	0.5
Breach 4	67.5*	17.8	4.25	0.33	0.3
Breach 5	133.01*	14.33	2.1	0.37	0.3
Breach 6	14.92	0.6	0.08	0.05	0.03

*Simulated using Linux quad quad-core (16) AMD Opteron™ 8354 processors with a clock speed of 2.21 GHz and 32 GB of RAM.

The computation times are greatly reduced when using coarser resolution simulations. Factors that reduce computation time as the grid is coarsened include reduced number of computational cells and the possibility of a larger time step based on the Courant Condition.

The impacts of grid resolution on simulation results were looked at in terms of flood inundation area, average peak depths, average travel time, and the socio-economic impact. In this study, the flood inundation area is taken as the maximum extent of flooding during the simulation, regardless of time. Two inundation area metrics are used to determine how the coarser resolution inundation areas compare to the baseline resolution. First a measure of fit, shown in Equation 4.4, is used to give an overall assessment on how the two datasets relate.

$$Fit = 1 - \frac{A(S_{\mathrm{mod}} \cap S_{obs})}{A(S_{\mathrm{mod}} \cup S_{obs})}(100) \tag{4.4}$$

where S_{mod} and S_{obs} are the inundation extents of the modeled and observed data (in this case, 10 meter simulation results), respectively. While Equation 4.4 gives an indication of the overall difference between the two datasets, it does not indicate any overestimation or underestimation. To accomplish this, a second metric is used. A statistical comparison between the two datasets can be made by rasterizing the two datasets with a cell size equal to the finest resolution (10 meter) and creating an error matrix. The error matrix consists of a comparison of flooded areas, assigned a value of 1, and non-flooded areas, assigned a value of 0. Using the error matrix, errors of commission (overestimation) and errors of omission (underestimation) may be calculated, as shown in Equations 4.5 and 4.6 below.

$$\textit{Commission Difference} = \left(1 - {P_e}\big/{P_t}\right)100 \tag{4.5}$$

$$\textit{Omission Difference} = \left(1 - {P_e}\big/{P_u}\right)100 \tag{4.6}$$

where P_e is the number of common flooded cells, P_t is the total number of coarser resolution simulated wet cells, and P_u is the total number of 10 meter resolution simulated wet cells.

The second metric used in comparison of the peak depths. The peak depths are defined here as the maximum depth regardless of time during the simulation for each cell. The peak depths are then averaged for each of the resolutions and compared to the 10 meter average peak depth.

The third metric is the flood wave travel time. Rather than compare velocities directly, the metric puts the comparison in terms of how much longer or how much sooner the flood wave reaches any given point. To determine the average flood wave travel time, the time it took each cell to become inundated is determined and then the entire flooded area is averaged to determine the average time to flood wave arrival. Each of the coarser resolution average travel times are then compared to the 10 meter average travel time.

The socio-economic impacts include an assessment of the impacts of PAR, as well as the economic impacts. PAR is defined as the sum of all people located within the maximum extent of flooding (again, regardless of time). To determine the PAR, two population raster datasets at 250 meter resolution representing both daytime and nighttime locations (McPherson and Brown 2004) were used. To prevent possible over counting of population due to the coarser nature of the population datasets, the population rasters were disaggregated to 10 meter resolution, with the population from the 250 meter cells being evenly distributed among the inner 10 meter cells. The economic analysis includes 1 kilometer raster datasets consisting of both direct and indirect cost available for the United States (NISAC 2009). These datasets are used to determine the cost associated with dam breach inundation. The economic data is a compilation of Bureau of Economic Analysis (BEA) and Dun & Bradstreet data to measure the gross domestic product (GDP) per day. The direct costs are defined here as those that can be directly traced to producing specific goods or services and indirect costs are those not directly related to a specific function or product, but those costs that have an indirect relationship with the damage (e.g. lost wages because of business closure). As with the PAR , the economic rasters are disaggregated to 10 meter resolution to prevent over estimation and the costs associated at the 1 km scale are evenly distributed among the inner 10 meter cells.

4.3 Results

The measure of fit and the errors of omission and commission for each of the dam breaches are shown in Fig. 4.3-4.5 below.

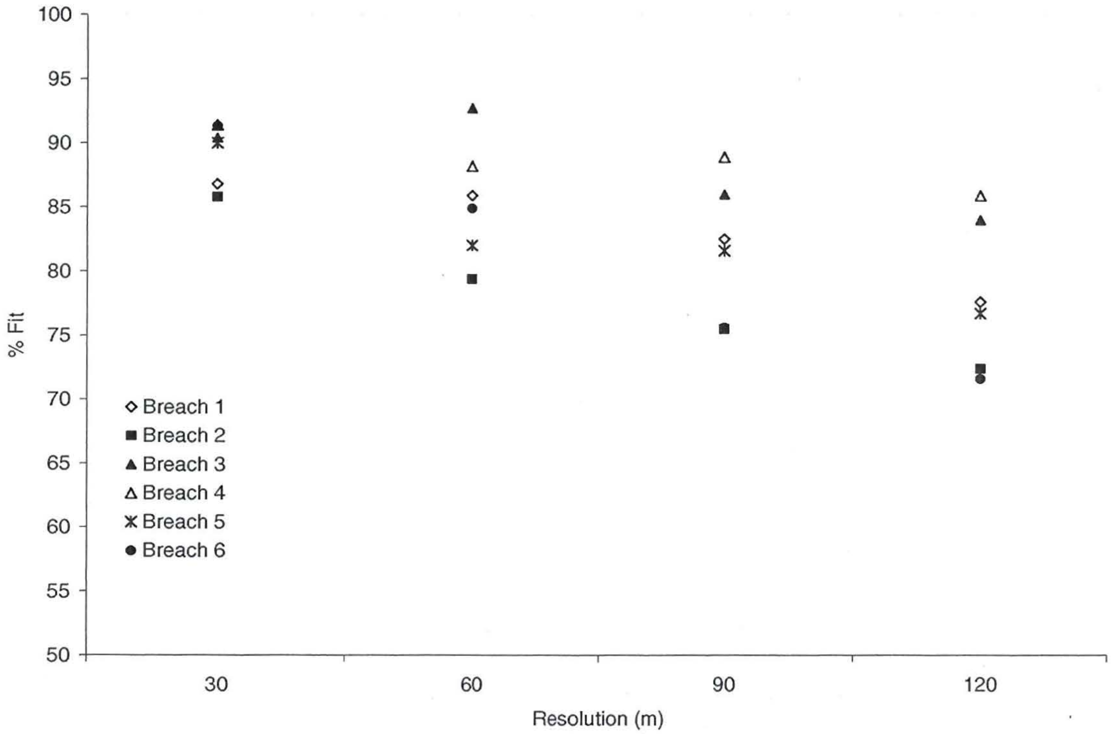

Fig. 4.3. Measure of fit of the inundated area for each of the dam breach simulations. Each of the coarser resolutions is compared to the simulation results using a 10 meter DEM.

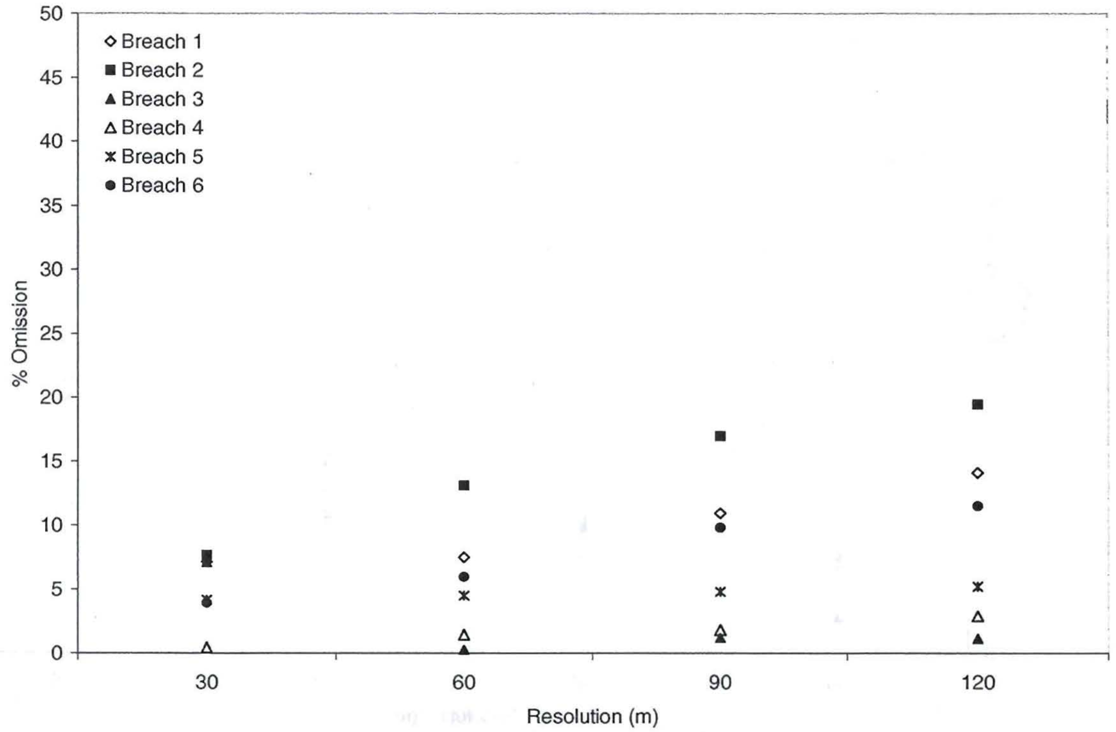

Fig. 4.4. Errors of omission (underprediction) of inundated area for each of the dam breach simulations. Each of the coarser resolutions is compared to the simulation results using a 10 meter DEM.

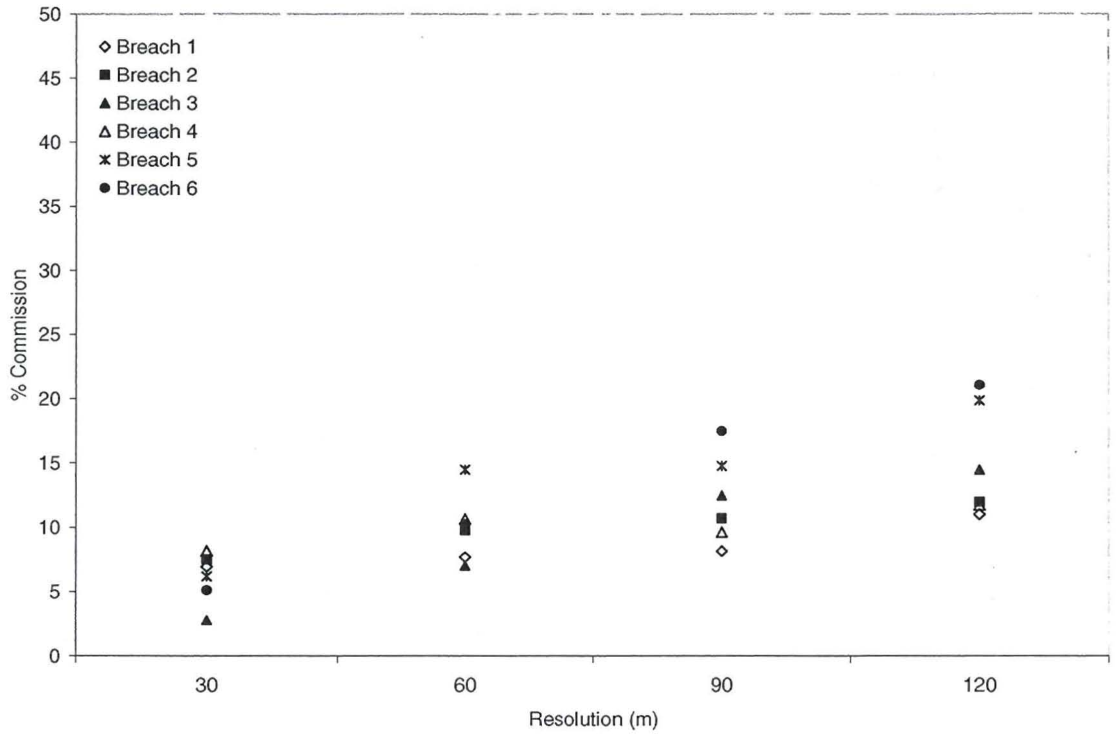

Fig. 4.5. Errors of commission (overprediction) of inundated area for each of the dam breach simulations. Each of the coarser resolutions is compared to the simulation results using a 10 meter DEM.

The measure of fit shows a slight decreasing trend as resolution decreases, although in general, the measure of fit seems good for all resolutions. The 30 meter resolution inundation results showed the most consistency in estimating inundation area for all breach simulations, and the range in error increases as resolution decreases. The omission and commission errors show similar trends to the measure of fit. Both errors tend to increase as the resolution is decreased, and the error is less consistent as resolution decreases. Overall, the resolution impacts on inundation are not large and is consistent with similar studies completed using raster-based flood simulation methods (Horrit and Bates 2001).

The effects of grid resolution on peak depths are also examined. As stated previously, peak depths are the maximum depth at a given cell at any time during the simulation. For comparison, the average peak depth for each resolution was determined, and compared to the average peak depth of the 10 meter simulation. The results, expressed as a percent difference from the 10 meter results, are presented in Fig. 4.6.

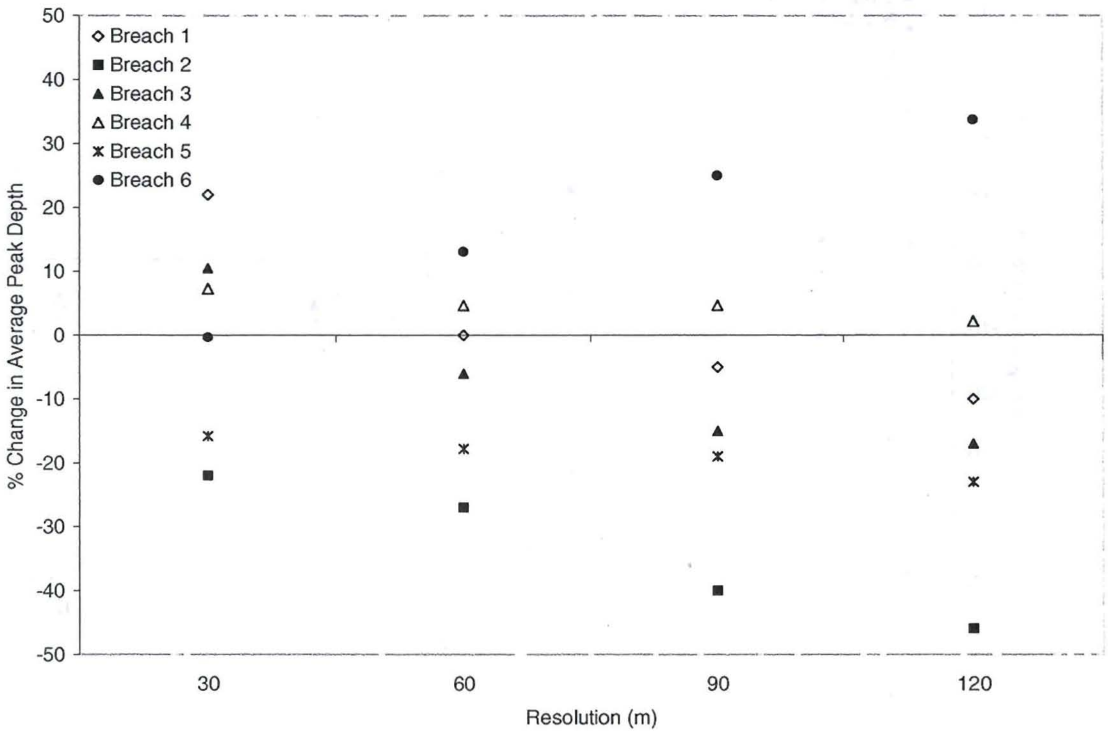

Fig. 4.6. Comparison of coarsened resolution dam breach simulation peak depths to 10 meter simulation.

The peak depths show a general trend of decreasing depths as resolution decreases with the noted exception of Breach 6, in which the depths actually increased with decreasing resolution. Explanation for this anomaly will be given later. Similar to the inundation results, the range of error increases with decreasing resolution. Studies have previously shown that as grid resolution decreases, the velocity tends to increase. With increasing velocities, it would be expected that the depths would therefore decrease to maintain the same flow rate. Though velocities are not explicitly compared in this study, the time it takes a cell to be inundated (or the arrival time of the flood) is compared. The coarser resolution average travel times were compared with the baseline simulations, and the results are shown in Fig. 4.7.

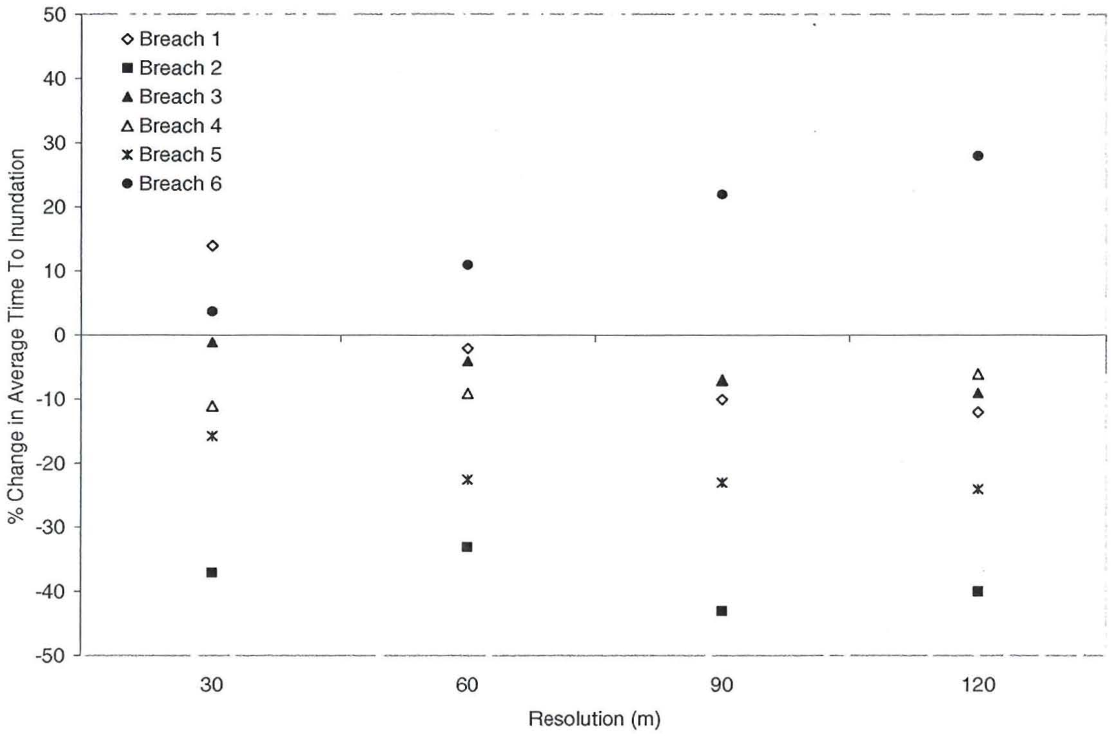

Fig. 4.7. Comparison of cell average time to inundation for dam breach simulations

In general, the results show that as grid resolution decreases, the average time it takes for the flood to inundate an area decreases, which indicates higher velocities. Interestingly, unlike the previous shown results, the inundation time does not show more consistency with higher resolution indicating that the timing of the wave is random with increased resolution. As seen in the peak depth comparisons, Breach 6 shows results dissimilar to the other 5 breach simulations in relation to flood wave time. Breach 6 flood wave is shown to actually slow down as grid resolution decreases, consistent with the increase in peak depths shown in Fig. 4.5. Closer inspection of this breach simulation showed that a narrow section of the downstream reach actually became constricted with coarsening resolution. The result was slight attenuation of the flood wave upstream of that point, increasing peak depths and decreasing velocities. Interestingly, although the noticeable change in depths and velocities resulting from this anomaly, the measure of fit was still reasonable for Breach 6.

The results for inundation area and velocity is consistent with other studies that have been completed for single locations (Horritt and Bates 2001; Haile and Rientjes 2005). However, what other studies have not shown is the relative over prediction and under prediction of flood extent, and more importantly, what impacts this has on subsequent analyses, such as socio-economic impacts. Because this study is directed at determining the impacts of grid resolution on dam breach inundation simulations for development of EAPs, it is important to also understand grid resolution in terms of PAR and economics. PAR, for this study, is defined as the sum of all people located within the maximum extent of flooding (again, regardless of time). The PAR was determined for each simulation, and compared to the corresponding 10 meter simulation. The results for daytime and nighttime PAR are shown in Fig. 4.7 and 4.8, respectively.

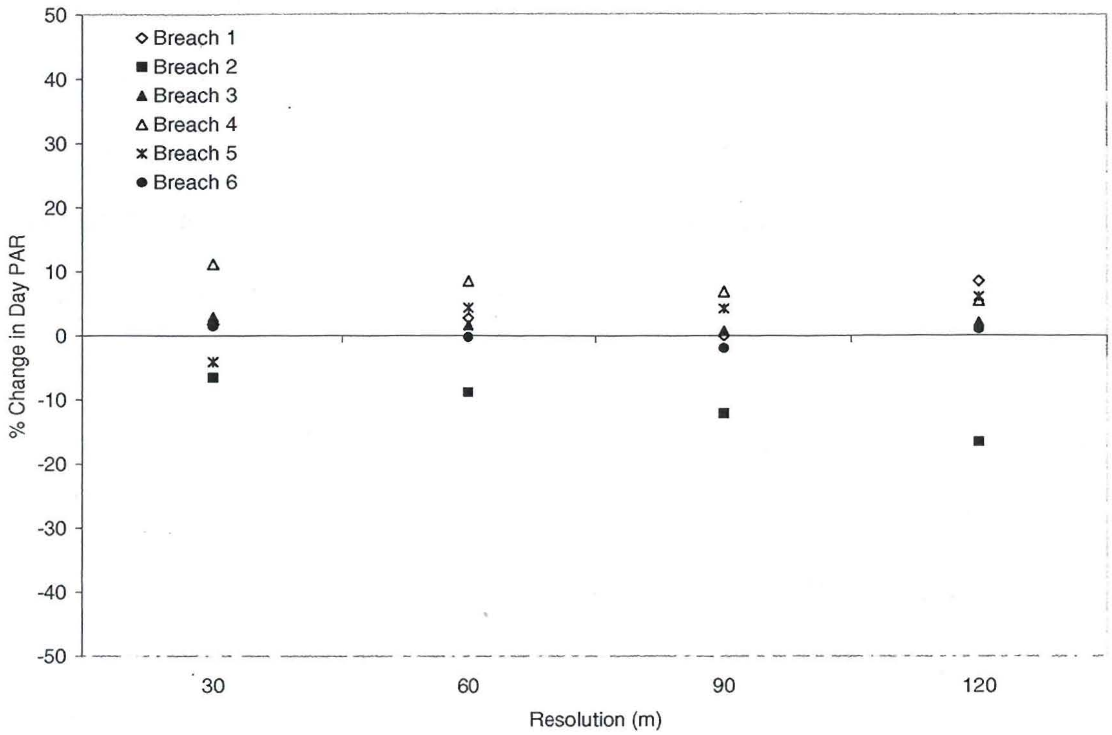

Fig. 4.7. Comparison of daytime PAR for dam breach simulations

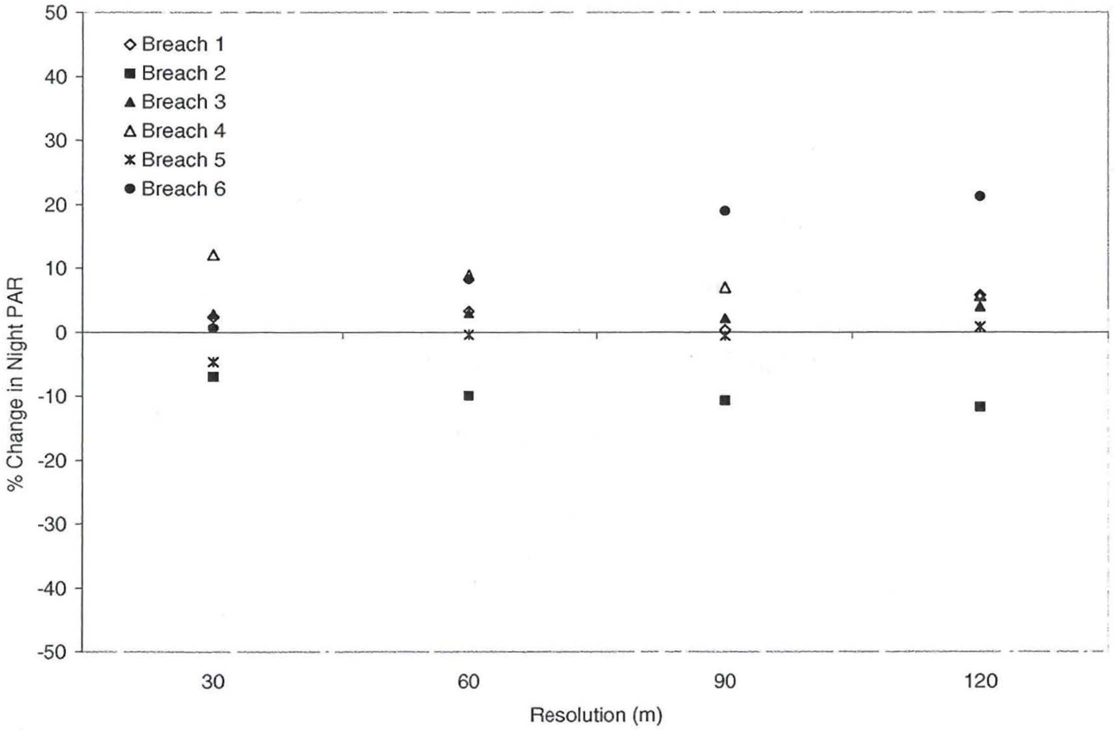

Fig. 4.8. Comparison of nighttime PAR for dam breach simulations

The PAR for both daytime and nighttime population shows little sensitivity to grid resolution, generally remaining within 10 percent of the PAR determined from the 10 meter simulations. This is contrary to the previous metrics analyzed, in which the general trend was a decrease (in area, depths, and travel time). This shows that the impacts of resolution on PAR cannot be accurately related to the percent fit of inundate area, as may be intuitively expected. The percent fit provides a general description of the overall comparison of the coarser resolution simulation to the high resolution simulation, but does not adequately indicate over prediction or under prediction. In reality, the simulation comparisons consist of both areas of over prediction and under prediction with population being included or excluded based on this. It is therefore likely that over estimated flooded area and subsequent PAR compensates for under estimated flooded area and subsequent PAR. Because of this, the PAR becomes less sensitive to grid resolution. The significance of the perceived insensitivity of PAR to grid resolution is that for instances in which estimates of population are needed quickly, low resolution simulations can still provide reasonable estimates of impacted population.

Finally, the economic impact of each of the simulations is considered. The results for direct and indirect economic impacts are shown in Fig. 4.9 and Fig. 4.10, respectively

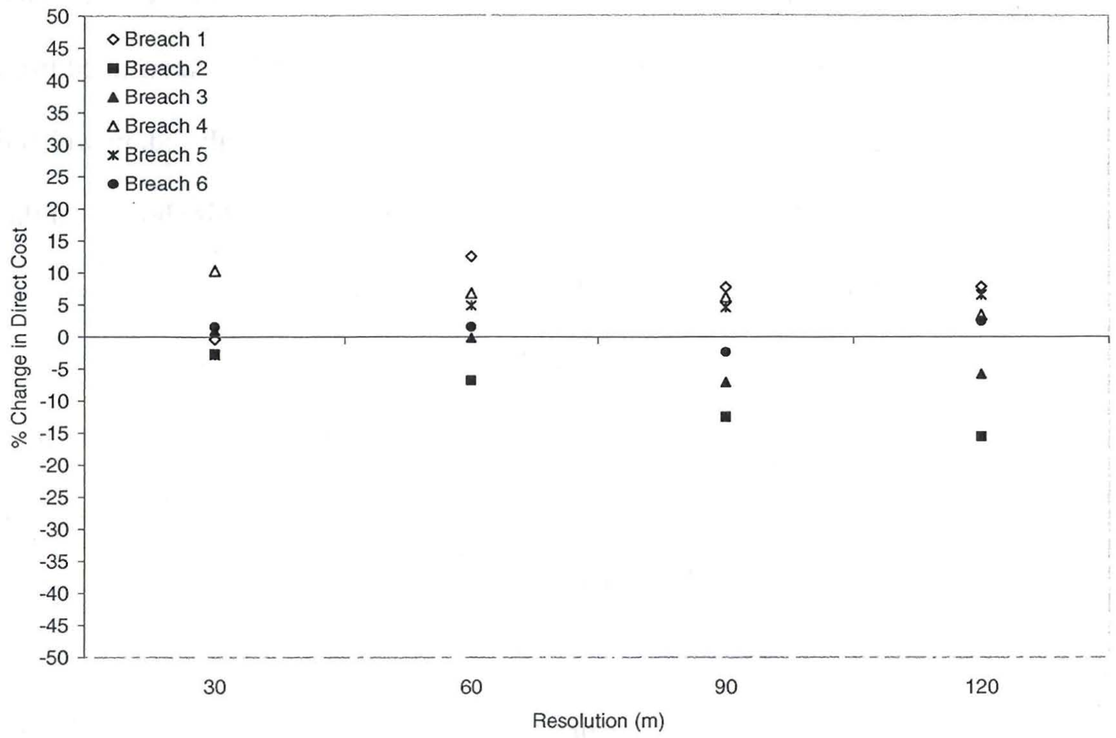

Fig. 4.9. Comparison of direct costs associated with dam breach inundation as a function of resolution.

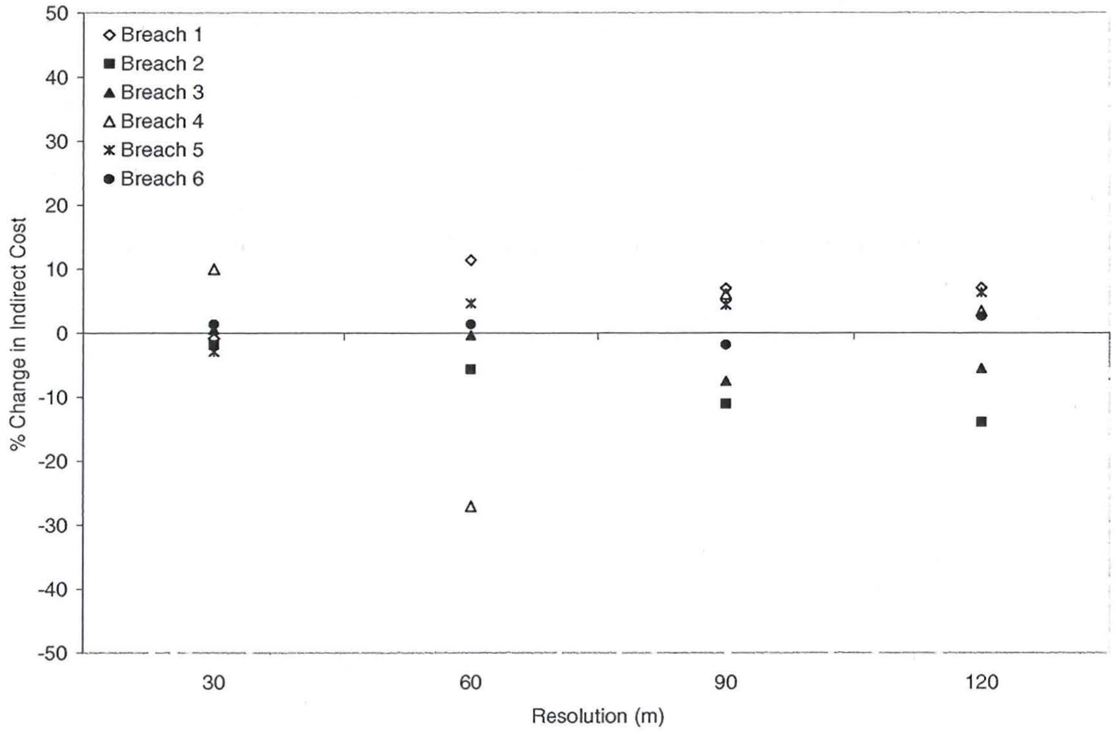

Fig. 4.10. Comparison of indirect costs associated with dam breach inundation as a function of resolution.

Similar to the PAR, the economic impacts of the dam breach simulation show little sensitivity to grid resolution. Generally, the economic cost associated with the breach inundation remains within 10% of the cost determined from the 10 meter simulations, regardless of grid size. The explanation of the insensitivity of economic impacts to grid resolution is likely the same as the PAR, where over estimation of inundated area and associated economic compensates for under estimation and associated economic impact.

4.3 Conclusions

A grid resolution sensitivity analysis using a two-dimensional flood inundation model has been presented in this paper. Simulations for 6 dam breaches located randomly in the United States were run at 10, 30, 60, 90, and 120 meter resolutions. The dams represent a range of topographic conditions, ranging from 0% slope to 1.5% downstream of the dam. Using 10 meter DEM simulation results as the baseline, the coarser simulation results were compared in terms of flood inundation area, peak depths, flood wave travel time, daytime and nighttime population in flooded area, and economic impacts. The results of the study were consistent with previous grid resolution studies in terms of inundated area, depths, and velocity impacts. The results showed that as grid resolution is decreased, the relative fit of inundated area between the baseline and coarser resolution decreased slightly. This is further characterized by increasing over prediction as well as increasing under prediction with decreasing resolution. Comparison of average peak depths showed that depths generally decreased as resolution decreased, as well as the velocity. It is, however, noted that the trends in depth and velocity showed less consistency than the inundation area metrics. This may indicate that for studies in which velocity and depths must be resolved more accurately (urban environments when flow around buildings is important in the calculation of drag effects), higher resolution DEM data should be used.

Perhaps the most significant finding from this study is the perceived insensitivity of socio-economic impacts to grid resolution. The difference in PAR and economic cost generally remained within 10% of the estimated impacts using the high resolution DEM. This insensitivity has been attributed to over estimated flood area and associated socio-economic impacts compensating for under estimated flooded area and associated socio-economic impacts.

The United States has many dams that are classified as high-hazard potential that need an EAP. It has been found that the development of EAPs for all high-hazard dams is handicapped due to funding limitations. The majority of the cost associated with developing an EAP is determining the flooded area. The results of this study have shown that coarse resolution dam breach studies can be used to provide an acceptable estimate of the inundated area and economic impacts, with very little computational cost. Therefore, the solution to limited funding may be to perform coarse resolution dam breach studies on high-hazard potential dams and use the results to help prioritize the order in which detailed EAPs should be developed.

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