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Estimation of Hydrologic Parameters of Kocanaz Watershed by a Hydrologic Model

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Abstract

The main goal of this study is to estimate the hydrologic parameters of Kocanaz watershed located in Western Black Sea Region, using a semi-distributed hydrologic model, Hydrologic Engineering Center – Hydrologic Modelling System (HEC-HMS). In this study, the hydrologic model was set up for two flood events occurred in 2002 and 2013, in which one was used for calibration while the other one was used for validation of the calibrated hydrologic parameters. The watershed was introduced into the model as a single basin. Hydrologic parameters used for transformation from rainfall to runoff and base flow estimations were searched using Nelder and Mead method and calibrated using the peak-weighted root mean square error. The model results were deliberated by statistical indicators such as Nash-Sutcliffe efficiency coefficient (E_{NS}), coefficient of determination (R^2), mass balance error (MBE) and peak flow rate error (PE). The model results were found to be very good for calibration and satisfactory for validation while the peak flow rate was under estimated for both calibration and validation. It can be concluded that small watersheds such as Kocanaz might be modelled as a single basin without sacrificing the estimation capability of the model and increasing the model simulation time. Though, slightly improved peak discharge estimations were obtained in case of using sub basins.

Keywords: Kocanaz, HEC-HMS, calibration, validation, hydrologic model

1. Introduction

A sound design and operation philosophy of hydraulic structures requires either determination of a peak flow rate or a runoff hydrograph to estimate the maximum runoff volume in a catchment area using rainfall data and flood history of the area. In order to improve the understanding of complex hydrologic processes between the amount of rainfall on a basin and the amount of runoff from that basin, many variable parameters such as meteorological, drainage basin and stream channel characteristics need to be considered. Hence, many studies have been carried out to assess these hydrologic processes and try to relate these parameters quantitatively to the discharge. One area of such research includes the usage of hydrologic modelling software such as Precipitation Runoff Modeling System (PRMS), Hydrologic Simulation Model (HYSIM), Model for Urban Stormwater Improvement Conceptualization (MUSIC), Storm Water Management Model (SWMM), Soil and Water Assessment Tool (SWAT), MIKE - SHE and HEC-HMS which is chosen for this research [1-3].

In the process of hydrologic modeling of a basin, firstly calibration of hydrologic parameters are carried out using the rainfall data obtained from meteorological stations situated in or around the basin and the stream discharge values obtained from stream gaging stations for a rainfall event. Then, those calibrated hydrologic parameters are validated using data of another rainfall or storm data. Hydrological analysis can be performed for short or long term time intervals. Short term hydrological analysis is used to understand the event based hydrological process, such as flooding in the watershed while long term hydrological analysis considers a long time span to estimate probable flooding events occurred in that time span [4, 5].

In the literature, there are many applications of HEC-HMS and other such hydrologic models for both short and long term calibration of hydrologic parameters. For instance, Chu and Steinman [6] investigated the implementation of an effective and accurate hydrologic modeling in case of using fine-scale and coarse-scale hydrologic modeling. HEC-HMS and Watershed Modeling System (WMS) were applied to Mona Lake watershed in west Michigan. The model parameters were first calibrated with fine scale event data adopting 5 minute time steps which was supplied by intensive field data and these calibrated parameters were then used in the continuous hydrologic model with coarser scale of hourly time step. In both hydrologic modeling, surface runoff was simulated and the relationship between the two rainfall-runoff models was analyzed. Outputs of those simulations suggested that fine – scale event modeling was efficient in improving the continuous modeling by providing more accurate and well calibrated parameters. Laouacheria and Mansouri [7] used Watershed Bounded Network Model (WBNM) and HEC-HMS to test the effect of catchment size and time steps on runoff hydrograph shape and to evaluate the catchment reaction to a given rainfall event in the Azzaba City located in the North East of Algeria. Characteristics of the simulated hydrographs were compared with the same characteristics of the same observed hydrographs and statistically analyzed. The results suggested that HEC-HMS provided acceptable simulations in the flood events where WBNM failed to simulate. Kaffas and Hrissanthou [8] also applied HEC-HMS to the basin of Kosynthos River in Norteastern Greece and compared the simulated runoff results with the field discharge measurements. The hydrologic modeling was performed for a relatively long period of time and the parameters of base flow component were determined by calibration. The model outputs showed that this approach for base flow component provided a more realistic assumption for the time variation of base flow. Zhang et al. [2] calibrated the hydrologic parameters for two storm events in Clear Creek, Iowa, USA and then cross validated the parameters using these two storm data to demonstrate the behavior of parameters under different flood conditions. Shahid et al. [9] calibrated hydrologic parameters for different storms and cross validated parameters using those of calibrated hydrologic parameters. Authors found the results with a significant range of reasonable to good. Though studies about improving existing engineering hydrology curricula has been emphasized especially in hydrologic modeling area with increasing availability of hydrologic data over a wide range of scales like remote sensing, only in the last decade application of various hydrologic models to watersheds in Turkey has begun to accelerate. For example Yilmaz et al. [10] used HEC-HMS and Large Basin Runoff Model (LBRM) to simulate snowmelt runoffs of Upper Euphrates Basin in Eastern Turkey for a relatively longer time period by using available data and basin properties. The performance of both models was found to be quite similar so the use of both models was recommended for the investigation of climate change influences on hydrology of the Euphrates Basin. Baloch et al. [11] used Hydrologic Simulation Program-Fortran (HSPF) model for the hydrologic modeling of Koycegiz Watershed in Turkey to investigate the effect of land-use and climate change on the hydrologic regime of the Namnam stream passing through that watershed. Findings of the study suggested that potential land-use changes and climate variability in the watershed would significantly modify the hydrologic regime of Namnam Stream. Akiner and Akkoyunlu [12], used SWAT model to calibrate the hydrologic parameters in Melen Creek and to forecast the flow hydrograph. The results of hydrologic simulations suggested the long term projection of the watershed characteristics. Baduna Kocyigit et al. [3] evaluated the effect of number of sub basins in the estimation of hydrologic parameters and hydrograph at basin outlet and its neighboring ungauged basin. The authors calibrated and cross-validated two flood events dividing the basin into seven different configurations. They used the calibrated hydrologic parameters of two storms and their averages to validate other four storms. Moreover, the authors estimated the hydrologic parameters of the neighboring ungauged basin. Then, they evaluated sub basin divisions giving the best results. They found that parameters of the whole sub basin estimated the hydrographs of donor and neighboring basins the best and the individual calibrations were more compatible with the hydrographs than those of cross validation.

In this study, HEC-HMS was used for hydrologic modeling of Kocanaz basin located in Northwestern of Turkey to investigate the validation of the calibrated hydrologic parameters to predict the runoff hydrograph of the basin. Hence, the hydrologic parameters of Kocanaz basin are calibrated using a storm data and then validated for another storm event by substituting the calibrated parameters into the validated model.

2. Study Area

In this study, a small basin, Kocanaz, located in the Western Black Sea Region Basin which has 30000 km^2 drainage areas; having 811 mm of annual average rainfall with 9.93 km^3 flow volume is chosen as the study area [13]. Kocanaz Creek which collects water drained from Bartin and Ulus counties is a tributary of Bartin Creek passing through Bartin city center. The maximum and minimum altitudes of Kocanaz Creek considered in this study are 1755 m and 130 m, respectively. The drainage area, basin perimeter and longest flow path are 322.4 km^2, 115.26 km and 37.05 km, respectively. The watershed is generally mountainous and forestry, and consists of agricultural land, pasture, meadow and grasslands. The watershed is very steep with an average slope of 39.4% where the gradient might exceed 360% at several locations. Due to this steep slope, downstream of the basin frequently experiences flash flooding causing agricultural lands to be inundated, motorways to be closed to traffic and infrastructures of the town seriously damaged. Hydrologic soil groups of the basin are determined as C and D using land use and soil maps of the basin. The average curve number of the basin is about 78.5 and this value typically ranges from 70 to 98 locally. These values show that the major part of the rainfall continues as runoff in the watershed. In the basin, there is Kocanaz stream gaging station which is taken as the outlet of the basin in the model study (Fig. 1).

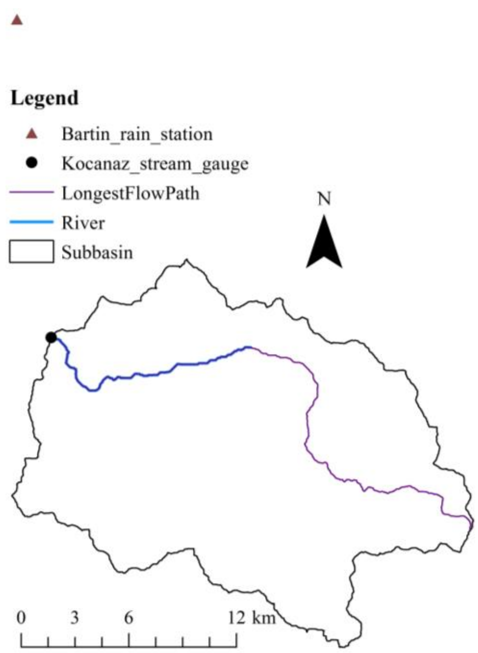

Fig. 1. General sketch of Kocanaz watershed and its main channel, longest flow path, stream gauge and meteorological stations

3. Method

Topographic maps with a scale of 1/25,000 resolution were introduced into ArcGIS 10.1 so digital elevation model (DEM) of the basin was established. The terrain model was created with ArcHydro toolbar and the basin model was produced with HECGeo-HMS 10.1. Of using the terrain model, sub-basins, slope of the basin and the tributaries can be specified. Basin and terrain models were then exported to HEC-HMS to set up the hydrologic model. Precipitation model for the hydrologic model can be obtained using precipitation data in or around the basin operated by State Meteorological Works. Kocanaz stream gauge with D13A039 local name operated by State Water Works (DSI) was taken as the outlet of the basin. Flow data provided by DSI was used to estimate the hydrologic parameters of the basin in hydrologic modeling.

4. Hydrologic Model

HEC-HMS was originally developed to simulate the precipitation-runoff processed of dendritic watershed systems. Later, it was improved to solve significant hydrologic problems including large river basin water supply, flood hydrology and small urban or natural watershed runoff [10]. HEC-HMS includes loss, flow transformation, base flow components for basins and routing processes for streams in the basis of semi-distributed hydrologic model. Furthermore, the model is capable of creating a meteorological model of the basin using precipitation, evaporation, temperature, humidity and radiation data for each sub basin. In the literature, there are many studies about the effect of number of sub basin on the estimation of flow data. Zhang et al. [2], Baduna Kocyigit et al. [3], Ao et al. [14] and Rouhani et al. [15] noted that as the number of sub basins increase, the model results are inversely affected. So, in this study Kocanaz basin was modeled as a single basin in the basin model in HECGeo-HMS.

Precipitation model was created using data of Bartin Meteorological Observation Station located near the basin as shown in Fig. 1. In this model, loss component was ignored as this is thought to be the worst scenario for the watershed, which frequently faces flash flooding. Thus, all the precipitation was assumed to be transformed to runoff. Clark’s unit hydrograph and recession method were chosen as the transformation from rainfall to runoff and base flow components, respectively. In Clark’s unit hydrograph method, transformation to runoff is calculated using time of concentration (T_c) and storage coefficient (S_c) parameters. In base flow recession method, base flow is computed using initial discharge (Q_0), recession constant (k) and threshold discharge (Q_{ts}). Direct runoff can be computed by subtracting base flow from storm hydrograph.

In this study, values of T_c and S_c for Clark’s unit hydrograph method and k and Q_{ts} values were calibrated. Seven target functions and two different search methods were used for optimization of parameters during calibration of HEC-HMS [2]. In this study, parameters were calibrated according to the peak - weighed root mean squared error (PWRMSE) and Nelder – Mead method as objective function and search method, respectively (Eq. 1).

$$\mathrm{PWRMSE} = \sqrt{\frac{\sum (Q_{obs} - Q_{sim})^2 \dfrac{Q_{obs} + Q_{obs,av}}{2Q_{obs,av}}}{N}} \tag{1}$$

where Q_{obs}, Q_{sim} and $Q_{obs,av}$ represent the observed, simulated and average values of the observed discharges, respectively.

Initial values of the parameters to be calibrated in the model must also be introduced into the model. T_c initial value was calculated by SCS (Soil Conservation Service) method (Eq. 2).

$$T_c = \frac{2.587L^{0.8}(\frac{1000}{CN} - 9)^{0.7}}{1900S^{0.5}} \tag{2}$$

where L represents the main channel length (m), CN the curve number, S the basin average slope (%). While L and S values were obtained from basin model, CN values were obtained from hydrologic soil groups and land use maps provided by Republic of Turkey Ministry of Food, Agriculture and Livestock General Directorate of Agricultural Reform.

S_c value can be estimated by Eq. 3. where c is the proportionality coefficient and its value ranges from 8 to 12 for densely forested areas, 1.5–2.8 for predominantly agricultural areas, and 1.1–2.1 for urban areas [9]. In this study the initial value of c was taken to be 1.

$$S_c = cT_c \tag{3}$$

Base flow recession values (Q_b) were computed as in the form of Eq. 4. The observed discharge value at the start of each event was input as Q_0, while the recession constant value was initialized as 0.8, for Q_{ts}, the minimum observed discharge value for the month in which the event occurred [9].

$$Q_b = Q_0 e^{-kt} \tag{4}$$

Model results were deliberated by means of certain criteria used for the evaluation of the outputs obtained in both calibration and validation processes. These criteria may generally be used for all output results, or for their average and maximum values. The Nash-Sutcliffe efficiency coefficient (E_{NS}), coefficient of determination (R^2), mass balance error (MBE) and peak flow rate error (PE) were used to evaluate the statistical indicators (SI) of the model outputs (Eq. 5 – 8). The E_{NS} ranges between $-\infty$ and 1 while values between 0 and 1 are generally viewed as acceptable levels of performance. If the E_{NS} value is less than 0.50, 0.65 and 0.75, the model performance is evaluated as unsatisfactory, satisfactory and good, respectively. However, if the E_{NS} value is greater than 0.75, the model performance is said to be very good [16]. The model results are stated as acceptable by Joo et al. [17] if $-30\% \leq PE \leq +30\%$ while by Moriasi et al. [16] if $-30\% \leq MBE \leq +30\%$.

$$E_{NS} = 1.0 - \frac{\sum (Q_s - Q_o)^2}{\sum (Q_o - Q_{o,av})^2} \tag{5}$$

$$R^2 = \frac{\left[\sum (Q_s - Q_{s,av})(Q_o - Q_{obs,av})\right]^2}{\left[\sum (Q_s - Q_{s,av})\right]^2 \left[\sum (Q_o - Q_{obs,av})\right]^2} \tag{6}$$

$$MBE = \frac{Q_{s,av} - Q_{o,av}}{Q_{o,av}} \tag{7}$$

$$PE = \frac{Q_{sp} - Q_{op}}{Q_{op}} \tag{8}$$

where $Q_{s,av}$, Q_{sp} and Q_{op} represent the average of simulated, peak of the simulated and peak of the observed discharge values, respectively.

In this study, the hydrologic parameters of the flood event occurred during 16 October – 06 November 2013 were calibrated using semi-distributed hydrologic model, HEC-HMS. Calibrated hydrologic parameters were validated using daily precipitation-runoff data for another flood event occurred in 17 June – 02 July 2002 (Table 1).

Table 1. Flood event characteristics for both calibration and validation processes

Flood duration	Q_p *(m^3/s)*	*Flood volume (10^3 m^3)*
17.06-02.07.2002	68.40	15903.65
16.10-06.11.2013	152.00	24947.14

5. Hydrologic Model Results

The initial and the calibrated values of the hydrologic parameters are presented in Table 2.

Table 2. Initial and calibrated values of hydrologic parameters

Hydrologic parameters	*Initial values*	*Calibrated values*
T_c *(hr)*	4.10	4.41
S_c *(hr)*	4.10	3.13
k (1/hr)	0.80	1.00
Q_{ts} *(m^3/s)*	1.16	3.63

The calibration of hydrologic parameters was performed for the period of 16 October – 06 November 2013, while the validation of hydrologic parameters was performed for 17 June – 02 July 2002. The calibrated and validated hydrographs are presented in Fig. 2. and the SI for both the calibration and the validation are presented in Table 3.

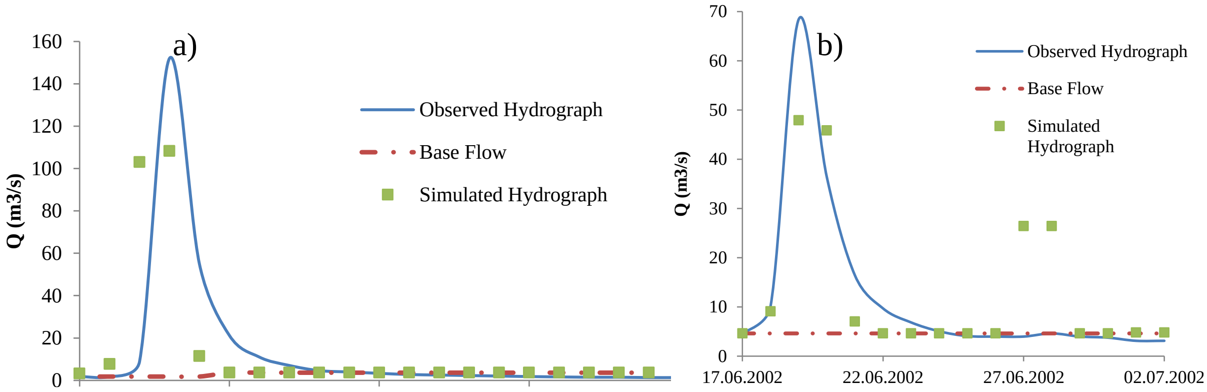

Fig. 2. Calibrated and validated flood hydrographs

Table 3. SI for both calibration and validation

Flood duration	E_{NS}	R^2	*MBE (%)*	*PE (%)*
16.10-06.11.2013	0.76	0.63	1.3	-28.7
17.06-02.07.2002	0.64	0.65	11.3	-29.9

It can be seen from the model outputs that calibrated hydrograph gave better results than validated hydrograph. While E_{NS} value for calibration can be accepted as very good, it can be evaluated as satisfactory for the validated hydrograph [16]. In both cases, the hydrograph is over estimated while the peak discharge is under estimated. Furthermore, the hydrograph estimation for calibration is closer to zero than for that of validation. All calibrated and validated hydrograph estimations are found to be in acceptable range. However, it should be noted that the model failed to reproduce the second peak discharge in the validated hydrograph. This anomaly can be explained by an error in the discharge data where the discharge reading might have been performed before the rain started. If the data discharge had been read after the precipitation, the model results would have been improved. As a result, *MBE* value would have been decreased and the E_{NS} and R^2 values would have been improved better.

6. Conclusions

In this study, the hydrologic parameters of Kocanaz watershed, a small basin in Western Black Sea Region, were estimated using a semi-distributed hydrologic model, HEC-HMS. The watershed was modelled as a single basin without dividing into sub basins. The hydrologic parameters of the model was calibrated by data of a flood event occurred in 2013 and then those calibrated parameters were validated by another flood event occurred in 2002. It is found out from model outputs that all calibrated and validated hydrograph estimations were in acceptable range.

Previous studies have shown that results obtained by modeling the whole basin as a single unit without dividing into sub basins gave improved results than using sub basins when they were evaluated according to the SI [3]. Increasing the number of sub basins would have a limited effect on peak flow, thereby resulting in some improvement in *PE* value. On the other hand, the disadvantage of increasing the number of sub basins is to calibrate more hydrologic parameters. Thus, determination of a large number of parameters would increase the uncertainty of the parameters determined by the model.

In this study, base flow values were determined by using the recession method. During calibration, the base flow values were kept constant while for validation process, they had two constant values forming one step. It is thought that the base flow increases with the change in flow in the rising limb of the hydrograph and possible errors arising from this increase are also affected in the results.

Acknowledgments

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Notations

c	Proportionality constant
CN	Curve number
DSI	State Water Works
E_{NS}	Nash-Sutcliffe efficiency coefficient
HEC-HMS	Hydrologic Engineering Center-Hydrologic Modelling System
hr	Hour
IMD	Indian Meteorological Department
k	Recession constant
L	Main channel length

LBRM	Large Basin Runoff Model
MBE	Mass balance error
MUSIC	Model for Urban Stormwater Improvement Conceptualization
PE	Peak flow rate error
PWRMSE	Peak-weighted root mean square error
Q_0	Initial discharge
Q_b	Base flow
Q_{obs}	Observed discharge
$Q_{obs,av}$	Average od observed discharge
Q_{op}	Peak of observed discharge
$Q_{s,av}$	Average of simulated discharge
Q_{sim}	Simulated discharge
Q_{sp}	Peak of simulated discharge
Q_{ts}	Threshold discharge
R^2	Coefficient of determination
S	Basin average slope
S_c	Storage coefficient
SI	Statistical indicators
SCS	Soil Conservation Service
SWAT	Soil Water Assessment Toll
SWMM	Storm Water Management Model
T_c	Time of concentration
USA	United States of America

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