Developing "Flood Loss Curve" for City of Sacramento

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Abstract

The current research presents the development of a "flood loss curve" for the city of Sacramento, California. A *flood loss curve* is defined as a functional relationship between direct flood damages and flood intensity. This study uses a series of design flood events for the American River to investigate possible damage caused at different flood intensities that the city may experience in future. These scenarios are generated using a Monte Carlo-based hydrograph generator, and are used as inputs for a HEC-RAS model to develop flood intensity parameters including flood inundation extents, depths, velocities and arrival time. These simulated flood parameters are input into HEC-FIA to compute direct damages. Results indicated a positive correlation between losses and flood intensity, reinforcing our flood loss curve concept and its value. This methodology can be used for preliminary vulnerability assessment and 'back of the envelope' loss estimates for impending flood events.

1. Introduction

Flood loss in the United States (US) has increased six fold since 1902 (Bhuyian et al 2014) and will cause even bigger issues as urbanization and climate change occurs and infrastructure deteriorates. Mitigating these flood losses requires a better understanding of flood hazards, their consequences, and potential rehabilitation measures, which is usually accomplished through hydraulic and economic models. This is challenging due to data availability, model complexity, and uncertainty. To address this issue, we propose the development of an easy to use "flood loss curve" that can be helpful to users for estimating losses due to any given flood scenario before embarking on a detailed and intricate analysis. A flood loss curve is defined by the functional relationship between direct flood damages (i.e. total financial loss, structural loss, loss of life etc.) and flood intensity (i.e. flow, flood extent etc.).

2. Research Objective

This study focuses on investigating the concept of a flood loss curve for an urban area. Therefore, the objective of this research is to ***"demonstrate the development of a flood loss curve for the city of***

Sacramento, California." To achieve this objective, a coupled modeling framework comprising a Monte Carlo-based hydrograph generator, a 1D hydrodynamic model, and a consequence assessment model was prepared. The framework was tested for selected flood magnitudes with 50%, 20%, 10%, 4%, 2%, 1% and, 0.2% annual probability of exceedance (also referred to as 2-yr, 5-yr, 10-yr, 25-yr, 50-yr, 100-yr and 500-yr return period events).

3. Methodology

The major steps followed in the study are shown in Figure 1 and a short summary is given below:

i. First, observed stream flows for the study area were analyzed to estimate peak flows for different annual probability of exceedance (PE) flood events. In this case, the 50%, 20%, 10%, 4%, 2%, 1% and 0.2% PE were selected.

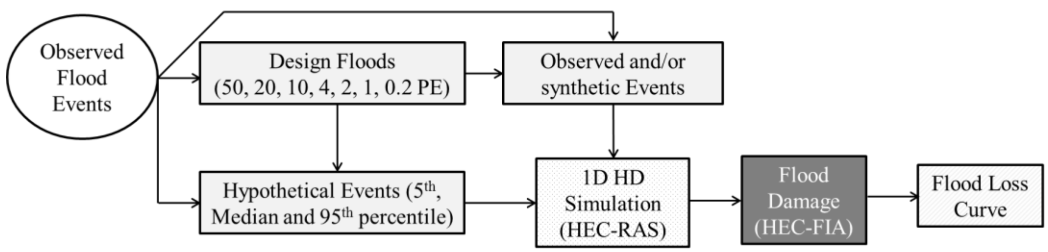


Figure 1: Flowchart of the process

ii. These peak flow estimates were then converted into synthetic flow hydrographs needed for performing unsteady flow simulations. According to Scawthorn et al (2006), Albano et al (2014) the flood loss is calculated as function of flood depth and flood wave. The peak flows were represented by selecting recorded hydrographs from past flood events (events with maximum flow close to the corresponding peak flow). For PEs that were larger than any past event, synthetic unsteady flows were generated using the maximum-recorded flood event and its shape as a representative profile (Kalyanapu et al., 2014). These flood event hydrographs are referred to as "deterministic event" hydrographs.

iii. A Monte Carlo-based hydrograph generator was used to create stochastic hydrographs for each of the PEs that represent various possible flood hydrographs and therefore generated various flood consequences. To do this, the 'representative hydrograph' for the maximum recorded flood event was processed in a stochastic hydrograph generator developed using GoldSim®, a dynamic simulation software. In this model, the hydrograph shape was repeatedly modified (around 10^5 times) using Monte Carlo sampling by introducing a "time lag" and generating many model realizations. These realizations were then statistically analyzed to obtain 5^{th}, 50^{th} and 95^{th} percentile hydrographs for all PE events. These flood event hydrographs are referred to as "probabilistic event" hydrographs.

iv. Both deterministic and probabilistic hydrographs for all PE events were then simulated in a Hydrologic Engineering Center River Analysis System (HEC-RAS) model to produce hourly and maximum flood depths and extents.

v. Simulated flood parameters (depth, inundation extent, and arrival time), topography, infrastructure data and census data were then input into a Hydrologic Engineering Center Flood Impact Analysis (HEC-FIA) model to estimate flood losses for each of the events.

vi. Correlation of flood damage and flood intensity (i.e. peak flow and inundation extent) were analyzed and flood loss curves were established.

4. Case Study

4.1 Study Area

The study reach is 22 miles along the American River in Sacramento, California. The model starts from Hazel Ridge Bridge and ends about a mile before the confluence with the Sacramento River. An upstream flow boundary was assigned at the Hazel Avenue Bridge (AHZ) location. The stage at the H Street Bridge (HST) on the American River was used for calibration. Figure 2 shows the study reach and gaging locations. This stretch of the river receives significant amounts of flow released from Folsom Dam located about seven miles upstream of the AHZ. This area is located in Sacramento County, California where dense urban settlement is present on both sides of the American River.

4.2 HEC-RAS Model Setup

A 22-mile HEC-RAS model acquired from the Sacramento Flood Control Agency (SAFCA, 2015) was used for hydrodynamic simulations. The model used 165 surveyed cross sections along with additional

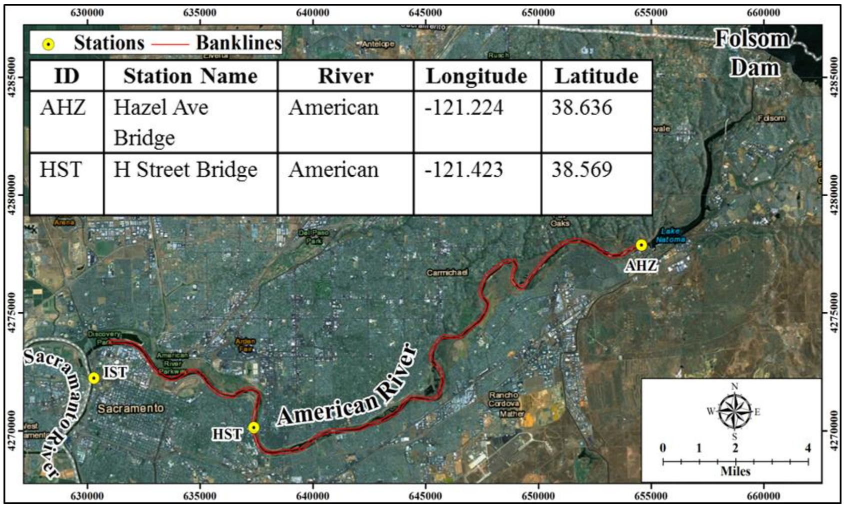


Figure 2: Study area with nearby gaging stations

185 interpolated cross sections. The model was extracted from a larger HEC-RAS setup that was prepared by the Hydraulic Design Section, Sacramento District, and USACE (referred to as the base model). For simplicity, the truncated model did not consider any control structure except levees and blocked areas. The downstream of the model was set to normal depth condition because using estimated stage as a downstream boundary would incorporate additional uncertainty for simulating flows with lower probability of exceedance.

4.3 HEC-RAS Model Calibration

The study reach was calibrated for flow data from December 15, 1996 to January 15, 1997. Initially the calibration parameters were kept the same as the base model and tested for different downstream friction slopes under normal flow. Several combinations were tested out of which a downstream slope of 0.0155 showed the best agreement in terms of Root Mean Square Error (RMSE), mean error and error in predicting peak flow. Figure 3 shows the efficiency of different test combinations and the calibration plot.

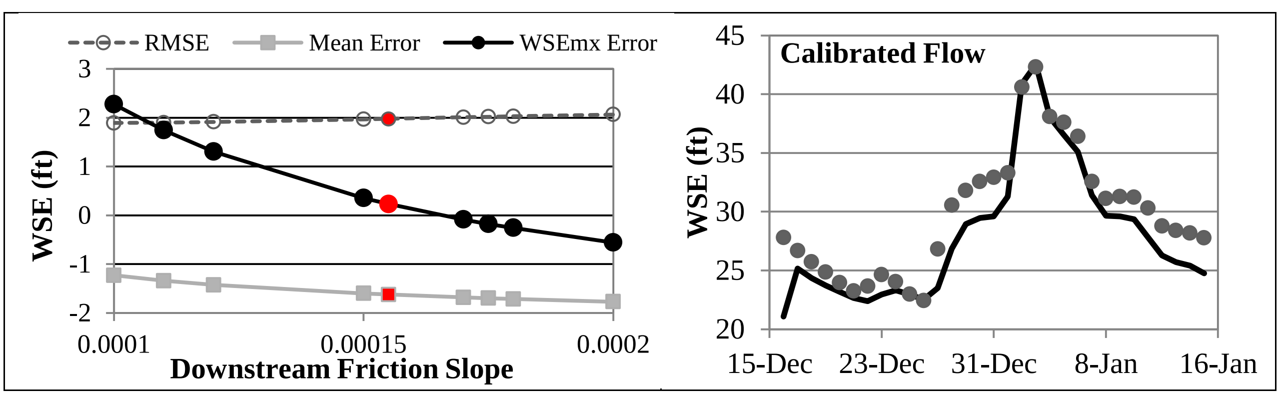


Figure 3: Efficiency of different test combinations (red combination is calibrated setup) and the calibration plot near HST is presented on the right

4.4 Generating Unsteady flood events

Annual exceedance probability statistics for peak flow were collected for the U.S. Geological Survey (USGS) gaging station 11446500 (station AHZ in Figure 2) using USGS Streamstats Reports (http://streamstatsags.cr.usgs.gov/gagepages/html/11446500.htm). Flow data from February 2 - 27, 1986 at USGS 11446500 was used as the representative hydrograph as explained in section 3. The representative hydrograph was stochastically lagged using a lognormal distribution (geometric mean of 60 hours and a geometric standard deviation of 2.5), and 100,000 Monte Carlo simulations (with Latin Hypercube Sampling). The resultant 100,000 hydrographs were compiled and hydrograph shapes corresponding to 5th, 50th and 95th percentiles were extracted. Then these hydrographs were scaled to each of the PE events to generate stochastic hydrographs for all of the PE events. Figure 4 shows Peak flow for different annual probability of exceedance (left) along with the deterministic and probability-weighted hydrographs generated using the peak flows (right).

Ann. Prob. of Exceedance	Flow (cfs)
50 %	32,500
20 %	72,100
10 %	108,000
4 %	164,000
2 %	214,000
1 %	271,000
0.2 %	432,000

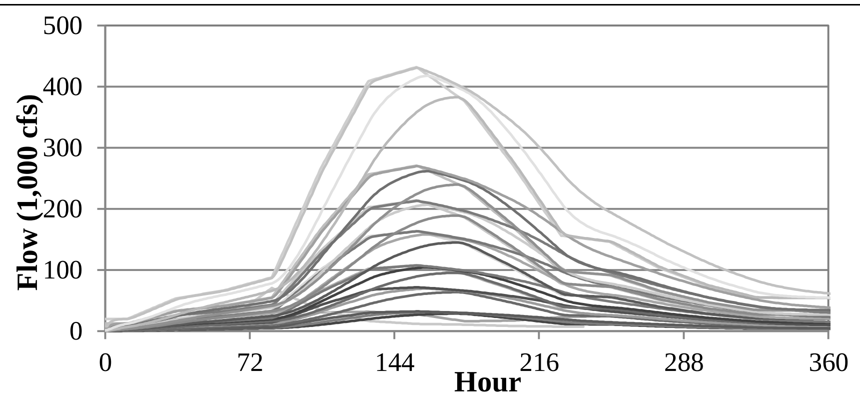


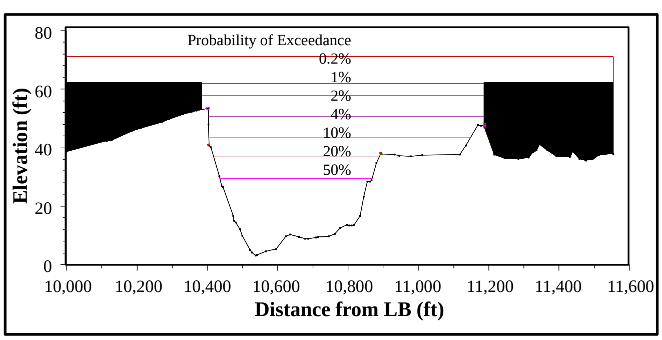
Figure 4: Peak flow for different annual probability of exceedance along with the deterministic and probability hydrographs generated using these peak flows

4.5 Simulating HEC-RAS and HEC-FIA simulations

In total, seven probable scenarios (annual probability of exceedance) were considered, each of which produced four (deterministic, 5th, median and 95th percentile) unsteady flow events. These resultant 28 events were simulated in HEC-RAS to produce flood parameters (i.e. stage, depth and inundation extent). These parameters were then input into a HEC-FIA model set up. The HEC-FIA model used here was not calibrated because the scope of this research was to demonstrate the approach of establishing a flood loss curve. The simulated FIA used local inventory such as structures, administrative area generated from the Hazus –MH 2010 database. The hydraulic parameters of the event were generated using either results from HEC-RAS or geometric files for each specific scenario.

5. Results and Discussion

Simulated flood stages for 1% and 0.2% exceeded the over bank elevations in the HEC-RAS cross sections and thus limited the width of inundation to the maximum cross-section width as seen in Figure 5. This limitation exaggerates the simulated water surface elevations for the two events. Therefore, the 1% and 0.2% PE events were excluded in developing the flood loss correlations. Figure 6 shows that flood extent and urban damage is positively correlated with peak flow (corresponding to each PE). The 5th and 95th percentile lines are plotted and extended to the peak flow of the 0.2% PE for representing the envelope of the 90% confidence limit. Similarly, another flood loss correlation was investigated using flood extent and urban damage using the 50% to the 2% PE for all the deterministic and probabilistic events. This correlation shows urban damage increases with a larger flooded area. The excluded PEs (1% and 0.2%) of both deterministic and probabilistic events showed good agreement with the urban damage versus flood extent flood loss curve (represented as hollow markers in right side of Figure 6). This indicates that the HEC-FIA results are less sensitive to flood dynamics (i.e. depth and velocity) and more strongly correlated with flood extent.



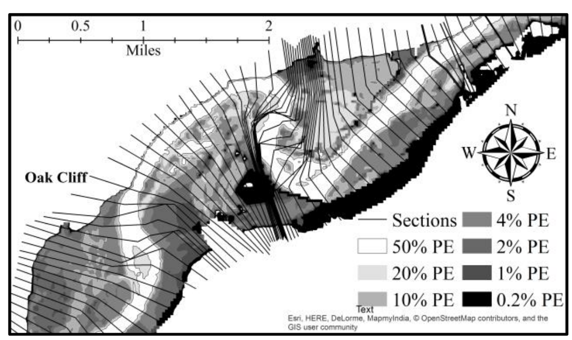


Figure 5: WSE for different PE events (left). Simulated flood map for same events showing that the1% and 0.2% PE events get confined by the limited width of cross sections (right).

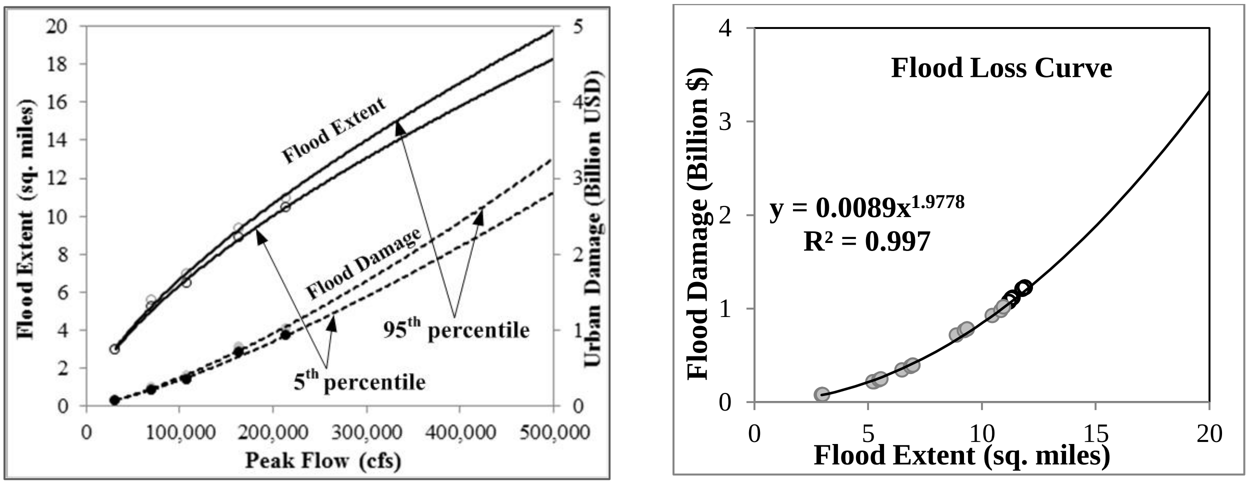


Figure 6: Flood loss curves. Left, peakflow versaus flood extenet and flood damage; right flood extent versus flood damage

6. Conclusions

The events were generated to cover a wide spectrum of possible flood events varying in both peak flow and flood wave propagation. The strong correlation between total loss and flood extent (Figure 6 – right) indicates, total damage will be higher for a wide spread flood with less depth than a confined flood with higher depth. This is because combined loss from smaller damages to multiple structures would be higher than catastrophic damage to one structure. Moreover, arrival of flood wave was also less sensitive to estimated total loss because for very large floods time for significant flooding depth (2 feet) was almost same for various times to peak. The assumption of arrival time to significant flooding depth would play vital role for evacuation measures instead of estimating total financial loss.

This study also showed limitation of the 1D hydrodynamic modeling for large flows that hints at the potential of using a 2D modeling platform. This in turn raises the issue of digital elevation accuracy of river bathymetry and its effect on computational performance. The flood loss curve covers a range of possible losses for different flood events that can help policy makers get a preliminary idea for required resources mobilization. Although, flood arrival time is less sensitive it still adds some uncertainty to the estimated total loss. Therefore, it is recommended to consider uncertainty when planning instead of using deterministic values. The whole process shown here are applicable for urban settlement as described in

HAZUS-MH 2010 but can be repeated with future urban growth to come up with separate envelops of incremental urban growth.

7. Acknowledgements

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