The impact of catchment management on emergency management of flash-flood

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Abstract: Flash floods cause damages and need emergency actions especially in urban areas. Flood forecasting and flood warning systems (FFFWSs) can be used for reducing flood damages and saving lives in areas vulnerable to flooding. However, researches are needed to evaluate the effect of urbanisation and the significance of implementing catchment-management plan (ICMP) on FFFWS. This paper describes a framework proposed to assess the impact of ICMP on expected lead time (ELT) of flash-flood warning and it was applied for an urbanised steep catchment in an arid region, north of metropolitan city, Tehran, Iran. The model is well calibrated and validated before and after ICMP by four observed floods. The results show that ICMP reduces mainly flood risk only in low-return periods (about 30%) than in high-return periods. Finally, this paper demonstrated the efficiency of ICMP in increasing emergency time for evacuation from possible inundated areas except in extreme floods events.

Keywords: flood warning systems; FWSs; expected lead time; ELT; flash floods; catchment management; Tajrish Catchment; HEC-HMS model; flood control.

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Azar Arabi received her MSc in Irrigation and Drainage Engineering from the Department of Irrigation and Drainage Engineering, University of Tehran, Iran. She studied flood forecasting and flood warning system for the north of Tehran, Iran, by using hydrological model and artificial neural network model. She has been an Academic Member of Rayan Pajooh Water Resources Management and Engineering Research Institute since 2012. Her research focus is flood and flow forecasting and groundwater resources studies. She simulated several basins and studied more than 10 aquifers in Iran.

1 Introduction

Flash floods cause damages and loss of lives in all continents and need emergency actions especially in urban regions. Frequent flash floods are reported in USA, Iran, Oman, Korea and Europe, which require emergency measures to reduce their impacts (Al-Rawas, 2009; Gaume, 2009; Golian et al., 2010; Johnson, 2000; Kim and Choi, 2012; Sauvagnargues-Lesage and Ayral, 2007). In addition, because of the global warming, flash floods are considered one of the most important growing natural hazards of the world (Hegedüs et al., 2013). Several papers and studies show that flash floods do threaten lives and properties in many countries around the world, thus innovative methods are essential to assess and estimate the ability of emergency action in mitigating these disasters.

Flood forecasting methods and flood warning systems (FWSs) can be used for lessening flood damages and saving lives (Liu and Chan, 2003) and would increase flood control plans efficiency (Andjelkovic, 2001). Flood forecasting is a non-structural and effective management method for flood damage reduction. Urbanisation of catchments affects the time of concentration and flood hydrograph; therefore, catchment management impact should be examined to determine the efficiency of flood mitigation plans. Currently, flood forecasting and flood warning system (FFFWS) have been accepted as one of the most economical and efficient non-structural flood mitigation methods (Yazdi et al., 2013). Olang and Fürst (2011) showed in a case study in Kenya that land cover change impacts flood peak. However, since benefit-to-cost ratio of the FFFWSs has been reported to be several times of other flood mitigation measures for flood damage mitigation in the world (Yazdi et al., 2013), the effect of urbanisation and urban catchment management on flood warning lead-time (FWLT) should be examined to measure the efficiency of action plans. FWLT is the time length between the detection of flood exceedance over certain hazard threshold to the start of flood damage and losses. During this time, emergency responders have to be able to take actions to decrease damage and losses. Technically, the longer the FWLT is, the greater the opportunity is to reduce damages and losses. More importantly, it is expected that urbanisation will grow flood risk in the next 30 years slightly (De Roo, 1999; De Roo et al., 2003) and this risk is more significant for areas characterised by small steep urbanised catchments because of the short time for emergency action related to a short catchment time-of-concentration.

Some researchers analysed runoff of different basins by different hydrologic models. For example, Vieux and Moreda (2003) simulated flash floods and debris floods of a basin in Taiwan by Veflo™ model. The model estimated two peaks of hydrograph with less error (Vieux and Moreda, 2003). Kafle et al. (2007) also analysed the effect of rainfall on Bagmati basin in Nepal using the hydrologic model hydrologic engineering center-hydrologic modelling system (HEC-HMS) in a geographic information systems (GIS) environment. The results showed that there is no exact agreement for low flow, but the model predicted properly the peak flow. Rainfall runoff models such as HEC-HMS are considered suitable for simulation of peak flow and flood forecasting (Kafle et al., 2007). Still, the effect of urbanisation and catchment management on FWLT needs to be tackled to assess flood mitigation efficiency.

The above-mentioned review shows that many researches focused on FFFWSs. However, evaluating urbanisation and catchment management impact on FWLT in urbanised flash flooder catchments is essential. Therefore, in this paper, a framework is proposed to assess the impact of catchment management on the lead time of flash-flood warning. The proposed framework was examined for an urbanised steep catchment in an arid region, north of metropolitan city, Tehran, Iran.

2 Case study area

The case study area is located in Central Iran, north of capital city, Tehran, Iran, so as to examine the applicability of the proposed framework in an urbanised steep catchment located in an arid zone. The Tajrish Catchment is located in the north of Tehran. The basin, with a gross slope of 25.6% and area of 3285 ha, is a steep basin and the main flash flooder catchment in the north of Tehran. The red, green and blue (RGB) map of Landsat Images of 1988 and 2002 as shown in Figure 1 reveals dramatic land use changes including fast urbanisation and the reduction of vegetation cover in the catchment. In this period, extensive catchment management measures were taken in this basin such as mechanical (including check dams and detention dams), biological (enhancing land cover) and other non-structural (prevention from overgrazing) measures all as part of the implementing catchment-management plan (ICMP). Therefore, this catchment is a suitable example of flash flooder basin to examine the effect of urbanisation and catchment management on FWLT.

The physical parameters and hydroclimatological data of the catchment were used for calibration, verification of HEC-HMS model and forecasting flash flood hydrographs. The physical parameters of the catchment were cross sections, length and width of the streams/rivers of the catchment. In addition, catchment land use conditions before and after ICMP was applied to determine initial curve number (CN) of soil conservation service (SCS) method as given in Figure 2. The initial CNs were improved by calibration, which are explained later in the paper. Historical data of flood hydrograph and rainfall data were used for calibration and validation of the model. First, the model was calibrated and validated before ICMP by using observed flood hydrographs of 3 April, 1996 and 29 March, 1998, respectively. Then, the same process was carried out for the after-ICMP condition by using the observed flood hydrographs of 18 September, 2001 and 18 March, 2002 for the after catchment management condition. The floods were simulated for different return periods in both conditions (before and after catchment management) using design rainfall temporal pattern of the catchment and one-hour rainfall intensity of Niyavaran Meteorological Station as shown in Figures 3 and 4, respectively. Consequently, the proposed framework was applied to assess the catchment management impact on FWLT.

Figure 1 Extent of urbanised areas (white polygon) and gardens (red colour) of Tajrish catchment in years 1988 and 2002 (see online version for colours)

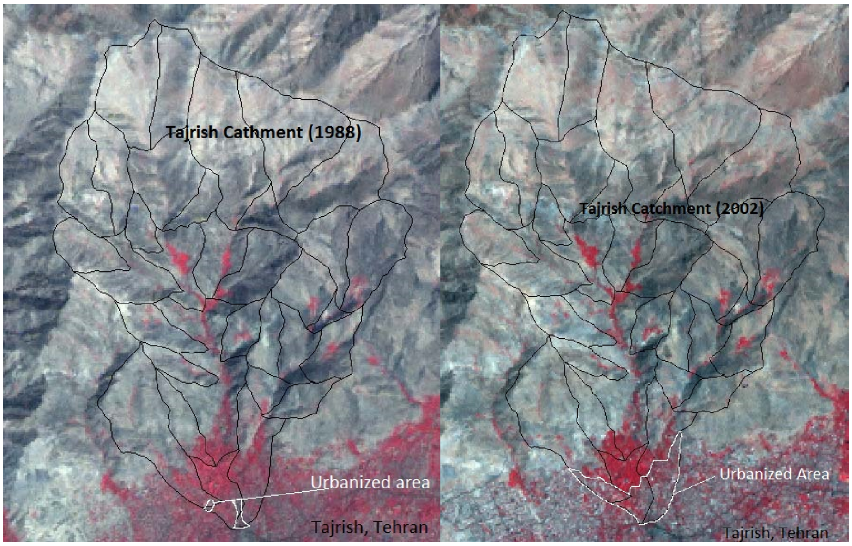


Figure 2 Percentage of the land covers of Tajrish catchment before and after ICMP

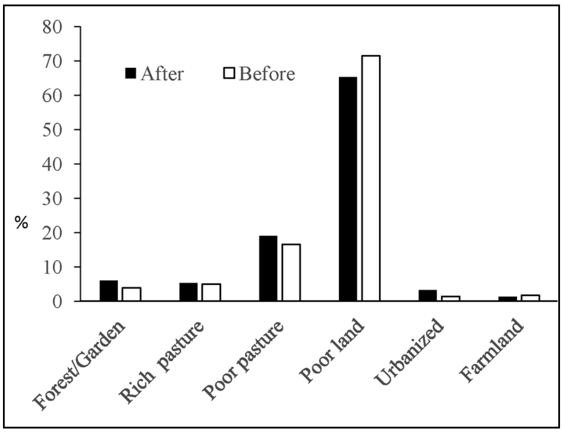


Figure 3 Design rainfall temporal pattern of Tajrish catchment (see online version for colours)

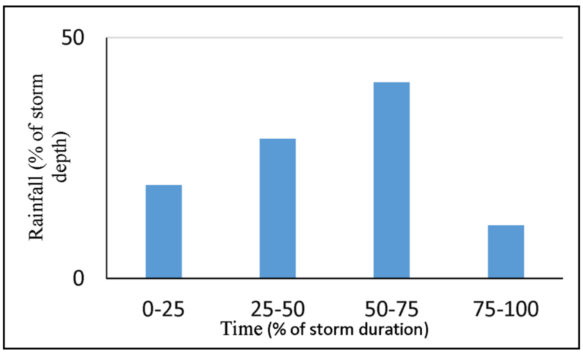
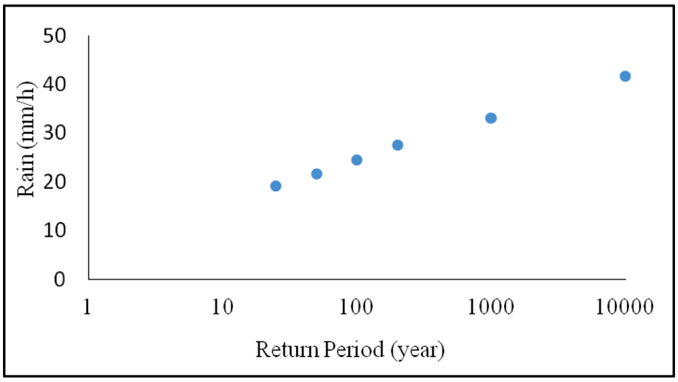


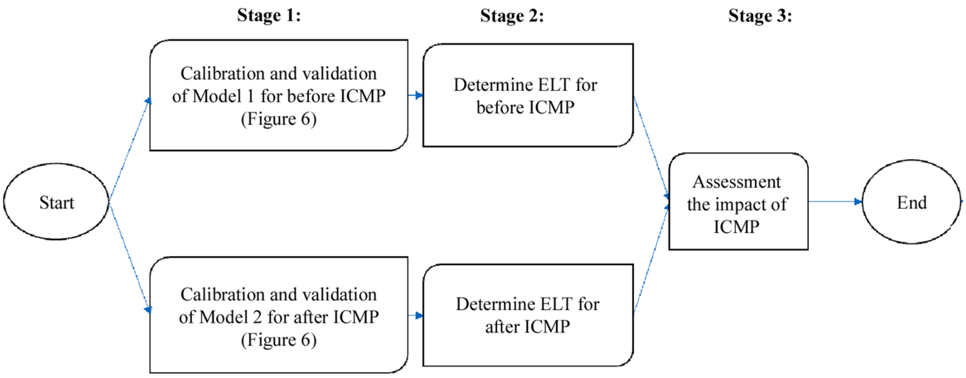
Figure 4 One hour rainfall intensity in Niyavaran Meteorological Station (see online version for colours)



3 The framework

The proposed framework has three stages: calibration of HEC-HMS for the conditions before and after the ICMP, determining expected lead time (ELT) of flood warning for the both conditions and comparing ELTs of the flood warning of the both conditions to assess the impact of ICMP as illustrated in Figure 5.

Figure 5 Framework of the research (see online version for colours)



Approach details of the framework are as follows.

The first stage was to calibrate hydrological model, HEC-HMS, for before and after the ICMP conditions. HEC-HMS was developed by the US Army Corps of Engineers (Scharffenberg and Fleming, 2006). That is a hydrologic engineering centre (HEC) package, a new generation of models developed for rainfall-runoff simulation. Since estimation of peak flow is very important for flood control, the initial CNs of sub-basins were determined using satellite images of the basin and then were calibrated by minimising the error function of peak flow using equation (1) as follows:

$$Z = \left| \frac{Q_0 - Q_s}{Q_0} \right| \tag{1}$$

where Q_0 is the observed peak flow and Q_s is the simulated peak flow. Flood in the channels was routed by using standard Muskingum-Cunge, which has a hydraulic base and produces more accurate results. Consequently, the effects of check dams on flood were estimated by applying improved bed sloped by the check dams in the flood routing calculation. These processes were done for both conditions, i.e., before and after ICMP. At the end of the first stage, two calibrated hydrological models can simulate the flood in before and after ICMP conditions.

The second stage of the framework was to determine the ELTs of flood warning for before and after ICMP. FWSs can decrease flood damage and protect lives if properly planned and functioned. The objective of FWS is to offer advanced warning of a flood. Thus, defensive activities may be applied (Pingel et al., 2005). Guidance by the US Army Corps of Engineers (USACE, 1996) proposes that the duration between the first forecastable rainfall and the time at which the flood flow surpasses the threshold for a flood risk to life or properties at a critical location is the maximum possible warning time. If a warning is recognised, the remaining time, until the threshold is surpassed, is the forecast lead time. Figure 6 demonstrates how the lead time was computed for each return period of floods. Initially, time was required for system operators to gather, evaluate and forecast based on available data. This data collection and evaluation time is considered as forecasted recognition time (T_F). The forecast lead time (T_L), as shown in Figure 6, is the difference of time between risk recognition (T_F) and the time of flow exceeds the threshold limit (T_E) and calculated by using equation (2) as follows:

$$T_L = T_E - T_F \tag{2}$$

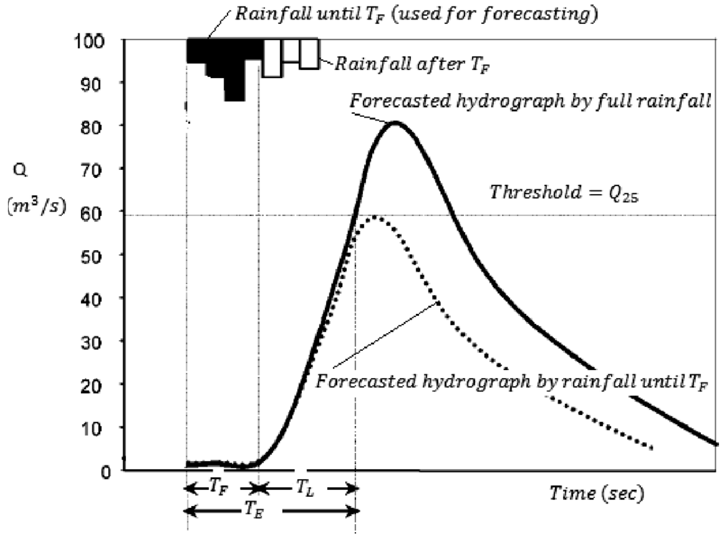
To compute T_L, we first use the full rainfall hyetograph of each return period to simulate a full flood hydrograph as shown by the solid line (Figure 6). This is the flood hydrograph that will occur when the rainfall event has completed. The time of threshold exceeded (T_E) is the time when the flow from the full hydrograph exceeds the threshold. The dotted line denotes the forecasted flow hydrograph based on the rainfall up until the forecasted recognition time (T_F). First, T_F starts from a specific time step and then it gets enlarged by adding more time steps (in this research as 1 s). Thus, as T_F is stepped forward in time, additional rainfall is used in the forecast until the peak flow of forecasted hydrograph simulated by hydrologic engineering centers river analysis system (HEC-RAS) reaches to threshold flow. The threshold flow was the discharge of flow that exceedance of it causes risk in the floodplain of a river. According to Iran Water Regulation, all activities in the rivers floodplain should be out of 25-year flood inundation zone (Standard and Technical Criteria Office, Iran Water Resources Management Company, 1997), and the flow threshold was considered as 25-year flood in this paper. The ELT can be calculated by equation (3) as follows:

$$\text{ELT} = \left(\sum_{i=thr}^{10000} \frac{T_{Li}}{T_i} \right) / \left(\sum_{i=thr}^{10000} \frac{1}{T_i} \right) \tag{3}$$

where T_{Li} is the forecast lead time for the return period T_i; i is the return period, which varies from the return period of threshold flow (*thr*) to 10,000 years. Using the calibrated HEC-HMS for before and after ICMP, lead-times could be determined for different return periods and ELT for the both conditions at the end of stage 2.

At the final stage of the framework, we compared the lead-times for different return periods and ELTs of before and after the ICMP conditions to judge the impact of implementing the plan. Consequently, the comparison of the lead-times and ELTs for the conditions demonstrates how efficient the catchment management plan is in improving emergency time for actions and evacuation from possible flooded area.

Figure 6 The components of lead time of flood warning



Source: Adapted from USACE (1996)

4 Results

Results of the comparison between observed and simulated peak flows denote that the model is well calibrated and validated for the conditions of catchment in before and after the ICMP. Initial CNs are determined using land use map of the catchment in the conditions of before and after ICMP and then changed by calibration process to minimise peak flow errors. The observed, calibrated and validated peak flows are shown in Table 1 for before and after the ICMP. The table shows that the relative error of the calibration of peak flow is less than 0.7%. The results indicate good agreement of calibration and validation results with observed ones. Accordingly, HEC-HMS model is appropriate for flood simulation of the Tajrish Catchment and provides a tool for the framework of ELT calculation.

Table 1 The peak of calibration and validation floods in conditions of before and after catchment management

	Before catchment management		*After catchment management*	
Data type	*Calibration*	*Validation*	*Validation*	*Calibration*
Observed (m^3/s)	13.7	13.3	2.4	4.06
Simulated (m^3/s)	13.8	13.7	2.1	4.06

After calibrating and validating the model, floods of different return periods were simulated for before and after ICMP conditions to compare their peak flows. The return periods were 50, 100, 200, 1000 and 10,000 years, respectively. The results of flood simulation for these return periods show that the ICMP implied 16% reduction on peak flow of 50-year flood as illustrated in Figure 7. However, this reduction is decreased by increasing return period and vanishes for 10,000-year flood. Therefore, ICMP reduces mainly flood risk only in low-return periods than in high-return periods.

Figure 7 Peak flow change by ICMP

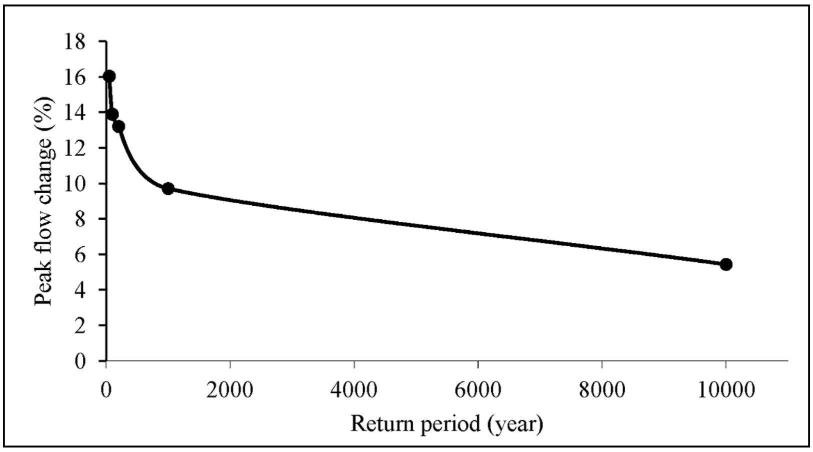


Figure 8 Forecasted lead time before and after ICMP

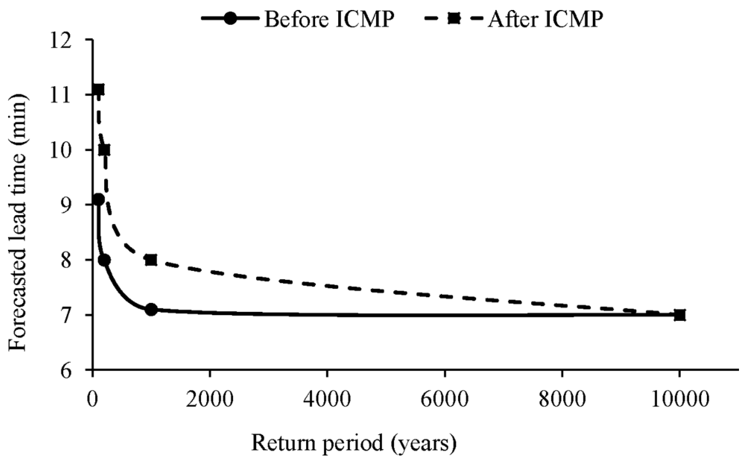


Table 2 Impact of ICMP on ELT

Condition	*ELT* (min)
Before ICMP	9.99
After ICMP	13.07
Increase by ICMP (%)	30.74

The comparison of ELT for before and after ICMP indicates that ELT is enhanced by ICMP and this is shown in Table 2. However, the impact of ICMP on the forecast lead time declines by growing return period (Figure 8). Table 2 illustrates that ELT increases from 9.99 min to 13.07 min by ICMP, which means about 31% increase in time for emergency actions. This increase is done by mitigating flood by catchment management measures such as check dams. These measures cause reduction of flood peak and delay on flood hydrograph. However, Figure 8 shows that forecast lead time decreases by increasing of return period. The forecast lead time for before ICMP was generally less than that for after ICMP and ICMP caused forecast lead time to be increased from 11 min to 15 min for 50-year flood, but it was the same for 10,000-year flood of before and after ICMP catchment management. So, the catchment management increased the forecast lead time in short return periods but it did not influence the same way on long return periods such as 10,000-year flood. Consequently, ICMP improves ELT and provides generally more lead time for emergency actions than before ICMP, but it also shows that it is not effective for extreme floods such as 10,000-year flood. For extreme floods, detention basins may be suggested to be added to ICMP to increase its flood control efficiency (Banihabib and Bahram, 2009; Banihabib et al., 2011).

5 Conclusion

This paper presents an approach for increasing the ELT as measures towards flood damages. Flash floods threaten lives and properties of all people around the world and advanced methods are essential to measure the effectiveness of emergency action in mitigating them. The effect of urbanisation and catchment management on FWLT was considered to assess the flood mitigation efficiency through integrating HEC-HMS model in a GIS environment for computing the ELT. Furthermore, the developed framework was examined for the assessment of ICMP impact on ELT in an urbanised steep catchment located within an arid region. The main findings are as follows:

- Calibration and validation results of HEC-HMS model show that the model is appropriate for flood simulation of Tajrish Catchment and provides a significant tool for the framework of ELT calculation.
- ICMP improves ELT and provides generally more lead time for emergency actions, but it is not effective for extreme floods such as 10000-year flood. Preferably, it reduces mainly flood risk only in low-return periods than in high-return periods.

Finally, the comparison of the lead-times and ELTs demonstrated how efficient is the ICMP in improving emergency time for planning and executing emergency measures such as evacuation from possible flooded areas but not in the case of extreme floods where it needs further research and assessment through coupling it with other applicable models.

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