Modeling the Propagation of DEM Uncertainty in Flood Inundation

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Abstract:

All GIS datasets suffer from inherent error and it is now generally recognized that error problems is significant in GIS analysis. In GIS integrated flood inundation modeling, where topographic conditions of the river network are obtained from a Digital Elevation Model (DEM), error inherent in the DEM will propagate through the analysis till its outputs. In this study, a methodology named as uncertainty propagation modeling (UPM) is presented for evaluation of DEM uncertainty while investigating its propagation in flood inundation modeling. Hydraulic computations are performed by integrating ArcView and HEC-RAS and Monte Carlo Simulations method is utilized for uncertainty propagation modeling. In UPM, a set of random realizations of the DEM are first created. Flood inundation modeling is then performed over each DEM to obtain a range of flood inundation modeling outputs. Finally uncertainty propagation is based on the analysis of all model performances.

1. Introduction

Floods are one of the most life threatening natural hazards on the earth. A significant rise in water level of a river would cause flooding of the surrounding areas. Accordingly, it is very important to estimate floods and to map areas under inundation by means of flood studies. The final stage of a flood study is known as flood inundation modeling (FIM) in which inundation area for a certain flood magnitude is determined.

In the last decade, with the advances in Geographic Information Systems (GIS), use of spatial data in flood studies is increased. But utilization of spatial data in flood analysis also brought the problems of error in spatial datasets. Error propagation, which is the spreading of error through GIS operations from input to outputs, is one such problem.

In GIS integrated flood inundation modeling, where topographic conditions of the study site are obtained from a Digital Elevation Model (DEM), error inherent in the DEM will propagate through the analysis till its outputs. In this study, a methodology is presented for evaluation of DEM uncertainty while investigating its propagation in flood inundation modeling. Hydraulic computations are performed by integrating ArcView and HEC-RAS and Monte Carlo Simulations method is utilized for uncertainty propagation modeling.

2. Study Site

Black sea region of Turkey is located along the Black Sea coastline, at the north of the Anatolia peninsula. The region is subject to flash flooding due to its high rainfall intensity and steep mountains. Therefore, urban areas of the region are under the risk of frequent flooding and in the previous years several devastating flood events are occurred.

In this study a small area within Ulus Basin, which is located in the west Black Sea region, is selected. Ulus basin covers the subbasins of Ulus and Ovacuma creeks which are the two upstream branches of Gökırmak River. An area of 120 km^2 (10 km and 12 km in x and y directions) within the Ulus Basin is selected around the intersection of these two creeks (Figure 1). The digital contour maps of the region are the source of elevation data used in this study. The contour maps have a scale of 1:25000 (10 m contour interval) and ± 5 m vertical accuracy. The DEM of the study site is created from these contour data and have a cell size of 10 m.

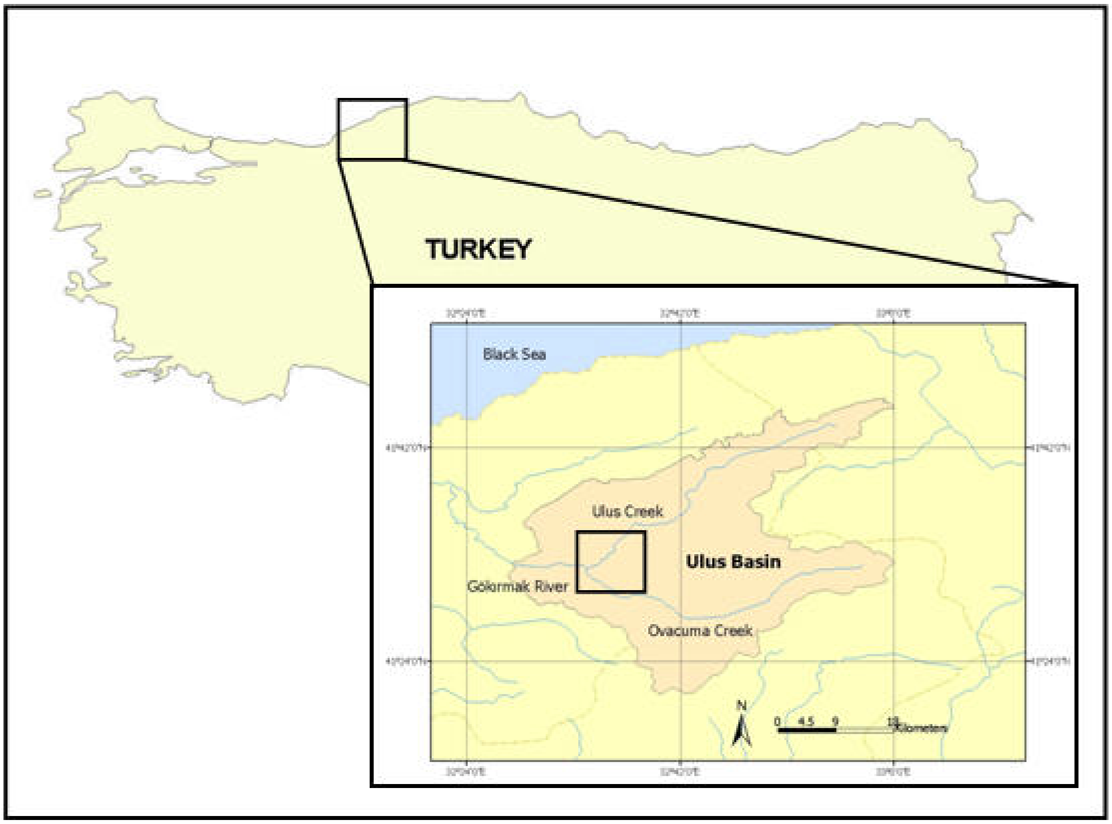


Figure 1. Location of the study site

3. Flood Inundation Modeling with HEC-RAS and ArcView

In the last decade, integration of GIS with flood studies increased the efficiency and visualization of basin and river modeling. Hydrologic Engineering Center River Analysis System (HEC-RAS) is a major hydraulic model which has a good GIS integration by means of an ArcView extension known as HEC-GeoRAS (HEC, 2000).

In hydraulic analysis with HEC-RAS, topographic conditions of the river network are represented by a number of cross sections. By integrating GIS with HEC-RAS, these cross sections are extracted from a Digital Terrain Model (DTM). In addition to this, area of inundation could be mapped by HEC-GeoRAS from HEC-RAS computation results.

The type of terrain model used for cross section extraction is Triangulated Irregular Network (TIN) which is derived from DEM of the region in this study. The digital contour map of the study area is the source of elevation data from which the DEM is determined. It is possible to obtain TIN directly from the contour map, but for studying the propagation of uncertainty DEM of the area is also created.

In this study, first the GIS integrated Flood Inundation Modeling of the study site is performed. Results of this analysis are stored and later compared with the results of the uncertainty analysis.

4. Problem of Error in Flood Inundation Modeling

Error is a quantitative value and defined as the difference between reality and our representation of the reality. In spatial datasets processing type errors are introduced by GIS operations and depend on the type of the operation. Since determining processing errors require information and the systems used to process it, they are the most difficult to be detected. On the other hand, errors in the source data are unavoidable but their effect on the analysis can be measured (Heuvelink, 1997).

The problem of error propagation is aroused by deriving new features from the available features capability of GIS. Since no map stored in a GIS is truly error-free when they are used as input to a GIS operation, then the errors in the input will propagate to the output of the operation.

The problem of error propagation is also encountered in GIS integrated FIM. The inaccuracies in the elevation data lead to errors in the terrain model. The error propagation continues through extraction of cross sections from this model and later utilizing them in hydraulic analysis. As a result boundary of inundation area obtained at the end is also erroneous.

Error in an analysis result can be measured only if the true value is known. But if the reality is unknown, then the error can be studied by means of uncertainty. In a GIS analysis uncertainty is the measure of the sensitivity of the analysis results to variations in some parameter involved in it.

In GIS integrated FIM, where a number of operations are performed sequentially, it is almost impossible to track the propagation of error through the study. For such complex GIS operations error propagation can be modeled by Monte Carlo method. This technique is based on performing the GIS operation a number of times, where each performance is referred as a simulation. In each simulation a random realization of the input is first created. Then for this input, output of the operation is computed and stored. Finally, uncertainty in the operation is based on the computed statistics of all stored outputs. Monte Carlo method can reach a high level of accuracy which can be achieved only when the number of simulations is sufficiently large.

5. Methodology

In modeling the propagation of DEM uncertainty in FIM, a number of Monte Carlo simulations are performed. In each simulation first a random realization of the DEM is created by adding a randomly generated error field in the form of a matrix of the same size of the DEM. Error field values are randomly generated according to normal probability distribution. According to Burrough and McDonnell (1998), it is the simplest way in uncertainty propagation to treat each input as having a normally distributed error with known mean and variance.

Parameters of the normal distribution are selected according to the accuracy of the source data. The DEM of the study site is created from a digital contour data having a vertical accuracy of ± 5 m. This accuracy value indicates that elevation values could depart from their true values on a range from - 5 m to + 5 m. In modeling the propagation of this error, random error fields are generated to have values within this range. Consequently, normal distribution with zero mean and 1 as standard deviation is used to generate error fields having cell values within the desired range.

Then, this error introduced DEM is converted to TIN, from which cross section data is extracted. For better investigation of random error intrusion on hydraulic computations, a total of 376 cross sections are taken over the three reaches modeled (Figure 2). After exporting topographic data to HEC-RAS, hydraulic analysis of the study site is performed for 100 year flood event. Rest of the operations is identical to the ones performed in GIS integrated FIM. In uncertainty propagation modeling of the study site 150 Monte Carlo simulations are performed and at the end of each simulation a GIS layer representing area of inundation is determined.

Since analysis of simulation results is performed on a cell by cell basis, the vector layers of inundation area are converted to raster type and referred as flood grids. The flood grids have cell values of 1 for flooding and 0 for no flooding conditions. Then all flood grids are summed to obtain a total flood grid. The total flood grid has integer cell values from 0 to N. These values represent the number of flooding calculated in each cell among N simulations. From total flood grid, another grid named as probability grid is calculated by multiplying all cell values with 100/N. This grid represents the probability of inundation of each grid cell at least once in the return period of the flood event.

After calculating the probability of flooding of each cell within the study area, cells having probability values within a certain range are grouped and called as flood zones. For this purpose, on a range from 0 to 100 %, 20 flood zones having an equal interval length of 5 % are selected. This selection is not based on any prior knowledge and made by the authors own judgment. Area of each zone and their sum giving the total area of inundation are calculated. Then percent of each zone area within the total area of inundation is also calculated. Analysis of simulation results is based on these 21 values.

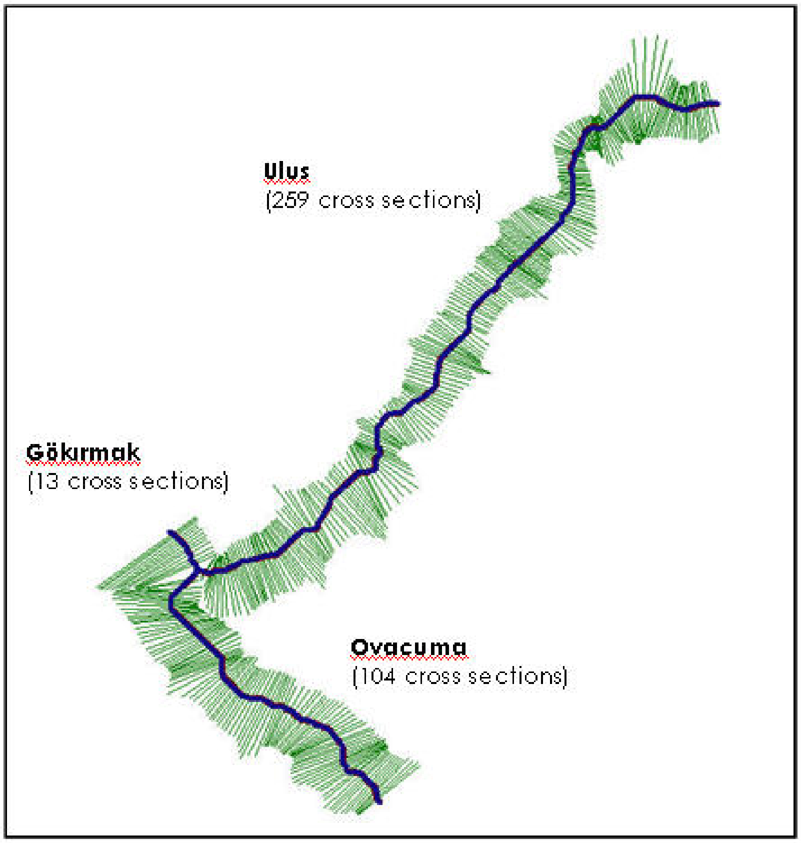
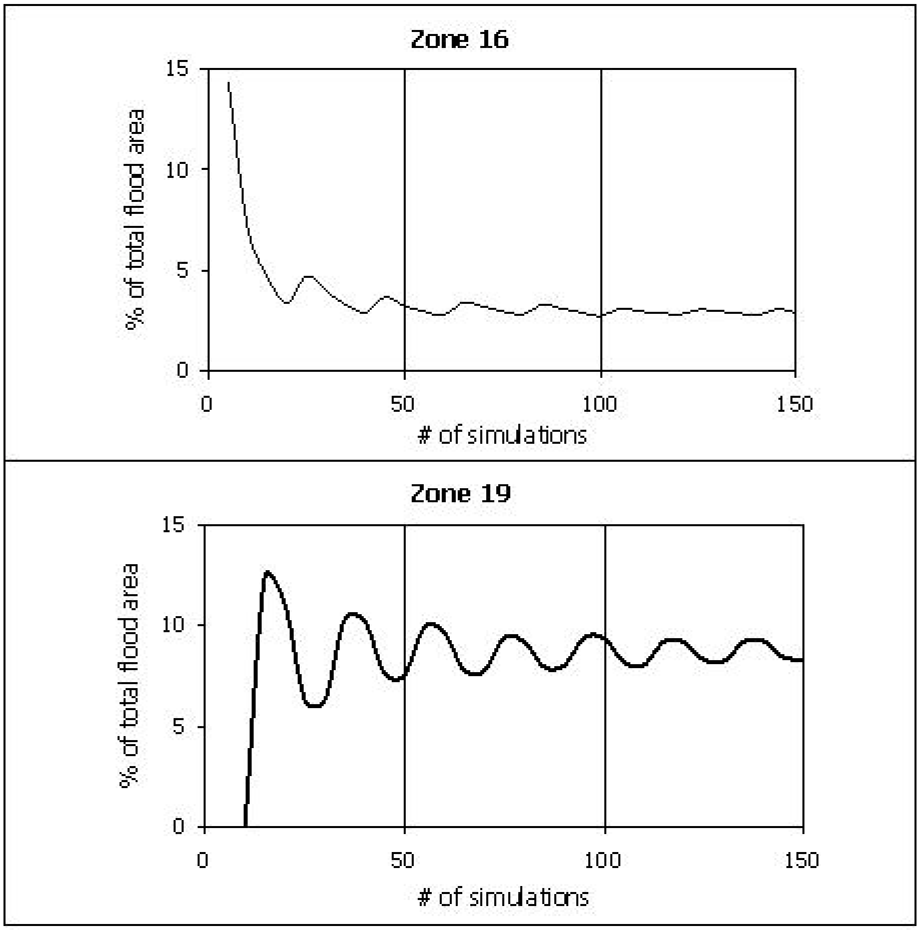


Figure 2. Cross sections taken along the river network

In analysis of all simulation results an approach, which is based on calculation of a number of total flood and probability grids, is used (Yilmaz, 2003). In this approach, starting from the first simulation, total flood grids are calculated by adding five simulations at a time. This process continues and probability grids are calculated for N = 5, 10, 15, 20... number of simulations, which are then divided into 20 flood zones.

6. Discussion of Results

Due to randomness involved in Monte Carlo method, total number of simulations is ambiguous and depends on the accuracy requirements. In this study 150 simulations are performed and variation of each flood zone area with the increasing number of simulations is plotted. In all graphs a similar fluctuating pattern is observed. As an example, plots of 16th and 19th zones (representing 75-80 % and 90-95 % of inundation probability) are presented in Figure 3.


Zone 16

Zone 19

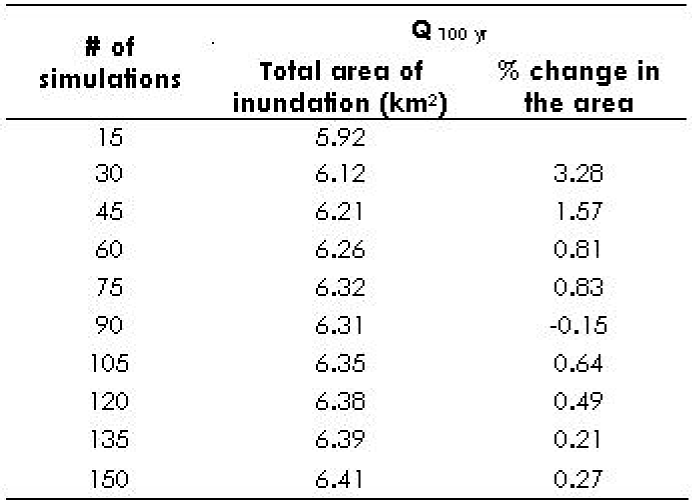
Figure 3. Variation of 16th and 19th zone areas

For the initial 20 simulations, zero probability of inundation values are observed in some of the zones. But for the probability grids evaluated from 20 or more simulations, none of the zones have zero values. As a result, it is concluded that at least 20 simulations should be performed for this type of study.

For the first 50 simulations, the percentage of each flood zone area within the total area of inundation show high fluctuations. But a rapid decrease in the oscillation peaks is observed as the number of simulations is increased to 100. Similarly, with the addition of 50 more simulation results, plots of 20 flood zone areas show a more decreasing fluctuating pattern.

In the analysis of simulation results, variation of the total area of inundation with the increasing number of simulations is also investigated. Percent change in the total area of inundation values are given in Table 1, from which a decrease in the values is observed as the number of simulations is increased. After considering the variations in these values, results of 150 simulations are found to be satisfactory. The probability grid calculated from the results of 150 simulations is named as final flood grid and represent the probability of inundation of the study area for the 100 year flood event.

Table 1. Percent change in total area of inundation with the increasing number of simulations



# of simulations	$Q_{100\ yr}$	
	Total area of inundation (km^2)	% change in the area
15	5.92	
30	6.12	3.28
45	6.21	1.57
60	6.26	0.81
75	6.32	0.83
90	6.31	-0.15
105	6.35	0.64
120	6.38	0.49
135	6.39	0.21
150	6.41	0.27

At the end of the study, the computed final flood grid is compared with the result of GIS integrated FIM of the same study area. First, total inundation areas, determined by two techniques are compared. For 100 year flood event, the final flood grid gives an area of 6.41 km^2 but FIM covers an area of 4.41 km^2. This result indicate a significant difference (31 %) in the flooded areas by two methods.

Then area of inundation determined from FIM is overlaid with the final flood grid and two grids; one including the cells within the boundary of FIM results and other including the cells outside the boundary, are obtained. Similar to final flood grids, these two grids are divided into 20 flood zones and percent of each zone with respect to the total area of inundation (determined from final flood grid) are calculated (Figure 4). It is observed from the overlay analysis that, even if a much smaller total area of inundation is determined in FIM, the cells within the boundary have high probability and the outside cells have low probability of inundation.

In Figure 5, both the final flood grid and area of inundation from FIM are shown at the intersection of the Ulus and Ovacuma creeks. It is observed from the figure that, area covered by FIM has high probability of inundation according to uncertainty analysis results. On the contrary, FIM failed to cover some critical areas having high inundation probabilities.

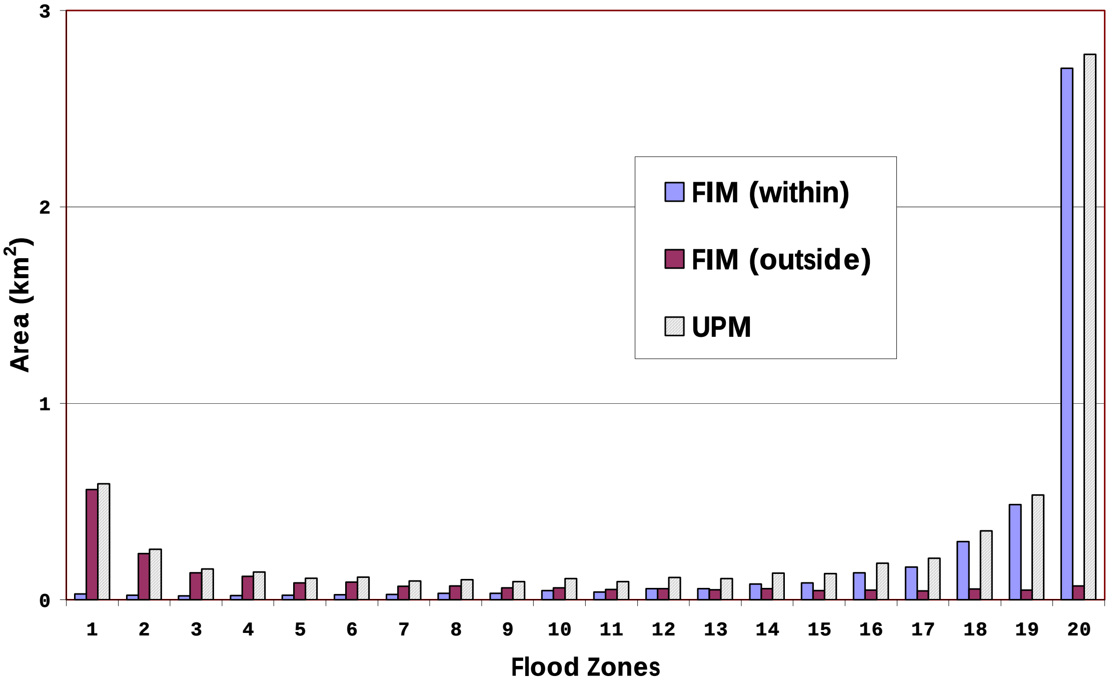


Figure 4. Overlay analysis for 100 year flood event

7. Conclusions

Certainly no map stored in a GIS is truly error free, and problems of error must be considered in great detail. One such problem is the propagation of error through GIS analysis. In GIS integrated flood inundation modeling, where a number of operations are performed sequentially, it is almost impossible to track the propagation of error through the analysis. In such complex analysis, error propagation is investigated by utilizing uncertainty modeling techniques. One of the uncertainty modeling techniques, Monte Carlo method, is used in this study.

A small study area of 120 km^2 in size and rectangular in shape is selected at the junction of Ulus and Ovacuma creeks in the West Black Sea region of Turkey. After performing uncertainty analysis and a single flood inundation modeling in the study site, results of these two methods are compared.

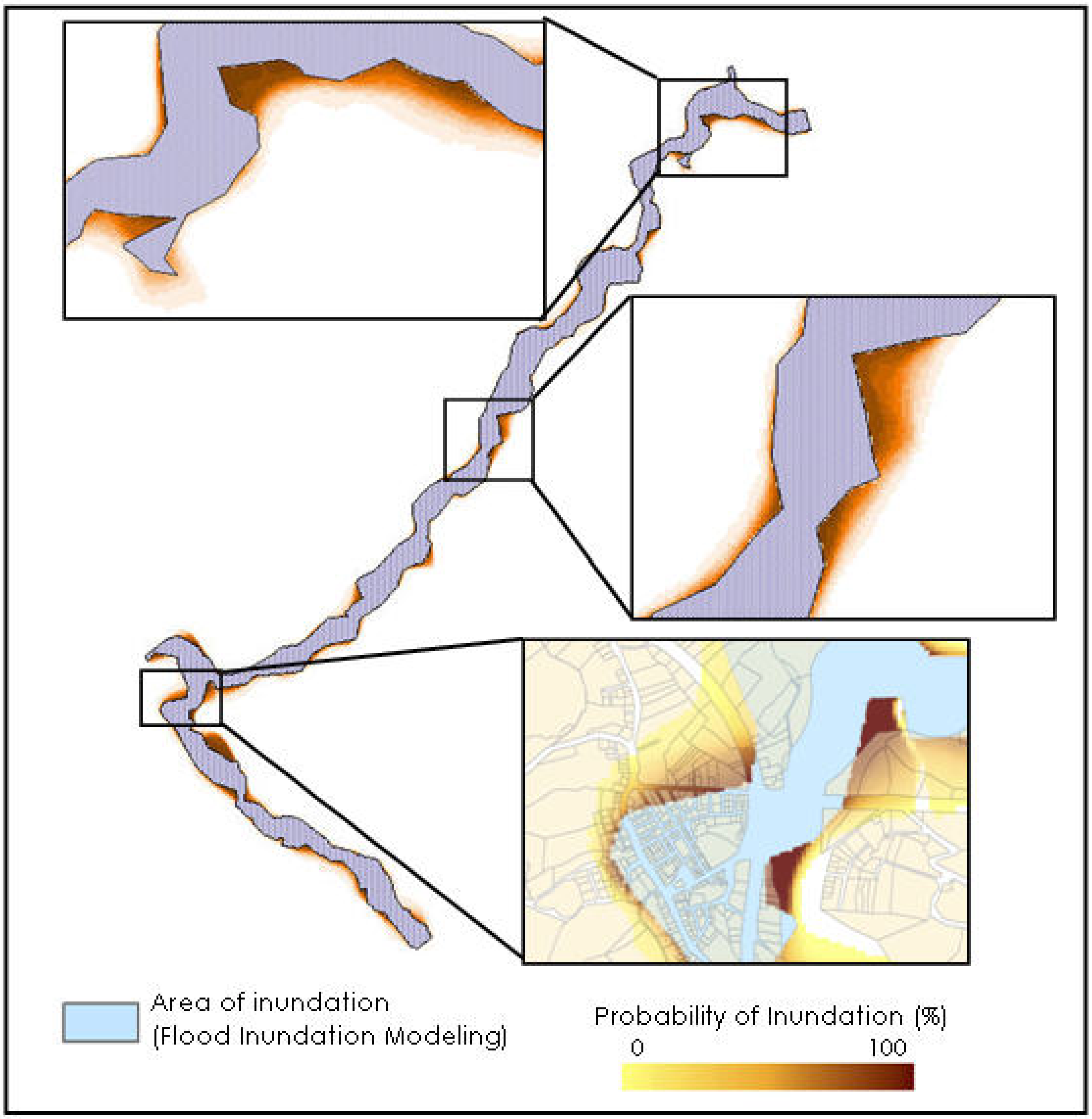


Figure 5. Comparison of uncertainty analysis and FIM results

The major difference between the results of FIM and uncertainty analysis is the amount of area found to be inundated in the two methods. It is seen that a significant part of the area having a nonzero probability of inundation, is found to be not flooded in FIM. Another important outcome of the study is that even if a much smaller total area of inundation is calculated in FIM, this area is calculated to have high probability of inundation.

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