

## Calibration of River Hydraulic Model Combined with GIS Analysis using Ground-Based Observation Data

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**Abstract:** In this research a method to calibrate a river hydraulic model (HEC-RAS) using ground-based measurements of an observed flash flood is presented. Applications of the ground truth measurement of flood water depths and flooded areas within a reach of Neka River in Northern of Iran are discussed. The model is calibrated using the Manning's roughness coefficient based on 200-year flood event that took place in this river basin in August 1999. The model performance with different sets of Manning roughness coefficients is compared to observed spatial inundation data. The comparison between observed and simulated flood water depths for the optimal values of Manning roughness coefficients has shown a significant correlation ( $p < 0.0001$ ,  $R = 0.82$ ). Moreover, an agreement between the observed and simulated flood inundated extents is 88.5%. Floodplain inundation maps in different return periods were derived using integration of calibrated HEC-RAS model and GIS analysis. Delineation of flood extents and depths within the floodplain could be used for many practical applications.

**Key words:** Calibration, floodplain mapping, GIS, HEC-RAS, manning coefficient

### INTRODUCTION

Floodplain mapping is an applied method in river engineering discipline and is essential for prediction of flood hazards and flood inundation risk assessment. Performance analysis of any flood mitigation measure using simulation models is an important stage for floodplain planning and management (Ghanbarpour, 2007). Accurate delineation of flood extents and water depths within the floodplain is necessary to simulate complicated hydraulic behaviour of the river system, for the purpose of floodplain management, evaluation of river training practices, flood insurance studies, urban planning and other practices on land and property potentially affected by flooding (Correia *et al.*, 1999; Noman *et al.*, 2003; Salimi *et al.*, 2008). Recently, advance computer technology for hydraulic simulation and GIS, greatly facilitates the operation of floodplain mapping and flood risk assessment for practical purposes. As Werner (2001) stated the end result of the process is not only quicker floodplain delineation with greater accuracy than traditional methods, but also a spatial flow depth grid could be extracted to show the level of inundation risk in the floodplain. High degree of uncertainty exists in a

floodplain mapping project due to complexity of the surface water level modeling processes including structure of the model, topography, parameters and data. As a result, calibration of a river hydraulic model is a necessary stage in floodplain zoning. For this purpose, discharges and high water marks measured during recorded historical events are used to calibrate and verify the model. However, few opportunities exist to calibrate the hydraulic models used to estimate discharge from historical evidences (Kidson *et al.*, 2006). Calibration of river hydraulics models for the purpose of accurate floodplain mapping have been conducted in previous studies using integration of HEC-RAS hydraulic simulation model and GIS, remotely-sensed and ground-based data (Aronica *et al.*, 1998; Pappenberger *et al.*, 2005; Kidson *et al.*, 2006; Horritt, 2006; Di Baldassarre *et al.*, 2009). Generally, Manning's roughness coefficient is an important hydraulic model parameter which can be used to calibrate the model. However, different techniques such as visual inspection, trial and error, semi-empirical equations and uncertainty analysis of discharge-Manning's  $n$  relation could be used (Kidson *et al.*, 2006). Aronica *et al.* (1998) used Monte-Carlo simulations of a two-dimensional finite element model of a flood in the southern part of Sicily to

explore the parameter space of distributed bed roughness coefficients. A procedure used to compare model predictions and observations for a certain event, coupled with both a fuzzy-rule-based calibration, and a calibration technique based upon normal and heteroscedastic distributions of the predicted residuals. Pappenberger *et al.* (2005) applied a methodological approach to formalize the uncertainty in the roughness parameters in HEC-RAS using inundation and downstream level observations with the generalised likelihood uncertainty estimation (GLUE) methodology. Horritt (2006) quantified the accuracy of a river model predictions through use of the reliability diagram and the associated root mean square error between uncertain predicted inundation and observed flooded proportion, and the precision measured through use of an entropy-like measure. Di Baldassarre *et al.* (2009) presented a methodology to calibrate hydraulic models using possibility of inundation maps derived from satellite imagery. Different flood extent maps were used to perform a sensitivity analysis to investigate the capability of the two different resolution images to calibrate the friction parameters of the flood inundation model.

In this research a methodology was applied to calibrate a river hydraulic model (HEC-RAS) using ground-based measurements of an observed flash flood within a reach of Neka River in Northern Iran that occurred in August 1999. The model performance with different sets of Manning roughness coefficients are compared to observed spatial inundation data using graphical and statistical criteria. Delineation of flood risk extents within the floodplain are performed in different return periods using calibrated model. The main objective of this study is accurate delineation of flood extents and depths within the floodplain based on the integration of calibrated hydraulic simulation model and GIS analysis. The results of this research could be used for flood mitigation planning, flood insurance studies and sustainable urban development regarding to the historical flood threatens in the study area.

## MATERIALS AND METHODS

**Study site and data:** Neka River Watershed in Mazandaran province was selected for this research located in northern Iran between  $36^{\circ}28'5''$  to  $36^{\circ}42'4''$  N latitude and  $53^{\circ}17'2''$  to  $54^{\circ}44'3''$  E longitude. Figure 1 shows the location of the city of Neka and selected river reach in this research. The length of river is approximately 160 km from the headwater that it flows into the Caspian Sea. The length of river reach selected in this study is about 3.7 Km along Neka River. The area has a super humid climate and the maximum precipitation occurs in autumn and minimum precipitation in summer. The average annual precipitation of Neka River Basin is about

600 mm. The maximum and minimum average annual temperature in watershed is 26 and  $7.5^{\circ}\text{C}$ , respectively. Mean annual temperature is about  $17^{\circ}\text{C}$ . The average annual river flow discharge recorded at Abelu hydrometric station is  $4.9 \text{ m}^3/\text{s}$ . The village, Abelu is located in the upstream to this reach of river. According to an observation reports from Mazandaran Regional Water Company some intense flash floods occurred in this river, as the occurrence of floods has accelerated by the conversion of rice paddies into residential areas, urbanization and intensive deforestation. The most intense flash flood ever recorded has occurred in August 1999 with the peak flow of more than  $1300 \text{ m}^3/\text{s}$ , based on field observations and estimation, which had an extremely disastrous impact on the metropolitan area. However, the watershed experienced an abnormal heavy rainfall, which intensified overflow of river system. Observed rainfall during 48 hours in Darabkola and Gelevard rain gauge stations were measured 134 and 123 mm, respectively (Ghanbarpour *et al.*, 2010). Devastating flood event of August 1999 in Neka River caused many losses of life and property destructions.

In this research two types of data are used, namely annual peak flow and GIS data including cross sections, elevation points, physical properties of the river system and topographic map. Peak flow data recorded at Abelu hydrometric station, located in upstream of the selected reach was used for this study. The length of data set is 44 years from 1969-70 to 2004-05 water years, with some missing data. Data filling conducted using correlation analysis between annual series of Abelu hydrometric station and adjacent stations. Different statistical distributions are used to analyze flood frequency computation, including Log-Normal, Log-Normal III, Pearson III, Log-Pearson III and Gumbel. Estimated peak flow in 2 to 200-year return periods are used as input for the hydraulic simulation of the river reach. Topographic map of area with scale of 1:25000 and river plan with scale of 1:1000 were applied for TIN generation, using 3D analyst capability of ArcView. TIN is used for preparation of required data for hydraulic simulation in HEC-RAS. Moreover, GPS have been used to determine the absolute and correct positioning of all cross sections, elevation points and water depth and flooded area observation points.

**Steady flow simulation and floodplain mapping:** Simulation of water surface profiles for steady gradually varied flow can be conducted using HEC-RAS model. This model could be used to perform one-dimensional steady flow computations. The HEC-RAS model was developed at the Hydrologic Engineering Center (HEC), which is a division of the Institute for Water Resources, US Army Corps of Engineers (HEC, 2010). The steady flow component is capable of modeling subcritical,

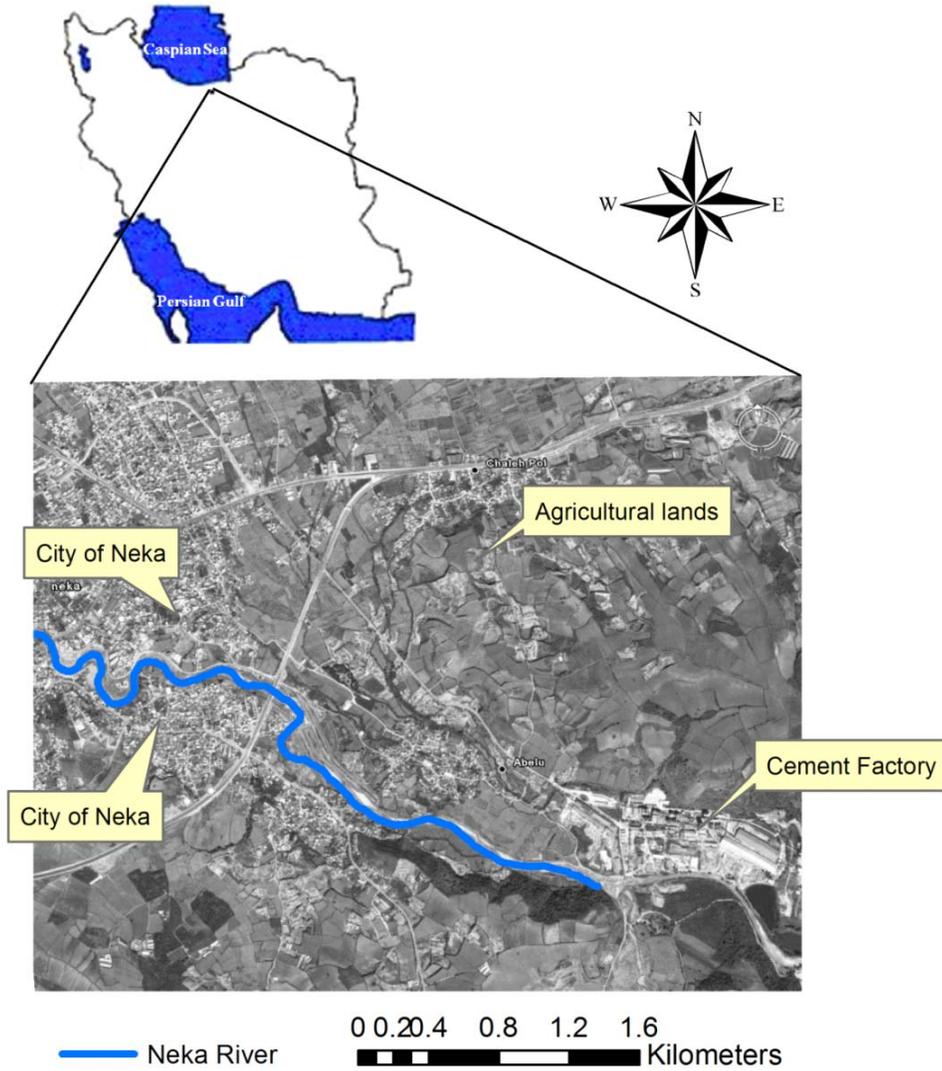


Fig. 1: Location of study area in selected reach of Neka River in Northern Iran

supercritical, and mixed flow regimes water surface profiles. The basic computational procedure is based on the solution of the one-dimensional energy equation, in which energy losses are evaluated by friction and contraction or expansion in river cross sections. Water surface profiles computation is based on solving the energy equation from one cross section to the next using an interactive procedure called the standard step method (HEC, 2010). The Energy equation is written as follows:

$$y_2 + z_2 + \frac{a_2 v_2^2}{2g} = y_1 + z_1 + \frac{a_1 v_1^2}{2g} + h_e \quad (1)$$

where  $y_1$  and  $y_2$  are depth of water at two adjacent cross sections, and are elevation of the main channel beds,

$v_1$  and  $v_2$  are average velocities (total discharge divided by total flow area),  $a_1$  and  $a_2$  are velocity weighting coefficients,  $g$  is gravitational acceleration and  $h_e$  is energy head loss between two cross sections. Cross sectional geometry of channel, river system schematic, ineffective flow areas, reach lengths, energy loss and Manning's coefficient and steady flow input are the basic data requirements for water surface simulations. Boundary conditions are specified to establish the starting water surface in a subcritical, critical and mixed flow regime. About 179 cross-sectional data was taken and integrated with the data derived from TIN for the modeling.

Hydrological data inclusive of cross sections and water level data is imported into the model. After

completing of all essential data inputs the model could be run. From these data, a model is created and later simulated for the process of calibration of the model. The HEC-geoRAS extension is used as an interface in conjunction with 3D analyst for interpolation of digital terrain data and Spatial Analyst for proper display of the output flow depth grids and flood extents in different return periods. It allows spatial-based visualization of flood extents and water depth, pre and post-processing of floodplain mapping to predict of flood hazard areas. However, it can be used to create an HEC-RAS import file containing geometric data from GIS layers and the results can be exported from HEC-RAS into GIS for further processes (HEC, 2009). A digital terrain model of the river system in the ArcInfo TIN format is used to create the import file. A series of line themes such as the stream centerline, flow path centerlines, main channel banks, cross section cut lines, and land use, ineffective flow areas, and storage areas are created to develop geometric data for HEC-RAS. Additionally, water surface profile data and velocity data are exported from HEC-RAS simulations to be processed by HEC-GeoRAS to use in further analysis using GIS capabilities.

**Model calibration:** The cross section information for model calibration including observed water level marks and dry and wet random points in the flood event of August 1999 along the Neka River, were collected in a field work during May and June 2009. The point information observed using GPS in the field along the Neka River reach. Interview with local people, witness and land owners has conducted during field survey in addition to observing marks of flood levels to make sure about observation points. Silt lines on the outcrop rocks, vegetation, litter debris and sand and silt deposits used as the stage indicators of the 1999 flood in the study reach. These points were later processed through ESRI ArcView to overlay directly on HEC-GeoRAS outputs as flood water depth and inundated flood extents, in order to use for calibration of the model. An important parameter used in calibration of HEC-RAS model is Manning's roughness coefficient  $n$ , which is used to reflect the resistance to flow from the river bed and floodplain at each cross-section. Manning's  $n$  roughness coefficient depends on channel material, surface irregularities, variation in shape and size of cross section, vegetation and flow condition, channel obstruction, and degree of meandering. All the procedures were started from the well-estimated values of the Manning's  $n$  based on filed works and well known literatures (Hicks and Mason, 1991) using photographic field guides and visual estimation method. Using this as a starting point the  $n$ -value is changed until an acceptable simulation is

achieved. The potentially distributed roughness coefficients are limited to one value for the channel and one for the floodplain (Horritt and Bates, 2002). These lumped criteria used to assess model performance in predicting flood extent areas.

The results of differences between observed and simulated water level can be either obtained from HEC-GeoRAS outputs using GIS spatial capabilities or extracted from maps to conduct a quantitative comparison. In order to reach an optimal calibrated coefficients, the model performance with different sets of Manning roughness coefficients chosen from a wide range, are compared to observed spatial inundation data. Simulations are grouped into runs, with each run applying to a slight change apply to coefficient. All cross sections were then parameterized with uniform Manning "n" values in main channels and floodplains. This geometry was then used as the initial uncalibrated model. Then, the calibration session involves a trial and error method where different sets of model options and parameters were used until an acceptable match between the observed and simulated flood water depth and flooded areas is achieved. For each HEC-RAS simulation, the average difference (D) between the observed and simulated flood water depths (m) is computed using Eq. (2).

$$D = \left[ \frac{\sum_{i=1}^n (d_{oi} - d_{si})^2}{n} \right]^{0.5} \quad (2)$$

where  $d_{oi}$  and  $d_{si}$  are observed and simulated flood water depth in point  $i$  and  $n$  is the number of point observations. This parameter shows the average vertical distance, over the study reach, and provides an intuitive measure of the accuracy. The significant differences between observed and simulated values are investigated using a paired sample t-test. A 0.05 level of significance was used for all comparison tests.

The second calibration criterion used in this research is inundated flood extent, which reflects the uncertainty in determining the actual boundary of flood hazard area. Model predictions of inundation flood extent are compared with the observed data using the random observation points in floodplain, approximately near the marginal parts of the flooded area. The percentage of correct overlap between predicted and observed inundated areas varies between 0 for no overlap between predicted and observed inundated areas and 100 for a model where these points coincide perfectly. This measure and similar criteria has been found to give good results in comparison between model performance and observed flood events (Horritt and Bates, 2002).

By performing many simulations, each using a different value of Manning’s n, the simulation with the minimum error could be identified and this Manning’s n is accepted as the calibrated value. Simulation would be the last process involving river hydraulic modelling for practical purposes.

**RESULTS AND DISCUSSION**

In this research, HEC-RAS model in combination with GIS capabilities was used to simulate steady flow along the selected reach of Neka River. The HEC-geoRAS extension is used in conjunction with spatial and 3D analyst for interpolation of digital terrain data proper display of flood water depth and inundated areas using GIS. Flood frequency analysis was conducted to select the most accurate input for the hydraulic simulation of the river reach. It has shown that Log-Pearson III, Log-Normal III and Log Normal are the best statistical distributions to estimate peak flow in different return periods with 9.78 and 12.03 and 30.83 mean relative deviation error, respectively. Log-Pearson III has used to estimate flood peak flow design for Neka River reach, regarding to the least differences between observed and estimated peak flow. Table 1 has shown magnitude of peak flow for 2 to 200-year return periods at Abelu hydrometric station. The peak flow of the flash flood that occurred in August 1999 in Neka River recorded more than 1300 m<sup>3</sup>/s, based on field observations and estimation (Ghanbarpour *et al.*, 2010). With respect to the Table 1, the return period of the observed flood in August 1999 is about 200-year. Therefore, this study is meant to reconstruct a 200-year flood event that took place in this river basin for calibration of the model.

The model calibration is conducted to find the values of Manning’s roughness, by comparing simulated and observed flood water depths and flood water extents at the randomly selected observation points. The criteria to choose the optimal coefficient is reaching to the least differences between simulation and observation points of flood water depth and flooded areas (Eq. 2). Twenty five points were observed in the main channel and floodplain for comparing the performance of the model to compute flood water depths. Additionally, twenty seven other points were observed to compare the performance of the model to delineate floodplain boundary.

Based on trial and error model runs, a Manning’s roughness coefficient of 0.037 and 0.055 produced the best fit ( $D = 0.54$ , Eq. 2) against the observed data for the river main channel and floodplain, respectively. The flood water depths simulated by the calibrated model were compared with the 25 observation points in Fig. 2. As can be seen in Fig. 2 the flood water depths from the optimal Manning’s n are in acceptable agreement with those

Table 1: Peak flow rates for 2 to 200-year return periods at Abelu hydrometric station

Return period (years)	Peak flow (M <sup>3</sup> /s)
2	83.4
5	180.8
10	274.9
20	426.3
25	481.6
50	691.5
100	972.5
200	1346.3

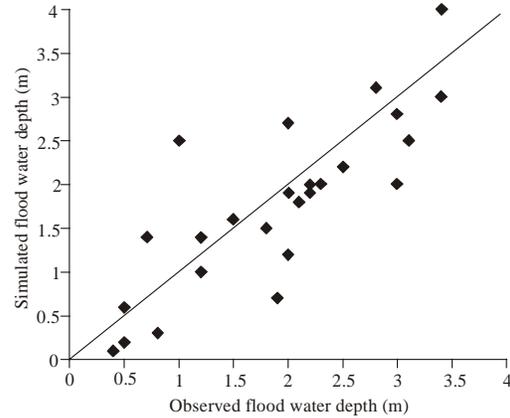


Fig. 2: Comparison of flood water depths between the result of calibrated model and observations for 1999 flood event in Neka River

simulated ones with a significant correlation coefficient ( $R = 0.82$ ,  $p < 0.0001$ ). Paired sample t-test analysis of observed and simulated flood water depths has shown that there is not a significant ( $p = 0.293$ ) difference between observed and simulated values. It can be concluded that the values of the Manning’s n in the river reaches are therefore acceptable, although not all surveyed points fall within an acceptable range of accuracy. This discrepancy is most likely due to a combination of two factors. First, the exact locations of the surveyed high water marks were difficult to determine. Second, the river configuration had changed somewhat through this flood event, causing difficulty in recreating the same local topographic and hydraulic conditions.

An agreement between the observed and simulated flood inundated extents, as the second criteria based on 52 observation points, is 88.5% for the mentioned optimal values of Manning roughness coefficients. Therefore, approximately 11.5% of points are incorrectly predicted as either dry when they should be wet or vice versa. The result using optimal Manning coefficient, n of main channel and floodplain show good correspondence between simulated and observed flood inundated extents and the acceptable delineated floodplain boundary. As a result, the overall comparison has shown an acceptable agreement between the model and the surveyed values, in two dimensions of flood depth and extent. The results

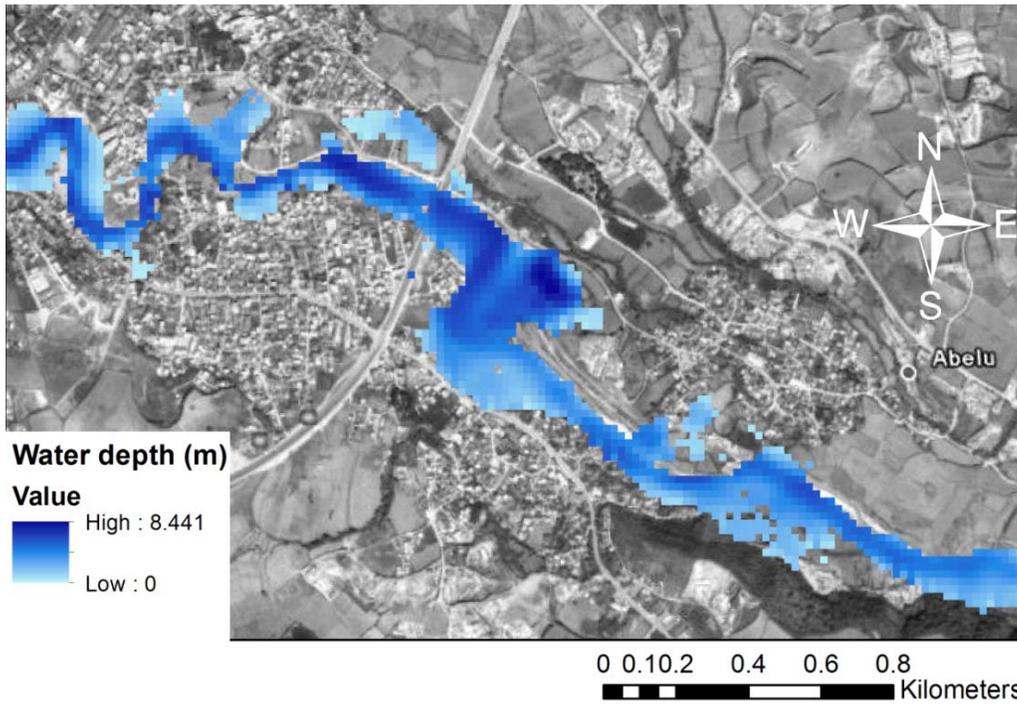


Fig. 3: Flood water depths and flooded areas simulated by HEC-RAS model for 100-year flood event in Neka River reach

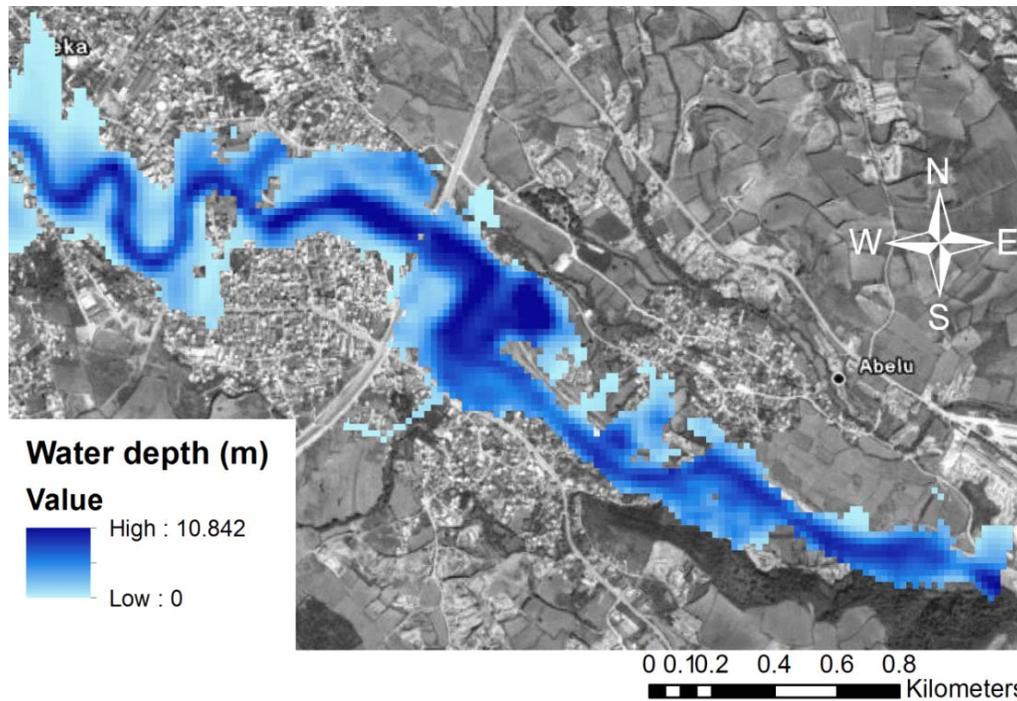


Fig. 4: Flood water depths and flooded areas simulated by HEC-RAS model for 200-year flood event in Neka River reach

indicate that for this reach the HEC-RAS model can be calibrated against water depth or inundated area data and give reasonable predictions of inundated flood extent. However, this research has been limited to model

calibration against a single 200-year flood event. Inundation extent data have also provided a second source of observed data in addition to flood depth, to increase the accuracy and reliability of model calibration. It provides

a possibility to calibrate a hydraulic model against one observed flood event. This is of practical importance, as the calibrated model could be used for further analysis such as flood insurance studies, flood mitigation and urban planning proposes based on 100-year flood risk.

Inundated flood extents and flood water depths simulated by HEC-RAS model after calibration have extracted for 100 and 200-year flood event. Figure 3 and 4 have shown subsequent maps of predicted 100 and 200-year flood inundation extents using calibrated model, respectively. Flood boundary is delineated in blue, with graduation of blue related to different flood depth in meter. Application of hydraulic modeling using GIS capabilities provides a platform to simulate flood water depth and inundated flood areas in different part of the floodplain (Correia *et al.*, 1999). One of the most important results of HEC-RAS simulation is preparing different water surface profiles of different T-year floods scenario, which can be used for further flood risk analysis. The 100-year flood extent (Fig. 3) could be used for identifying flood hazard areas and flood insurance studies as the base flood standard. Critical flooding area along the river could be distinguished based on the spatial layers of flood water depths and inundated flood areas (Fig. 3 and 4). As can be seen in Figure 4 flood affected areas for 200-year flood event is much larger than inundated 100-year flood extent (Fig. 3), as it has affected some residential area of Neka city. Flood water levels can be seen very variable, which is depends on geometry of the channel, topography and the hydraulics condition of the river system.

### CONCLUSION

A numerical hydraulic model is applied to the Neka River system, and a set of calibration based on an observed flood extent boundary and flood water depths is presented. Use of these two measures has allowed a rigorous assessment of simulation results in two dimensions of both flooded area and depth, as a means of increasing modeling accuracy. This research investigated the possibility of calibrating hydraulic model by using only one observed flood event with limited data observations and even with no available concurrent satellite-derived data sets. It is noticeable that many operational flood inundation predictions are made in situations when the observation data to calibrate and evaluate the model performance are limited (Beven, 2002; Pappenberger *et al.*, 2005).

This experience suggests that there will be some degree of uncertainty in reproducing both flood extent boundary and flood water depths (Aronica *et al.*, 1998; Pappenberger *et al.*, 2005; Horritt, 2006; Di Baldassarre *et al.*, 2009) especially when predictions tend to be used for flood mitigation purposes in residential

areas. The best calibrated model run produced a significant correlation between observed and simulated flood water depths. Moreover, the best inundation extent observations capture more than 88 percent of the true flooded area. However, the decision making process for this hydraulic model calibration is still involved a degree of subjectivity. It strongly suggests the need for more research into methods for calibration of a hydraulic model with very limited observation data, although the overall calibration results are encouraging and acceptable. This study focused on integrating of hydraulic simulation with GIS analysis. Results of this study can reasonably specify high flood risk from low flood risk areas in the floodplain to mitigate future flood damages.

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