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154

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A hydrological model for Ayamama watershed in Istanbul, Turkey, using HEC-HMS

C. M. Kazezyılmaz-Alhan[a,*], İ. Yalçın[a], K. Javanshour[a], M. Aytekin[b] and S. Gülbaz[a]

[a] Department of Civil Engineering, Istanbul University-Cerrahpasa, Avcılar, 34320, Istanbul, Turkey

[b] Department of Forest Engineering, Istanbul University-Cerrahpasa, Sarıyer, 34473, Istanbul, Turkey

*Corresponding author. E-mail: meleka@istanbul.edu.tr

Abstract

In order to overcome the flood risk in urbanized regions with high population density, generation of hydrological models is essential. The aim of this study is to generate a hydrological model for the Ayamama watershed by using HEC-HMS, simulate the flood event that occurred in Ayamama River in Istanbul, Turkey, on September 9, 2009 and evaluate the modeling performance of the HEC-HMS. For this purpose, the basin area is divided into the subbasins; the sections and parameters of the natural water channel are defined; infiltration is taken into account with the Green-Ampt method and the Clark Unit-Hydrograph method is used for calculation of the hydrograph over the watershed. The rainfall data measured during the aforementioned flood event is used in simulation. Peak flow of the hydrographs for the subbasins, which were heavily affected by the flood, are obtained and compared with the results of the calibrated hydrological model generated by Rational Method in WMS in a former study. The results obtained by HEC-HMS model are in good agreement with the results obtained by Rational Method in WMS. The strength of the HEC-HMS model over Rational Method is emphasized. Moreover, the subbasins located downstream of the Ayamama River are determined as the most critical region.

Key words: Ayamama watershed, flooding, HEC-HMS, hydrological model

Highlights

- Generating a hydrological model for the Ayamama watershed by using HEC-HMS.
- Simulating the flood event that occurred in Ayamama River in Istanbul.
- Evaluating the modeling performance of HEC-HMS.

INTRODUCTION

The intensity and frequency of floods have increased due to several reasons in recent years (Xiao *et al.* 2019). Climate change is undoubtedly one of the most important reasons among others. According to the Intergovernmental Panel on Climate Change evaluation report (IPCC 2014), concerns about climate change are generally seen as an increase in temperature, an increase in heavy rainfall events on land, and coastal floods. Another main reason for floods is the increase in impervious surfaces due to urbanization (Vaillancourt *et al.* 2019). The decrease of vegetation and the disappearance of the natural reservoir result in malfunction of the stream flow regime that influences the balance of hydrology (Legowo *et al.* 2019). Floods occur after extreme regional rains in many countries (Wurjanto *et al.* 2019) and are the biggest economic natural disasters after earthquakes (Uşkay & Aksu 2002). For example, in the United States, floods cause annual damage over USD 4 billion and the deaths of almost 200 people (Pielke *et al.* 2002). In recent years, as a result of the increase in population, settlements in urbanized regions have increased and spread towards riverbeds in Turkey. As a result, the number of flood damages has increased (Bayazıt 2002). Between 1955 and 1995, more than 1,000 people lost their lives due to the floods in Turkey. The economic loss of these floods was more than USD 650 million (Ceylan *et al.* 2007).

In the Marmara region, the most severe floods occurred in the last years; particularly, the one that occurred during the period of September 7–10, 2009, was one of the severe floods. Istanbul and Tekirdağ provinces were the most affected provinces of the Marmara region. The said flood event was the third greatest disaster among the flood events in Turkey after the floods that occurred in Izmir and in the Western Black Sea (Kömüşçü & Çelik 2013). The flooding event that occurred in Ayamama River in Istanbul was the result of successive and persistent storms with high intensity over a 3-day period that generated more than 250-mm rainfall over the region. The flood resulted in fatality of 32 people and caused extensive environmental and infrastructural damage in the region (Gülbaz *et al.* 2019).

In order to investigate the physical mechanisms of floods and take precautions, flood simulations of the specific regions are necessary. Therefore, generation of hydrological models for different watersheds has gained importance (Sikder *et al.* 2019). The aim of this study is to generate a hydrological model for the Ayamama watershed by using HEC-HMS to simulate the flood event that occurred in Ayamama River in Istanbul, Turkey on September 9, 2009 and to evaluate the modeling performance of HEC-HMS by comparing its results with observations and with the results of a calibrated model generated using WMS in a former study by Gülbaz *et al.* (2019). In WMS, the Rational Method is employed, which is a lumped-parameter method that can only predict a single (usually large) flow, without incorporating the mechanics of the flow process through the watershed, nor antecedent moisture conditions, land use, soil composition and infiltration processes, or groundwater interactions. On the other hand, HEC-HMS is a distributed, one-dimensional kinematic wave overland and channel flow simulation model, fully incorporating soil groups, infiltration, and storage, which makes the hydrological model stronger than the previous hydrological model.

MATERIAL AND METHODS

Study site

Ayamama watershed is located on the European Continental side of Istanbul in Turkey. The mainstream length is 21 km with many tributaries feeding the river. The Ayamama river begins from Esenler and discharges into the Marmara Sea. The surface area of the watershed is 74 km^2 and it has an average slope of 7%. The concentration time for the basin is about 7 hours. The middle and lower parts of the area are urbanized regions of the watershed. The exponentially growing population of Istanbul has resulted in a huge land cover change (Saral *et al.* 2010). The urbanized area in Ayamama watershed grew from 15.86 km^2 in 1987 to 42.84 km^2 in 2013 (Nigussie & Altunkaynak 2016). TEM highway, International Atatürk Airport and Ikitelli Organized Industrial Zone are among the areas in the Ayamama watershed that are exposed to rapid urbanization (Gülbaz *et al.* 2019). Figure 1 shows the location of Ayamama watershed and Ayamama Stream and the areas affected by the flood event.

The Ayamama watershed is located in Marmara region and therefore is exposed to the precipitation regime of Marmara region. The highest precipitation amounts and extreme rains occur in November, December and January in this region (Temuçin 1990). The average annual precipitation of the region is 852 mm.

Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS)

Hydrologic Modeling System has been developed by the U.S. Army Corps of Engineers (Fieldman 2000). HEC-HMS models precipitation-runoff processes of dendritic watershed systems. It has the

Figure 1 | Location and boundary of Ayamama River watershed (Google Earth, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image Landsat/Copernicus © 2018 Basarsoft, © 2018 Google).

capability of simulating the floods and natural watershed runoff as well as meteorological phenomena such as evapotranspiration, snow melting and precipitation. The software is able to report a database, data entry tools, calculation engine and results. The modeling results are employed in evaluating current water budget and flow estimations. The primary model components are basin models, meteorologic models and control specifications. A simulation calculates the precipitation-runoff response in the basin model given input from the meteorologic model. The control specifications define the time period and time step of the simulation run (Fleming & Brauer 2016). All hydrological elements are connected to a network in order to model the relationship between precipitation and flow. Basin-subbasin, reaches and junctions are the main hydrological elements (Scharffenberg 2016).

Basin models

The system provides a variety of methods for calculating loss in a subbasin and transforming precipitation to flow. Green and Ampt, Deficit and Constant, SCS Curve Number are the main methods to estimate the amount of infiltration in the basin. The Green and Ampt method is chosen in this study to calculate infiltration. This method is based on a physical model and takes into account many parameters that characterize the soil conditions. The parameters of the method are initial moisture content, saturated moisture content, wetting front soil suction head, and hydraulic conductivity (Rossman 2015).

Clark Unit Hydrograph, ModClark, and user specified Unit Hydrograph methods are among the options in HEC-HMS to calculate precipitation-flow transformation. The Clark Unit Hydrograph method chosen in this study is a synthetic hydrograph method that utilizes an instantaneous unit hydrograph (Clark 1945). Obtaining a unit hydrograph through the analysis of past observed hydrographs is not requisite (Scharffenberg 2016). The technique called the time-area method (Kull &

Feldman 1998) assumes that the discharge at any point in time is a function of the translation and storage properties of the basin. The translation is obtained by calculating the surface and channel travel time of runoff. Delay caused by the storage effects of a watershed is also taken into account (Viessman & Lewis 2012). The translation of the hydrograph is satisfied by routing through a linear reservoir to account for storage attenuation effects in the basin (Scharffenberg 2016). The components of the method are time of concentration and storage coefficient.

Kinematic wave, Modified Puls and Muskingum translation are among the routing option methods in pipes or open channels. The current study performed the routing with kinematic wave. In the kinematic wave routing method, the acceleration and pressure terms in the momentum equation are negligible. The wave motion is described by the equation of continuity (Chow *et al.* 1988). The energy slope is equal to the bed slope according to this method. As the method allows flow and area to vary both spatially and temporally within a conduit, it can result in attenuated and delayed outflow hydrographs (Rossman 2015). The parameters of the method are length, slope, Manning's coefficient and cross section.

Meteorologic model

Meteorologic model purposes are preparation of the meteorologic boundary conditions for subbasins. A common meteorologic model can be used with many different basin models. The method of precipitation is selected as a specified hyetograph for the meteorologic model of this study. The Specified Hyetograph method allows for definition of a specific time-series rainfall data at subbasins (Scharffenberg 2016).

The elements of the hydrological model of HEC-HMS and the selected methods in this study are presented in Figure 2.

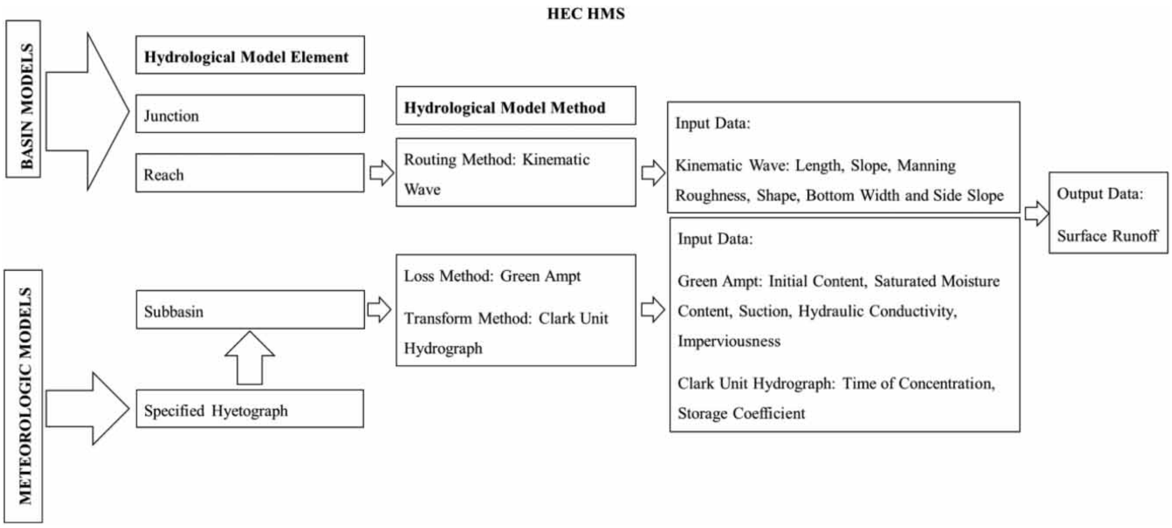

Figure 2 | Flow chart of HEC-HMS.

Modeling

For modeling of the Ayamama watershed with HEC-HMS, a topographical map, cross-sectional area of the main river, soil properties of the study area and precipitation data for the flood event are used. Area information and Ayamama river length of the watershed are determined based on ArcGIS. Soil type is determined as loamy sand and required characteristics are obtained from EPA SWMM User's Manual. The precipitation data for the flood event was provided by the Turkish State Meteorological Service (MGM).

Basins are divided into sub-basins in order to generate a more precise hydrological model. For this reason, sub-basins were formed by specifying the relevant exit points in the Ayamama Basin. The basin area is divided into 11 subbasins and area information is defined. Infiltration is taken into account with the Green-Ampt method. In order to find the amount of loss, the values of the initial moisture content, saturated moisture content, suction head, and hydraulic conductivity parameters are defined. These values vary according to the soil type. Due to the high urbanization in the watershed, 95% imperviousness is defined. The Clark Unit Hydrograph method is used for calculation of the hydrograph over the watershed. Within the scope of the method, time of concentration of subbasins and storage coefficient parameters of the soil are defined in the system. Junctions are added to each sub-basin outlet to route the surface runoff. The reaches representing the Ayamama river are defined in the model. Total length of all reaches is approximately 20 km. As a routing method for each reach, the kinematic wave method is used, which asks for the roughness and the channel cross section shape. Their length, slopes, Manning's roughness coefficient (n) and cross sections are defined into the model.

Figure 3 presents the hydrological model of the Ayamama watershed generated in HEC-HMS. Here, blue squares represent the subbasins, dark blue lines represent the reaches and blue rectangles

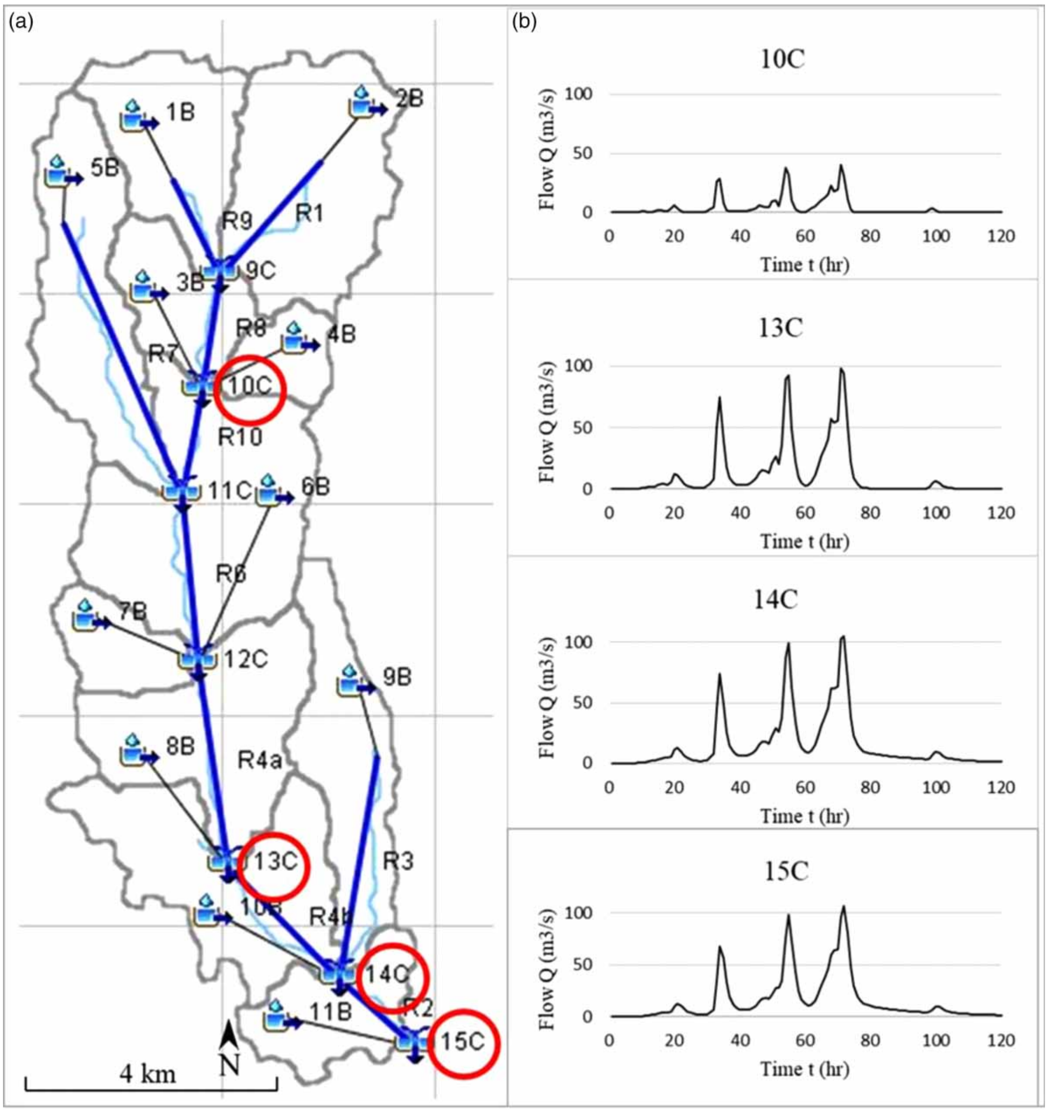

Figure 3 | (a) Hydrological model of the Ayamama watershed with HEC-HMS; (b) hydrographs obtained at selected outlets of subbasins.

represent junctions. After the basin model is formed, the Meteorologic model is selected as the Specified Hyetograph. The rainfall data, which belongs to September 7–11, 2009, is provided by the Turkish State Meteorological Service (MGM) and is used in the watershed model to simulate the hydrological response of the region. The hyetograph belonging to the flood event is given in Figure 4.

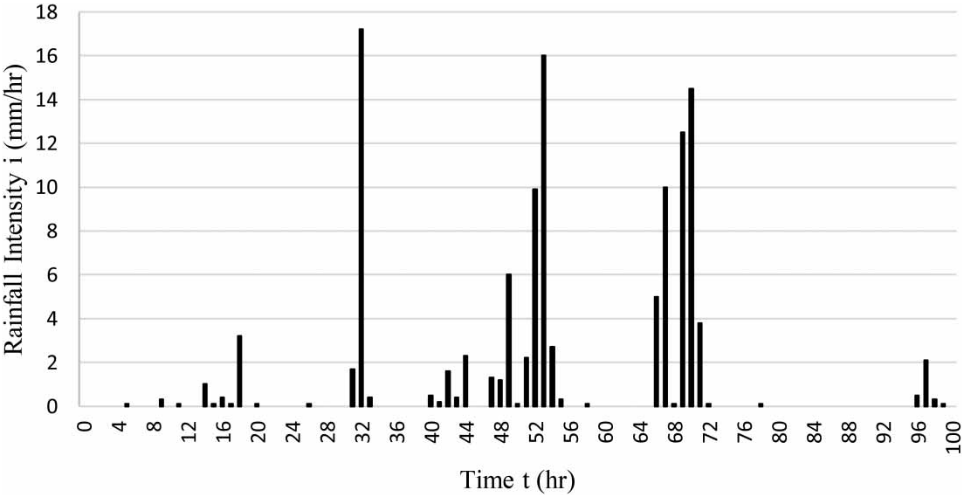

Figure 4 | Rainfall intensity during the flood event that occurred on September 7–11, 2009.

RESULTS

The flood event that occurred on September 9, 2009 is simulated by using HEC-HMS. The watershed is divided into 11 subbasins and they are named 1B-11B, respectively. The junctions are defined for routing of surface water towards outlets of subbasins and they are named 9C-15C. The flood hydrograph is obtained at different locations along the Ayamama River. Atatürk, Evren, İnönü, and Çobançeşme districts's outlets are represented as 10C, 13C, 14C, and 15C, respectively, which were heavily influenced by the flood. The locations of these outlets are seen in Figure 3. Flood peaks of the hydrographs are obtained as 40.3 m^3/s, 98.5 m^3/s, 105.2 m^3/s and 107.4 m^3/s at these locations. Flow reaches these peak values at the 74th hour.

Results for critical points in HEC-HMS modeling are compared with the results of the calibrated hydrological model generated by Rational Method in WMS in a former study done by Gülbaz *et al.* (2019). Gülbaz *et al.* (2019) calibrated the hydrological model developed by WMS by using the field observations and event reports. They used Rational Method, which is one of the surface runoff calculation methods used in WMS for hydrological modeling. WMS includes an interface to the Rational Method, which can be used for computing peak flows on small urban and rural watersheds. In this study, the HEC-HMS model was adapted to obtain similar rates in the regions towards the basin outlet. Table 1 presents the HEC-HMS results and WMS peak flow values and the difference between the two hydrological models.

CONCLUSIONS

In this study, a hydrological model is generated for Ayamama River watershed in Istanbul using HEC-HMS. Hydrographs for Atatürk, Evren, İnönü and Çobançeşme districts, which were heavily affected by the flood event, are obtained. Hydrographs show that high rainfall intensities at the 31st, 71st and 51st hours triggered the flood and peak flow rates. The subbasins located in the downstream of the Ayamama River are determined as the most critical regions. This area is under high flood risk. In

Table 1 | Peak flowrate of the hydrographs and the difference between rational method used for hydrological modeling in WMS (Gülbaz *et al.* 2019) and HEC-HMS

	Peak flow (m^3/s)		
Location	**HEC-HMS**	**Rational Method (Gülbaz *et al.* 2019)**	**% Difference**
10 C	40.3	53.6	33.0
13 C	98.5	103	4.6
14 C	105.2	104	1.1
15 C	107.4	105	2.3

addition, results are compared with the results of the calibrated hydrological model generated by Rational Method in WMS in a former study (Gülbaz *et al.* 2019). The results obtained by HEC-HMS model are in good agreement with the results obtained by WMS. The generated hydrological model can be used in development of flood management plans for this basin. Both HEC-HMS and WMS are capable of hydrologic modeling of a watershed and flood simulation. However, HEC-HMS is a physical model whereas the rational model is a lumped parameter model. Therefore, HEC-HMS provides an insight into the physical characteristics of the watershed, which makes the hydrological model stronger than the previous one.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Bayazıt, M. 2002 Türkiye'de taşkınlar ve taşkın kontrolü yönetimi (Floods and flood control management in Turkey). *Türkiye Mühendislik Haberleri* **47**(2), 27–29.

Ceylan, A., Alan, İ. & Uğurlu, A. 2007 Causes and effects of flood hazards in Turkey. In *Proceedings of the International Congress on River Basin Management*, 22–24 March, Antalya, Turkey.

Chow, V. T., Maidment, D. R. & Mays, L. W. 1988 *Applied Hydrology*. McGraw-Hill, Inc., New York, NY, p. 283.

Clark, C. O. 1945 Storage and the unit hydrograph. *ASCE Transactions* **110**, 1419–1146.

Fieldman, A. D. 2000 *Hydrologic Modeling System HEC-HMS Technical Reference Manuel*. U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center (CEIWR-HEC), Davis, CA.

Fleming, M. & Brauer, T. 2006 *Hydrologic Modeling System HEC-HMS Quick Start Guide*. U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center (CEIWR-HEC), Davis, CA.

Gülbaz, S., Kazezyılmaz-Alhan, C. M., Bahçeçi, A. & Boyraz, U. 2019 Flood modeling of Ayamama River Watershed in Istanbul, Turkey. *Journal of Hydrologic Engineering* **24**(1), 05018026.

IPCC 2014 Climate change 2014: synthesis report. In: *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Core Writing Team, Pachauri, R. K., Meyer, L. A., eds). IPCC, Geneva, Switzerland, p. 151.

Kömüşçü, A. Ü. & Çelik, S. 2013 Analysis of the Marmara flood in Turkey, 7–10 September 2009: an assesment from hydrometeorological perspective. *Natural Hazards* **66**(2), 781–808.

Kull, D. & Feldman, A. 1998 Evolution of Clark's unit graph method to spatially distributed runoff. *Journal of Hydrologic Engineering* **3**(1), 9–19.

Legowo, S., Hadihardaja, I. K., Haji, T. S. & Enung, A. 2019 Application of digital elevation method (DEM) for flood estimation on Upstream Ciliwung River, West Java, Indonesia. *International Journal of Geomate* **17**(59), 154–165.

Nigussie, T. A. & Altunkaynak, A. 2016 Assessing the hydrological response of Ayamama Watershed from urbanization predicted under various landuse policy scenarios. *Water Resources Management* **30**, 3427–3441.

Pielke Jr., R. A., Downton, M. W. & Barnard Miller, J. Z. 2002 *Flood Damage in the United States, 1926–2000: A Reanalysis of National Weather Service Estimates*. UCA, Boulder, CO.

Rossman, L. A. 2015 *Storm Water Management Model, User's Manual Version 5.1.* EPA- 600/R-14/413b. Water Supply and Water Resources Division, National Risk Management Research Laboratory, USEPA, Cincinnati.

Saral, A., Özcan, O. & Musaoğlu, N. 2010 Flood risk analysis using information diffusion theory – a case study: Ayamama Creek. In *30th Annual EARSel Symposium*, May, Paris.

Scharffenberg, W. 2016 *Hydrologic Modeling System HEC-HMS User's Manual*. U.S. Army Corps of Engineers, Institute for Water Resources, Hydrol. Engineering Center (CEIWR-HEC).

Sikder, M. S., Ahmad, S., Hossain, F., Gebregiorgis, A. S. & Lee, H. 2019 Case study: rapid urban inundation forecasting technique based on quantitative precipitation forecast for Houston and Harris county flood control district. *Journal of Hydrologic Engineering* **24**(8), 05019017.

Temuçin, E. 1990 Aylık değişme oranlarına göre Türkiye'de yağış rejimi tipleri (Types of precipitation in Turkey according to the monthly rate of change). *Ege Coğrafya Dergisi* **5**, 160–183.

Uşkay, S. & Aksu, S. 2002 Ülkemizde taşkınlar, nedenleri, zararları ve alınması gereken önlemler (Floods in Turkey, causes, harm and precautions to be taken). *Türkiye Mühendislik Haberleri* **47**(4–6), 133–113.

Vaillancourt, C., Duchesne, S. & Pelletier, G. 2019 Hydrologic performance of permeable pavement as an adaptive measure in urban areas: case studies near Montreal, Canada. *Journal of Hydrologic Engineering* **24**(8), 05019020.

Viessman, W. & Lewis, G. L. 2012 *Introduction to Hydrology*, 4th edn, Pearson Education, Inc., Upper Saddle River, NJ, p. 294.

Wurjanto, A., Tarigan, A. T. & Mukhti, J. A. 2019 Flood routing analysis of the Way Seputih River, Central Lampung, Indonesia. *International Journal of Geomate* **17**(63), 307–314.

Xiao, Z., Liang, Z., Li, B. & Hou, B. 2019 New flood early warning and forecasting method based on similarity theory. *Journal of Hydrologic Engineering* **24**(8), 04019023.