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RESEARCH ARTICLE

Flood forecasting and analysis within the Ulus Basin, Turkey, using geographic information systems

Nurünnisa Usul · Burak Turan

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Abstract Floods have been the most severe natural disasters in the West Black Sea Region of Turkey for many years; therefore Ulus Basin is selected as a study area for a thorough hydrologic flood analysis. The lack of embankments around the Ulus River and careless changes to the riverbed made by villagers, resulted in major flood events in the basin, causing significant damage in the area. In this study, the hydrodynamic characteristics of the basin and the riverbed are determined by calibrating the hydraulic module of the MIKE 11 modeling system with the observed 1991 flood. Then, for the 25-, 50- and 100-year floods the highest water levels in the river are forecasted by integration of the MIKE 11 hydrologic and hydraulic modules. Afterwards, inundation maps are obtained by using together the hydraulic and GIS modules of the MIKE 11 system.

Keywords Flood analysis · GIS · MIKE 11 · Inundation maps · Ulus Basin

Introduction

River floods result from a lack of streambed capacity to carry large volumes of runoff caused by heavy rainfall or snowmelt. Floods cause significant disasters in many parts of the world, resulting in loss of life, damage to property and infrastructure. Turkey, in particular, is badly affected by floods (Bozkurt and Kulga 1993), with related losses that are as devastating as those associated with earthquakes.

The types and degree of remedial measures that may be taken against flooding depend on various topographical, hydrological and geomorphological factors, in addition to the size and

N. Usul (✉)
Civil Engineering Department, METU, Ankara 06531, Turkey
e-mail: nurusul@metu.edu.tr

B. Turan
DSI, Ankara 06100, Turkey
e-mail: bturan@metu.edu.tr

socio-economic status of the area. In November 1999, 35 researchers from nine countries met in Ravello, Italy at a NATO sponsored Advanced Study Institute (Coping with Flash Floods) to discuss flood losses and prevention, and to develop a research agenda that incorporates the various components required to cope with floods. The key recommendations from the study were: (1) to place greater emphasis on increasing understanding of the social processes involved in flash-flood warnings, particularly in the response phases, and (2) the need to reduce vulnerability in sustainable ways compatible with long-term economic and social goals. The relationship between hydrometeorology and social science is seen as critical to advancing abilities to cope with flash floods (Montz and Gruntfest 2002).

In Turkey, there are considerable climatic, topographic and geologic variations among basins. Most Turkish basins show great variation in precipitation regime and most Turkish rivers have large fluctuations in flow rates throughout the year and with respect to geographical regions. As a result of these changes in flow and precipitation regimes, floods may occur randomly in any basin. Rapid urbanization and improper use of watersheds result in serious flooding problems (Yanmaz and Usul 1999). The precipitation regime of Turkey ranges from 63.3 mm (1933) in Himmetdede in Central Anatolia to 4043.3 mm (1931) in Rize, located on the Eastern Black Sea Coast. Mean annual rainfall in Turkey is around 643 mm and distribution in the geographic regions are as follows: 750.7 mm in the Mediterranean, 611.2 mm in Eastern Anatolia, 388.8 mm in Central Anatolia, 816.5 mm in the Black Sea, 640.6 mm in the Marmara, 672.2 mm in the Aegean and 609.8 mm in South Eastern Anatolia. As can be seen from these values, the Black Sea region receives the highest precipitation. It is also affected by high rainfall intensity and high runoff coefficients due to steep, hilly topography. This is why flash floods are observed frequently in this region. In addition, most of the settlements are located along the rivers partly on the flood plains because of a lack of suitable construction sites. Obviously, these parameters combined make the region highly suitable for flood studies.

While analyzing flood events, classical methods are still being used by government and private organizations. In the current study, the integration of hydrologic-hydraulic models with geographic information systems (GIS) not only makes the study more extensive, but also gives the opportunity to make more trials in the analysis. Moreover, the results can be presented more visually, which is especially useful for non-technical people, the public and, more importantly, decision-makers.

Coppock (1995) notes that there are grounds for believing that GIS has an important function to play because natural hazards are multi-dimensional phenomena, which have a spatial component. Examples include cartographic approaches for mapping the physical hazard, integrative hazard modeling and spatial decision support systems (de Silva et al. 1993), and disaster response planning (Zografos et al. 1994).

Zerger (2002) examines existing approaches to assessing model decision utility with a particular emphasis on GIS and spatial modeling. Decision utility is an emerging theme in GIS literature that focuses on cognitive issues of GIS and human interactions. The research presents a technique for flood risk modeling using GIS and digital elevation models to map relative risk in urban communities.

Runoff models are not well suited to the process of environmental planning: substantial hydrological expertise is required to run them. It takes many hours to run a single test, and visual display of the planning scheme for the catchment is rudimentary. Mathematical models are good for producing information to design flood works, but they are not so good at answering the 'what if' questions of the planner. GIS has the potential to overcome all these problems (Coroza et al. 1997).

GIS allows us to determine basin characteristics and to change the conditions of river components easily for any size of basin. Furthermore, GIS tools make it very easy to extract any number of cross-sections from the digital elevation model (DEM) of the basin for a hydraulic study. GIS also gives, to the end-user, a bigger and more complete picture of what is likely to happen in a watershed during and after a flood. For example, it can provide the picture of recent or historical flood map boundaries as a result of routing a certain size flood on the site.

The basin selected for the pilot study, Ulus Basin, is the drainage area of the Ulus Runoff Gauging Station (No: 13–14), which is operated by State Hydraulic Works (DSI) of Turkey. This basin, which is a sub-basin of Bartin Basin, is located in the West Black Sea Region of Turkey (Fig. 1). The West Black Sea region has steep mountains, which continue parallel to the coast, and as mentioned before, receives relatively high rainfall compared to the mean rainfall of Turkey. As the area has steep sloped mountains, the agricultural lands are small and scattered, and take the form of vegetable gardens close to the riverbanks, as shown in Fig. 2. Most of the people living in Bartin City, a major city in the basin, earn their living from agriculture and have similar yards in front of their houses. These agricultural areas have narrowed the riverbed and the flood plains. The surroundings of the riverbeds are afforested carelessly by the villagers, as shown in Fig. 3. As a result, the resistance of the bed has increased and the water-carrying capacity has decreased, causing water levels to reach even higher depths during flood events. Moreover, some parts of the forests on the mountains are cut to be used for different purposes. So, when rainfall occurs it immediately creates overland flow, and in addition, this overland flow brings large amounts of sediment to the riverbed. The statistics in the study of Gruntfest and Handmer (2001) suggest that losses caused by flash floods are not diminishing. Indeed, many believe that losses due to flash floods will rise in the future, in part because of climate change, but mostly because of increases in human activities in flash flood-prone areas.

The Black Sea climate is dominant in the basin with cold and wet winters and warm and wet summers. When moving from north to south, terrestrial climate is observed. In the north, due to the effect of the Black Sea climate with heavy rainfall, variable plant cover is observed. In the inner regions, generally frontal-type rainfalls are observed, except in spring when convective-type rainfalls are common. The mean annual rainfall observed at Ulus meteorological station is 984.5 mm (DSI 1998). Three major flood events occurred on the basin in 1991, 1995 and 1998. The peak discharges of these floods are 596, 372 and 587 m^3/s, respectively. Among these flood events, the 1991 flood is selected to be used in this study as it has the highest discharge and rainfall intensity. The peak discharges for the 25-, 50- and 100-year floods are obtained as 650, 770 and 890 m^3/s, respectively (Usul et al. 2002).

There are no adequate runoff gauging stations and no flood maps that show the extent of potential flooding in high-risk areas in the basin. In Turkey, the maps created for the purpose of establishing flood insurance rates are generally developed for the 100-year return period. Therefore, 100-year flood maps are derived in this study also.

After a search among widely used hydrologic and hydraulic models, the MIKE 11 program of Danish Hydraulic Institute (DHI 2000a), which gives the hydrologic and hydraulic models as the modules of a package, is chosen and used to model the floods and compute their depths in this study. In a previous study (Usul et al. 2002), the hydrological module of the same package was used to determine the flood hydrographs. These flood hydrographs are used in this study.

Fig. 1 The location of Ulus Basin in Turkey and in Bartin Basin, and the position of the runoff gage station

Hydraulic model

The chosen model, the MIKE 11 Hydrodynamic (HD) module, performed hydraulic analysis for the floods, using an implicit, finite difference scheme for the computation of unsteady flows in rivers and estuaries (DHI 2000a).

The MIKE 11 HD module was also used in a flood-protection study for Prague, Czech Republic (Zeman 1997). All the topographic information was extracted from the 1/5,000

Fig. 2 Vegetable gardens around river in the Ulus Basin

Fig. 3 Afforested river beds

scaled map sheets. The modeled peak discharge was 3,975 m^3/s, as observed in 1890. Model calibration was achieved by using the areas of previous floods. Since there were settlements in the investigated area of Prague, the resolution of the topographic maps is chosen to be large enough to show streets and parks.

The flood routing over the Senio River in northern Italy was made by using the same module (Menozzi 1997). Since there was no runoff gauging station in the study region, the module was calibrated at the downstream of the river where there was a stage level measuring station with updated data. In the hydrometeorologic system, there were three rainfall observation and four runoff gauging stations at downstream parts of the river. The module is calibrated by comparing observed hydrographs at the outlet point of the river basin and the simulated hydrographs. The calibration study was done by using three major observed floods in Italy. After the calibration period, river flows were simulated for the 25- and 100-year floods.

Baga (1999) made the calibration of the MIKE 11 HD module for the Çayboğazı Basin in southwestern Turkey and extracted water surface profiles and inundation areas for various floods. Since no cross-section was extracted at the site, only the cross-sections obtained from the DEM, determined from 1/1,000 scale map sheets for the immediate areas around the river, were used in the study. Doğanoğlu (2000) determined the flooded areas in the same river basin by integrating the HEC-RAS program (HEC 2001) and GIS techniques. The geometric data necessary for HEC-RAS were prepared by the program AVRAS (HEC 2000).

Real-time observations, combined with hydrometeorological models, allow for increasingly accurate and timely forecasts and warnings. Meteorological features, such as precipitation intensity, distribution and amounts, as well as hydrologic responses to these variables, are being incorporated into models aimed at improving understanding of rainfall–runoff relationships, upon which forecasts and warnings are based (Rochette and Moore 1996; Schwein 1996).

The studies mentioned above integrate GIS with either the hydrologic or hydraulic models. Unlike these studies, the present study integrates both the hydrologic and hydraulic models and GIS. After determining the 25-, 50-, and 100-year flood hydrographs (Usul et al. 2002) by using the hydrologic (NAM) module of the MIKE 11 software, its hydraulic module, MIKE 11 HD, is used to route these hydrographs and the 1991 flood hydrograph. Flood water depths are determined for these four flood cases. Then, the MIKE 11 GIS module (DHI 2000b) is run with the results of the hydraulic module to obtain inundation maps and to prepare presentations. In addition, GIS can be used for further analyses that visualize the extent of flooding through flood damage estimation maps or flood risk maps (Hausmann and Weber 1988; Clark 1998).

As seen in Fig. 1, there are three main river branches (Ulus, Ovacuma and Gokirmak) in the Ulus Basin. In this study, by using the results of hydrologic module (Usul et al. 2002), the flow of the three sub-basins are linked in the river network. The first has 145 km^2 of area and connects the upstream chainage of ‘Ulus 0 m’ and the downstream chainage of ‘Ulus 12,067 m’. The second has 18 km^2 area and connects the upstream chainage of ‘Ovacuma 0 m’ and the downstream chainage of ‘Ovacuma 5004.22 m’. The last has 143 km^2 area and connects the upstream chainage of ‘Gokirmak 0 m’ and the downstream chainage of ‘Gokirmak 1089.67 m’. The river network of the Ulus Basin, with flows coming from sub-basins, is shown in Fig. 4.

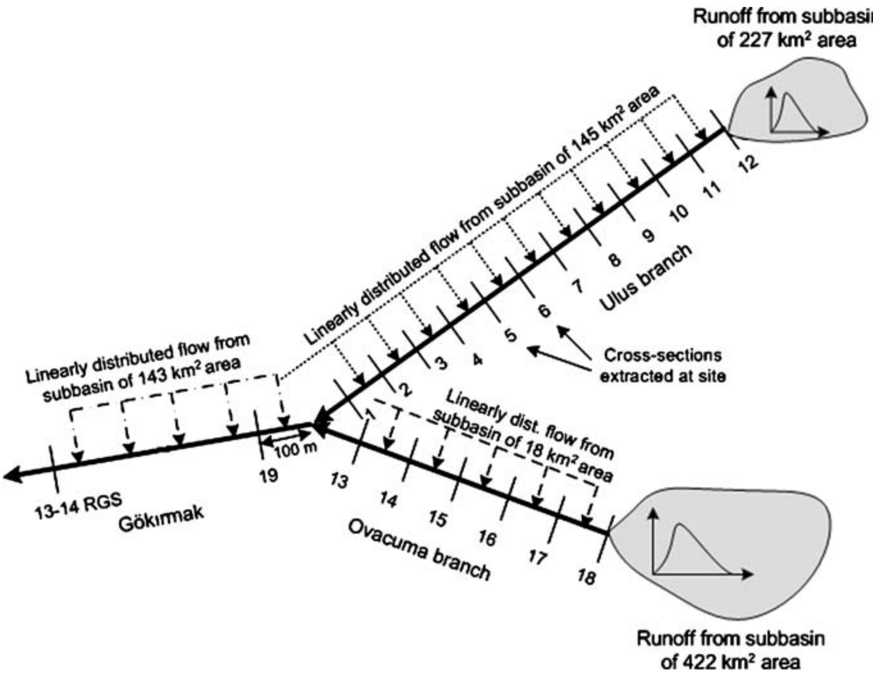

Fig. 4 Sub-basin and river network plan of Ulus Basin

Knowing the cross-section and profile of the actual riverbed and the valley is very important for hydraulic models; therefore, 20 cross-sections are derived at the site by DSI personnel. Twelve of these are taken on Ulus Branch (Nos. 1–12), six of them on Ovacuma Branch (Nos. 13–18) and two of them on Gokirmak River (No. 19 and the gauging station cross section). Two examples for cross-sections extracted at the site and the regular riverbed are shown in Fig. 5. In these cross-sections, it is seen that the flood plain area is very flat and large, which indicates that settlements and infrastructure near to the riverbed are high-risk areas.

Hydraulic module calibrations

A hydraulic module needs to be calibrated by comparing the results of the model with the observed data. In this study, calibration is achieved by using the discharge and water levels observed at the DSI Ulus runoff gauging station. The rating curve used for this purpose spans the period of 21.7.1991–30.9.1992, as determined after the severe 1991 flood and obtained from DSI for the cross-section, 13–14 (RGS). The hydrographs are those simulated by using the hydrologic module of the MIKE 11 program (Turan 2002).

Model setup

To run the MIKE 11 HD module, downstream and upstream boundary conditions and inflows along the river path must be defined. A rating curve is used as a downstream boundary condition for the river network in the hydraulic module. Hydrographs of the 1991 flood, obtained from the hydrologic model (Usul et al. 2002) for upstream sub-basins of Ulus and Ovacuma branches, are used as upstream boundary conditions. The hydrologic module results for the flows coming from the sub-basins—with areas of 145, 18 and 143 km^2 along the branches—are taken directly as an input file to the MIKE 11 HD module. The flows in

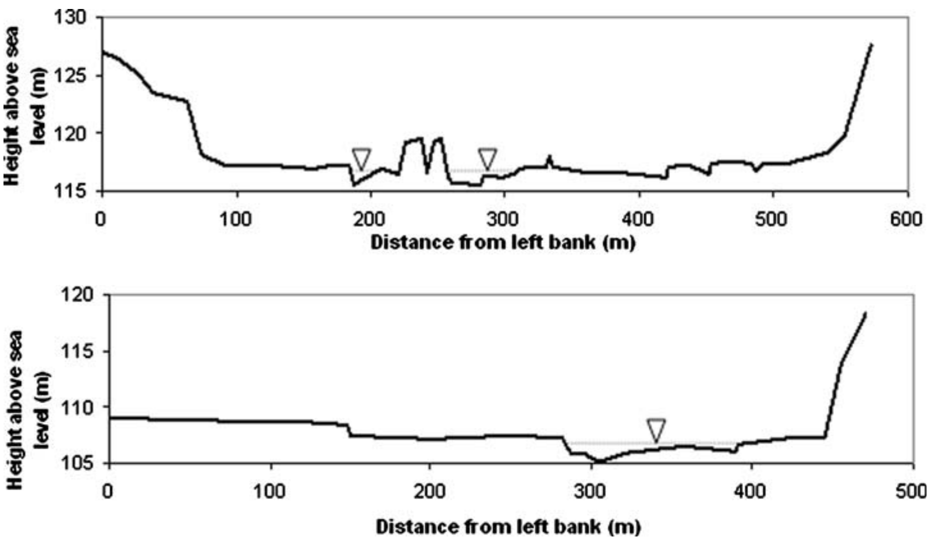

Fig. 5 Some of the cross-sections used in the model studies

these areas are accepted as uniform, as shown in Fig. 4. The same procedure is followed to determine the boundary conditions and input files for the 25-, 50- and 100-year floods.

The Manning roughness coefficient is used for the calibration of the module by matching the observed rating curve with the one obtained from the module. In the HD module, it is possible to use different Manning coefficients at different points. Moreover, using the linear interpolation between two points, the Manning coefficient for any location between these two points can be computed. Additionally, in the HD module the user can give resistance values for flood plains relative to the values given for riverbed. Since actual values of the coefficient were not known for the study area to start with, the Manning coefficients are taken as 0.033 for the riverbed and 0.06 for the flood plains. Then, in a trial-and-error process, the coefficients are changed in the range 0.020–0.075 for the riverbed and 0.040–0.14 for the flood plains by referring to the well-known Manning coefficient tables. The process continues until an acceptable match is obtained for the rating curve.

In a river network, the time to peak of the hydrograph is generally larger downstream than upstream. Similarly, the peak is higher downstream since there are other inflows on the way. In contrast, the results found in this study using the given Manning coefficients were different than the expected situation. To overcome this problem, the Manning coefficients were modified using several tables of Manning coefficients for different land-use types (Fleckkenstein 1998). Table 1 shows the value ranges for Manning coefficients tested in the HD module to compute the time to peak and peak discharges similar to observed ones. Table 2 shows the Manning coefficient values selected for the river network and flood plains at the end of the trials. After using these coefficient values, the hydrograph peak at the upstream end point of the Ulus River is observed to have a 1-h delay through a 14 km distance at the downstream end.

Finally, the observed rating curve of the runoff gauging station and the simulated one are compared for the 1991 flood and are found satisfactory. These results are given in Fig. 6. The highest water depths at the cross-sections obtained from the 1991 flood simulation run are given in Table 3, including the chainage information on three branches.

The water surface profiles of the Ovacuma–Gokirmak Branches for a 100-year flood are given in Fig. 7 in the format of the MIKE 11 HD module output. The date and time of the flood are indicated above the figure. The velocity values of the same flood along the Ulus–Gokirmak branches are obtained from the hydraulic module and are again shown in Fig. 8 as software output.

Table 1 Manning coefficient value ranges tested in HD module

Branches	River bed	Floodplains
Ulus	0.020–0.070	0.036–0.13
Ovacuma	0.020–0.075	0.036–0.14
Gokirmak	0.020–0.060	0.036–0.11

Table 2 Selected Manning coefficient values for the river network and the flood plains

Branches	Chainage (m)	River bed	Floodplains
Ulus	0	0.045	0.082
	12,968	0.040	0.072
Ovacuma	0	0.050	0.091
	4,900	0.040	0.072
Gokirmak	0	0.040	0.072
	1089.67	0.050	0.091

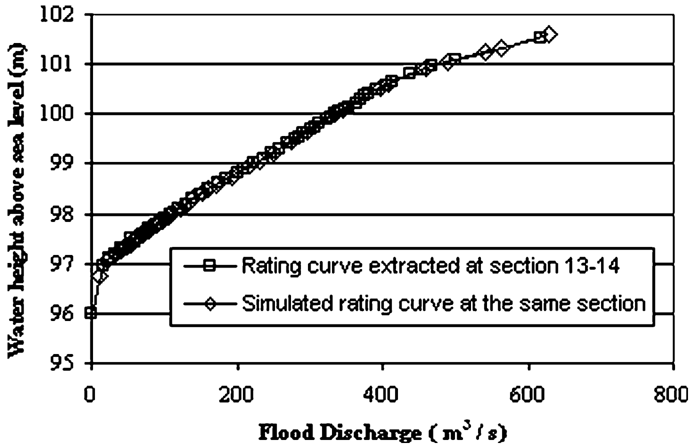

Fig. 6 Actual and simulated rating curves at the runoff gauging station

Table 3 Water depths determined for 1991 flood simulation

Rivers	Section	Chainage from upstream (m)	1991 Flood water depths at center axis (m)
Ulus	12	0	2.10
	11	1127.75	2.25
	10	2304.26	3.35
	9	3537.39	2.66
	8	4468.50	2.90
	7	5465.50	2.56
	6	6496.27	2.66
	5	8339.07	1.82
	4	9102.44	2.83
	3	9653.63	2.81
	2	10883.89	3.50
	1	11544.33	2.82
	21	12067.91	3.00
Ovacuma	18	0	2.68
	17	1132.32	3.00
	16	2310.77	4.17
	15	2902.92	2.10
	14	3622.86	2.10
	13	4284.21	2.20
	22	5004.22	2.72
Gokirmak	23	0	3.54
	19	103.75	3.20

Obtaining flood maps

The HD module is run using the cross-sections extracted at the site and for four different flood conditions as observed in 1991, and forecasted for 25-, 50- and 100-year floods. By this process, the water surface elevations in the riverbed and in the flood plains are computed. Afterwards, a GIS-based module, MIKE 11 GIS (DHI 2000b), which is a part of

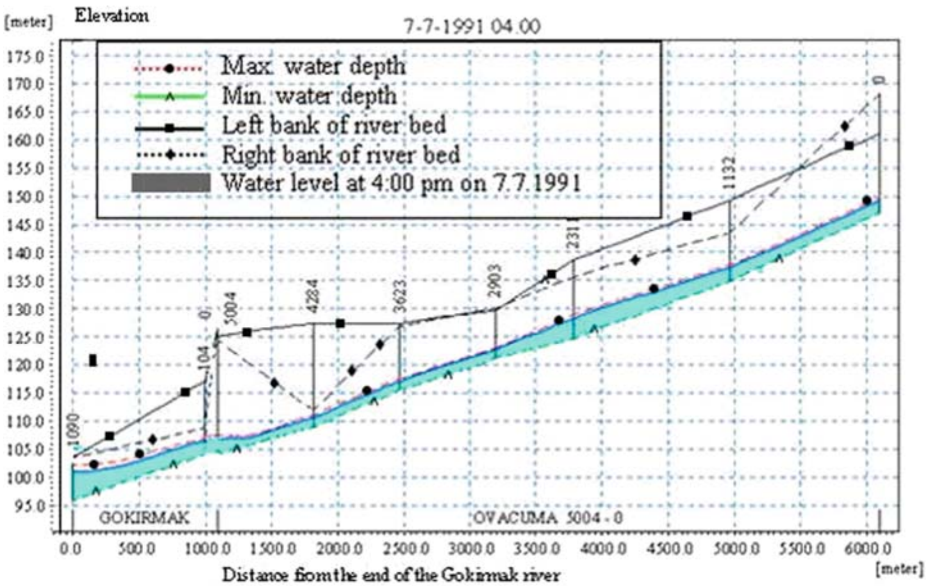

Fig. 7 Water surface profiles determined by the 100-year flood simulation

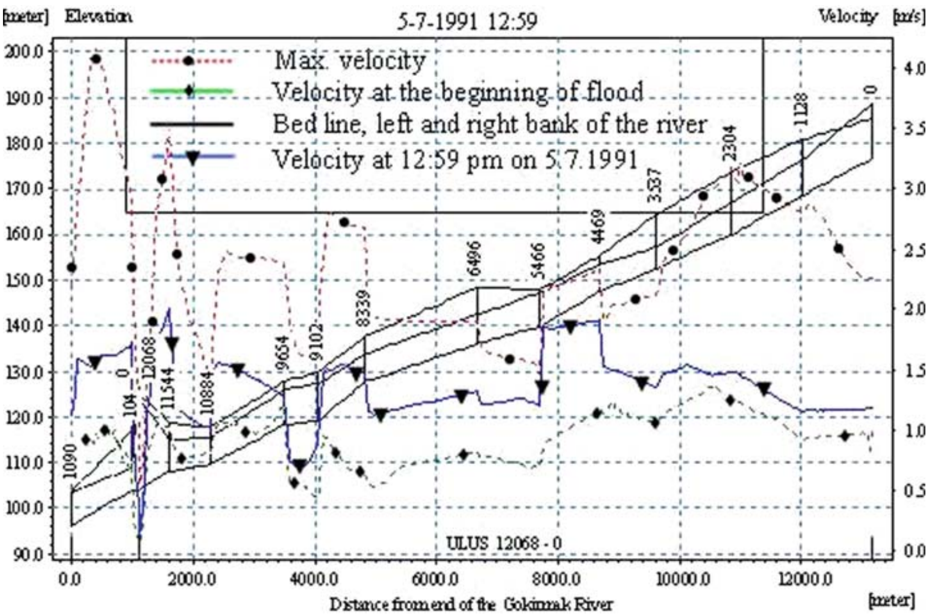

Fig. 8 Velocity profiles determined by the 100-year flood simulation

the same modeling system and run using the results of the hydraulic module, is used to obtain the inundation maps. To do so, flood depths computed using the hydraulic module are overlaid on the 10 m cell-sized DEM, obtained previously from a 1/25,000 scale map.

In the MIKE 11 GIS module, it is possible to form flood maps corresponding to any time, hour or day during the flooding. At the end, the module gives the highest water depths (H_{max}) in the riverbed during the flood.

Longsection profiles are derived from flood maps at a point located on the Ulus River, with a chainage value of 11,251 m. This point is selected, due to the high flood depths at this location. The longsection profile obtained from the results of the observed 1991 flood simulation is shown in Fig. 9 in the format of software output.

In flood studies, not only the extent of flooded areas but also the depth of water in this area should be determined to help predict the damage that water will cause to both land property. For the current study, inundation maps are obtained for the Ulus Basin at the end of the four different simulations made for the 1991 flood (Sim. 1), 25-year (Sim. 2), 50-year (Sim. 3) and 100-year (Sim. 4) floods. To begin, the maximum water depths in the central axis of the cross-sections are computed separately for each simulation (Table 4). Then, the flooded areas corresponding to different water depths in the cross-sections are determined for each simulation (Table 5), with results shown in Fig. 10. The values of highest water depths in different cross-sections can be used to determine the heights of embankments that may need to be built around the riverbed for protection of the surrounding areas.

Since the cadastral information of the Abdipasa district, located at the outlet of the Ulus Basin (Fig. 1), was available in digital format, it was possible to view both flood maps and parcels together. Additionally, after overlaying the 1/25,000 scale maps with the river network, those buildings, which are close to the riverbed and susceptible to the flood because of the topography, are digitized. Then, they are superimposed to the flood maps in the digital format. All parcels of land and the buildings under flood near the junction region

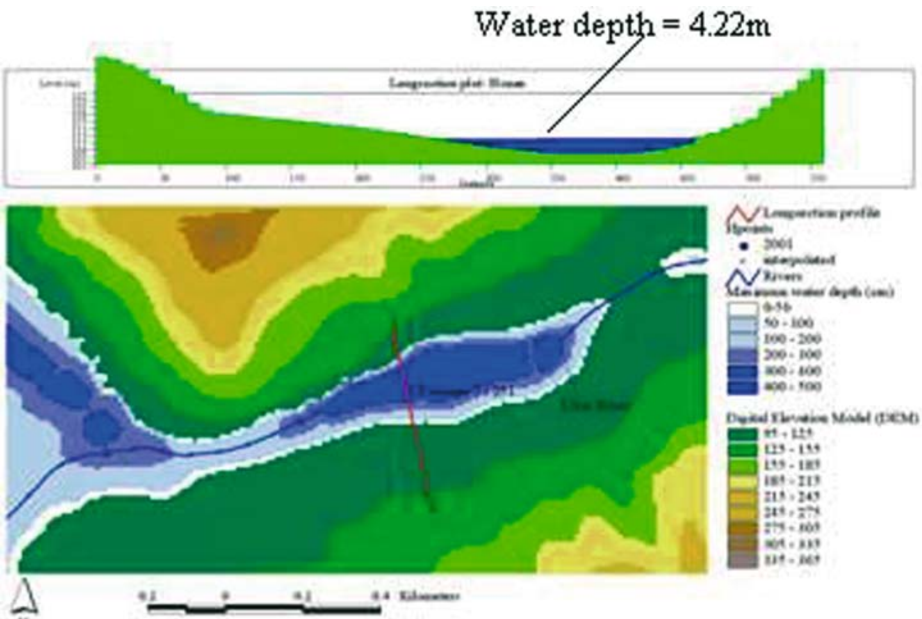

Fig. 9 Longsection profile and maximum water depth determined from 1991 flood simulation at chainage 11,251 m of Ulus River (DEM elevations in ''m'')

Table 4 Maximum water depths determined from four simulations

Simulations	Sim. 1	Sim. 2	Sim. 3	Sim. 4
Maximum water depths (m)	4.49	4.56	4.73	4.81

Table 5 Flooded areas (m^2) corresponding to different water depths determined from four simulations

	Depth (m)						Total area
	0–0.5	0.5–1	1–2	2–3	3–4	>4	
Sim. 1	306,200	449,900	1,025,600	1,122,000	380,800	17,800	3,302,300
Sim. 2	302,400	437,700	1,014,100	1,162,500	432,700	20,900	3,370,300
Sim. 3	315,600	434,400	997,000	1,209,400	514,700	38,300	3,509,400
Sim. 4	326,900	430,400	975,800	1,228,500	577,400	65,000	3,604,000

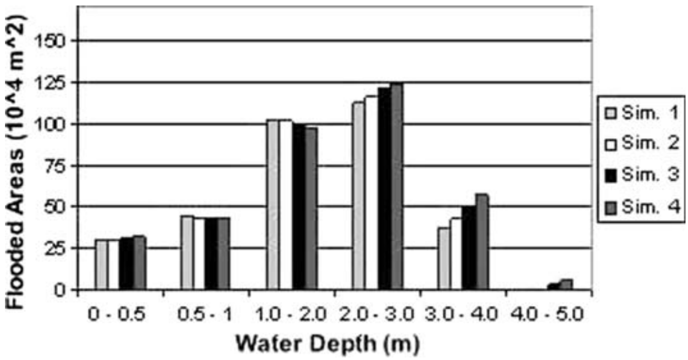

Fig. 10 Flooded areas corresponding to different water depths determined from four simulations

of the Ulus and Ovacuma branches that form Gokirmak Branch, are shown in Fig. 11 in detail.

The flood maps can show the extent of the possible inundated areas for future floods in the region. To know how many and which parcels will be flooded, together with their total area, and also the possible water depth in case of a certain magnitude future flood, is important for the purpose of informing people. In this way, people in critical locations can relocate all their important belongings. The information can also be important for damage assessment purposes after a flood. Such a study is made for the Abdipasa District with different flood cases. The total number and area of the flooded parcels, each having an area around 2,000 m^2, are computed and given in Table 6 and shown in Fig. 12. The derived inundation maps can also be used by insurance companies and the government to determine the amount of flood insurance for different areas or buildings.

The flooded areas are also given in 3-D view in Fig. 13. As it can be seen, some parts of the Ovacuma–Bartin highway, which is at the left-hand side of the river, are under flood around the junction area of the branches.

Finally, the land-use map (Fig. 14) of the region and the flood maps are superimposed in the ArcView program. In this way, the flooded areas of different land-use types are determined for different floods (Table 7 and Fig. 15).

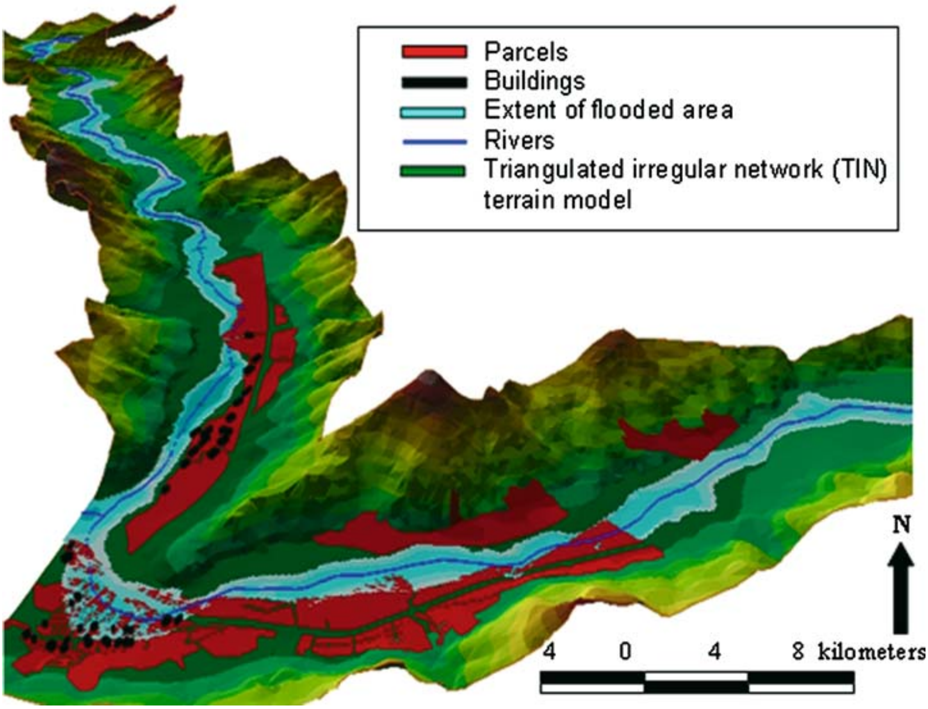

Fig. 11 Flooded areas on Ulus Basin determined from the 100-year flood simulation

Table 6 Total number of flooded parcels and their areas determined from simulations

Simulations	No. of parcels	Parcel area (m^2)
1991 Flood (Sim. 1)	289	592,105
25-year Flood (Sim. 2)	298	595,511
50-year Flood (Sim. 3)	314	668,022
100-year Flood (Sim. 4)	321	670,615
Total	1,222	2,526,253

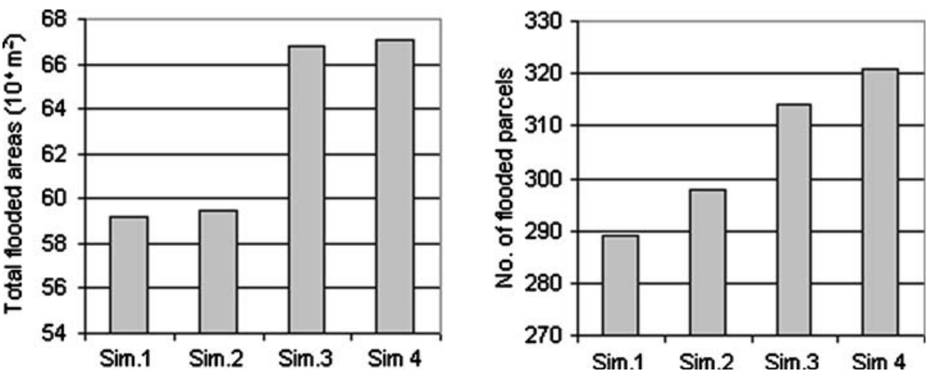

Fig. 12 Total area and number of parcels under flood determined from four simulations

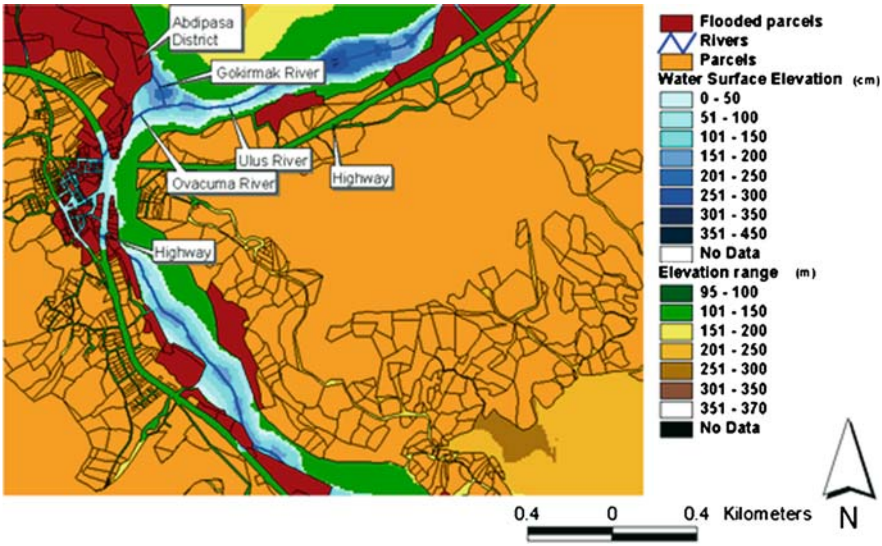

Fig. 13 Parcels under flood found from the 100-year flood simulation

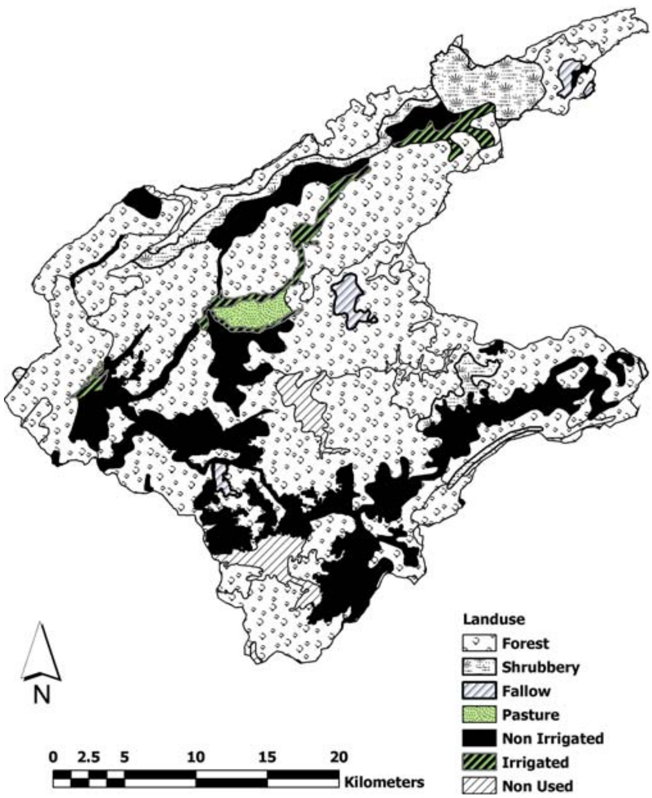

Fig. 14 The land-use map of Ulus Basin

Table 7 Areas of different land-use types under water determined from simulations

Simulations	Flooded areas of different land use types (m^2)		
	Forest	Irrigated	Non-irrigated
1991 Flood (Sim. 1)	395	7,462	25,166
25-year Flood (Sim. 2)	434	7,621	25,648
50-year Flood (Sim. 3)	444	8,015	26,635
100-year Flood (Sim. 4)	474	8,165	27,401

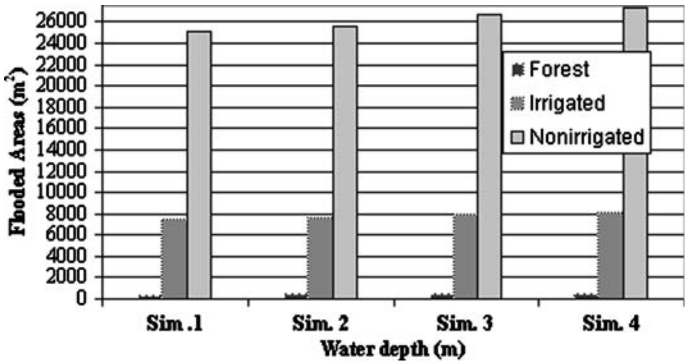

Fig. 15 Flooded land-use types determined from four simulations

Conclusion

Floods are uncontrollable natural events causing loss of lives and damage to public property. Therefore, a set of measures should be implemented to mitigate the floods to a certain extent, and also give as much information as possible to land-use planners, local authorities, emergency services and the people who may be affected.

In this study, a modeling technology is used successfully for flood analysis in a pilot basin in Turkey. Inundation maps and water depths in potentially flooded areas are derived for the entire basin by using flood hydrographs.

The highest water depths obtained in the riverbed for the observed 1991 flood, and for forecasted 25-, 50- and 100-year floods, are 4.49, 4.56, 4.73 and 4.81 m, respectively. As the peak discharges of the observed 1991 flood (596 m^3/s) and 25-year flood (650 m^3/s) are close to each other, the highest water depths corresponding to these floods are also close to each other.

In addition, the flooded areas corresponding to different water depths are obtained and compared for the same floods. For example, the flooded areas having more than 4 m water depths are 17,800 m^2, 20,900 m^2, 38,300 m^2, 65,000 m^2, respectively, for the four studied flood cases. According to different water-depth ranges, different insurance rates can be determined around the riverbeds. Similar results can be given for different land-use types.

In such studies, more detailed hydrometeorological and topographical data with smaller observation time intervals, such as hourly instead of daily values, higher resolution DEM, and satellite images or aerial photographs taken during and/or just after a previous flood, would improve the results considerably by providing better calibration means for the model.

With the help of these new technologies, the loss of human lives and the damage to properties due to flooding can be decreased. Using the information obtained about the extent of flooded areas, water depths and road conditions, systems, policies and strategies can be developed to evacuate people more quickly from flooded areas. Results can also be used for the determination of economic losses.

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