Environ Earth Sci (2015) 74:3629–3643
DOI 10.1007/s12665-015-4426-3

ORIGINAL ARTICLE

Changeability of simulated hydrograph from a steep watershed resulted from applying Clark's IUH and different time–area histograms

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Received: 12 April 2014 / Accepted: 15 April 2015 / Published online: 29 April 2015

Abstract Reflecting the shape and drainage characteristics of the watershed, time–area histogram (TAH) seems to be the most important parameter for derivation of the transformation hydrograph. In this study, a semi-distributed instantaneous unit hydrograph was established and applied to the steep 103 km^2-Galazchai watershed in Iran to improve the results of the rainfall–runoff modelling. Towards this attempt, twenty-three runoff producing events with wide different characteristics were used for the analysis. The direct surface runoff hydrographs (DSRHs) were obtained and consequently compared for the study area using Clark's instantaneous unit hydrograph (IUH) and through applying different TAHs calculated based on channel profile, dimensionless TAH, average velocity and spatially distributed travel time methods. A weight grid developed from kinematic wave travel time equation for overland flow was prepared and used as input to derive the spatial TAH of the watershed. The results indicated that the different TAHs had noticeable impacts on the estimated hydrographs. The results also proved that the spatial TAH method performed well with efficiency criteria of 0.75 and 0.69 in calibration and validation steps. The implemented method also offered the advantages of flexibility, efficiency and physically powerful links to the spatial data set and GIS software.

Keywords Hydrological modelling · Time–area histogram · Isochrones · Rainfall–runoff transformation · Spatially distributed unit hydrograph · Travel time

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Introduction

The time–area rainfall–runoff transformation method is widely known as a hydrologic watershed routing technique to derive the discharge hydrograph due to a given excess rainfall hyetograph (Ponce 1994). Time–area method has the potential to perform as a distributed model by incorporating non-uniform excess rainfall and spatially variable watershed characteristics (Saghafian et al. 2000). The basic idea of the time–area method is a time contour or an isochrone. Splitting the watershed into zones depending on the time needed for water to flow to the watershed outlet was the idea of the time–area method (Nash 1957; Dooge 1959; Singh 1988; Matei 2012; Odeh et al. 2015). The time–area diagram indicates the distribution of travel time of different parts of the watershed drains to the outlet (Singh 1988). The TAH is really a translation hydrograph because the volume of water on each area within the basin is simply translated to the outlet using the calculated travel time for the translation time.

An isochrone is a contour joining those grid cells in the watershed which are separated from the outlet by the same travel time (Maidment 1993; Sadeghi and Asadi 2010). If the quantity of runoff produced in each of these intervals can be calculated, the runoff hydrograph can be then obtained by integrating the runoff from each of these intervals in the outlet according to flow time (Rodriguez-Iturbe and Valdes 1979; Matei 2012; Bertrand et al. 2014). Different methods are available in the literature to development of TAH (e.g. Singh 1988; Usul and Yilmaz 2002; Ahmad et al. 2009). The produced runoff of each area in TAH reaches the outlet at the travel time associated with that area. The time–area histogram is convolved using an event hyetograph, and the resulting convolution integral is the direct storm runoff hydrograph. Figure 1 is a sketch illustrating these relations.

A concept of the instantaneous unit hydrograph has been accordingly revealed by Clark (1945). The Clark's unit hydrograph (Clark 1945) is based on time–area concept in which watershed storage effects are also taken into account (Saghafian et al. 2002). The Clark's UH is a very valuable analytic technique in flood hydrology, since the hydrographs' shape and peak discharge are supposed as a function of watershed characteristics, time–area histogram, time of concentration and watershed storage characteristics—storage which can be entirely calculated for the watershed with lack of hydrologic stations (Ahmad et al. 2009; Sadeghi and Asadi 2010; Rivard et al. 2014). The time–area (TA) technique is very close to distributed modelling in the sense that it is able to consider the differences in the arrival times of the sub-catchments at the system outlet (Gad 2013).

Thus, the contributions of the individual areas can be illustrated with a histogram that can be used to understanding the spatiotemporal behaviour of simulated flood events.

A flow simulation process, accounting for both translation and storage effects in grid cells, was presented by Maidment et al. (1996), where watershed response was predicted as the sum of the responses of individual sub-watersheds. The rainfall intensity in travel time calculations based on a spatially varied Manning's formula was implemented by Chiang et al.(2004) that relates the discharge at a grid point to the flow accumulation value (i.e. the number of accumulating upstream cells). Sarangi et al. (2006) compared performance of a deterministic, an inverse distance weighting, and ordinary Kriging method for mapping the surface elevation and runoff travel time of the St. Esprit watershed, Canada. They found that the performance of geostatistical interpolation methods in prediction is better than the deterministic methods. A storm runoff prediction model based on spatially distributed travel time was proposed by Melesse and Graham (2004). Applicability of IUH model based on Clark's time–area model in an Iranian large watershed has also been successfully proved by Sadeghi and Dehghani (2006). The Clark's method has also been adapted in GIS environment by different researchers (Sarangi et al. 2007; Seong et al. 2008; Ahmad et al. 2009; Gibbs et al. 2009; Seong and Lee 2011). A similar concept of the Clark's IUH model has been used in different runoff modelling frameworks (Ammukutty and Nair 2009; Ghavidelfar et al. 2011; Her 2011; Matei 2012). Performance of several techniques for estimating storm-water runoff has been assessed by Hadadin (2013) in arid watersheds located in south-eastern desert of Jordan. According to the results, there is uncertainty in defining the accuracy of storm-water volume, that can be attributed to several methods were utilizing the estimation the time-related components of hydrographs. Lee et al. (2013) applied a spatially distributed hydrologic model of rainfall–runoff-sediment yield simulation for flood events and erosion at a catchment scale in Korea. Measured versus predicted values of runoff and sediment discharge were in good agreement. A GIS-based automated semi-distributed time–area model (SDISTA) has been developed by Gad (2013) as a useful tools for engineering applications in semi-arid regions of Egypt. The result of the study showed that, the most attractive feature of SDISTA is its ability to automatically delineate and simulate any number of

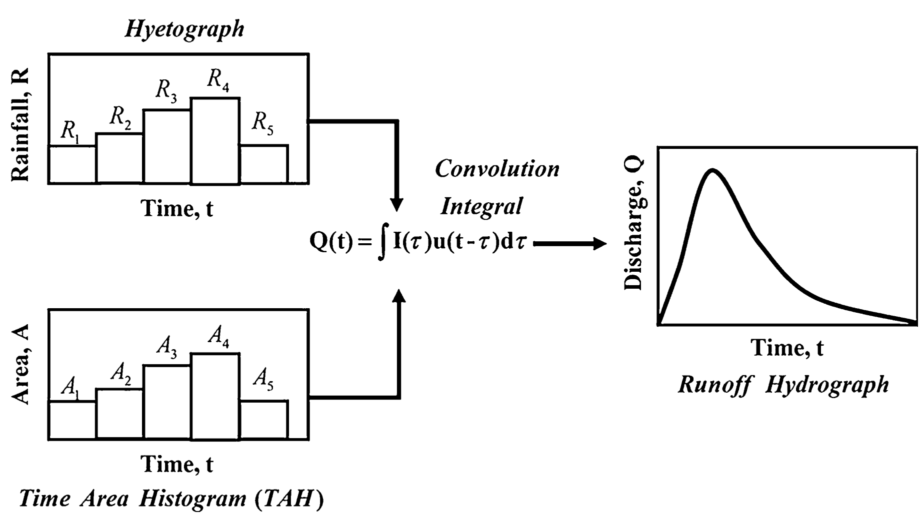

Fig. 1 Time–area–convolution to produce a runoff hydrograph (Modified from Fang et al. 2005)

catchment areas simultaneously on digital elevation models. It is understood from the concept of the Clark's IUH method and reviewing the literatures that the Clark's IUH method integrates several factors that influence runoff within a certain area with the least accessible input data. It is also implied from the literatures that the results of the Clark's IUH model are subject to the accuracy of the time–area histogram, there is no comprehensive study which reported the effects of different TAHs on accuracy of simulated hydrograph. Therefore, the present research has been conducted to explore the effects of different TAHs on the storm hydrographs simulation in Galazchai steep small watershed in West Azarbaijan, Iran. The study area has been chosen owing to data accessibility and reliability and fast hydrologic response. The study, therefore, aimed to assess the performance of different TAHs development approaches for simulating IUH and consequent storm flood hydrographs in the study area. Also, the different methods were chosen due to different natures of the methods used in the extraction of TAHs and representation of resulted hydrologic response in the study area.

Materials and methods

Study watershed

The Galazchai watershed is located in the western part of the West Azarbaijan Province, Iran. It has an area of about 103 km^2 and lies between 44°56′ and 45°35′E longitudes, and 37°01′ and 37°09′N latitudes (Fig. 2). The length of the main stream is some 19.3 km, and the average watershed slope is approximately 32 %. The altitude of the study area ranges from 1480 to 3300 m above mean sea level. The study area is mountainous and has a homogeneous climatic regime. The area is steep and prone to soil erosion and high flooding. Average annual precipitation from 1981 to 2010 is 482 mm, at Oshnavieh meteorological station, which is located adjacent to the watershed in the immediate downstream of the main outlet (Ab Banan-Azardasht Engineering Consulting Inc. 2010). Annual average temperature is 11.8 °C. According to the De-Martonne and Emberger classifications, dry arid and dry semi-arid climatic classes can be attributed to the climatic condition of the study area, respectively (Ab Banan-Azardasht Engineering Consulting Inc. 2010). Rangelands (85 %), forest (7 %), rainfed farming (5 %), irrigated farming (3 %) exist in the watershed. To conduct the study, the available rainfall data events were taken from the Oshnavieh recording rain gauge station (Fig. 2). The corresponding discharge data events recorded at the Galazchai River gauge station in the outlet of the watershed (Fig. 2) was used for modelling purposes.

Data analysis

Physical properties (watershed delineation, slope, stream lengths and drainage areas) of the watershed were derived from the 20 m digital elevation model (DEM) of the

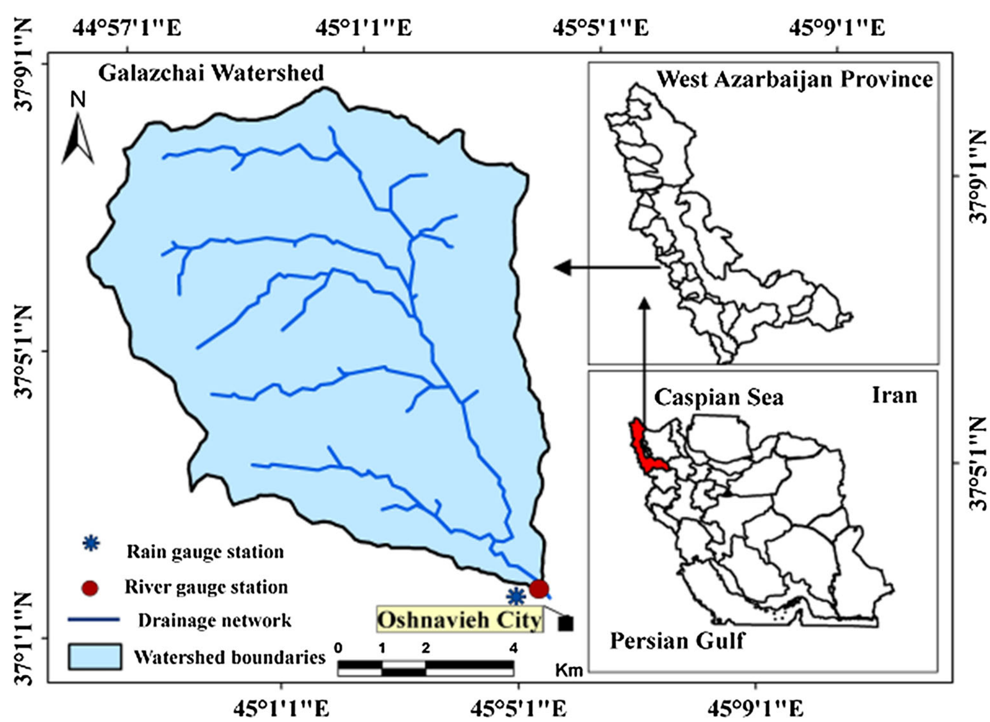

Fig. 2 A general view and location of the study area in West Azarbaijan Province and Iran

Table 1 Characteristics of rainfall storm events and corresponding hydrographs

No.	Variable date	Rainfall duration (h)	Total rainfall (mm)	Phi-index (mmh^{-1})	Average intensity (mmh^{-1})	Peak flow (m^3s^{-1})	Time to peak (h)
1	6 April 2003	5.0	6.3	0.8	1.1	19.5	6.5
2	9 December 2003	6.5	9.2	1.1	1.2	9.2	5.5
3	23 April 2004	5.0	5.1	0.2	0.8	16.5	7.5
4	29 May 2004	7.0	18.8	0.4	2.5	31.2	16.0
5	14 April 2005	3.0	4.6	0.2	1.3	10.5	9.0
6	17 December 2007	7.5	8.6	0.9	1.0	2.4	11.0
7	14 April 2008	6.0	9.1	0.9	1.4	9.8	8.0
8	23 April 2008	6.0	11.3	0.6	1.7	12.4	8.0
9	29 May 2008	5.0	13.6	0.1	2.5	30.3	8.0
10	1 October 2008	6.0	12.4	2.0	1.9	5.7	8.0
11	25 October 2008	14.0	33.1	4.0	2.3	7.1	6.0
12	10 March 2009	6.5	12.9	4.1	1.8	2.6	8.5
13	14 March 2009	4.5	3.9	0.5	0.8	2.8	11.5
14	17 May 2009	4.0	5.1	0.9	0.9	5.3	9.0
15	22 September 2009	3.0	3.2	0.2	0.9	9.6	9.0
16	21 April 2011	8.0	6.3	0.6	0.7	2.7	15.0
17	23 April 2011	10.0	8.0	0.4	0.8	6.6	8.0
18	29 October 2011	5.0	9.3	2.9	1.7	1.4	12.0
19	30 October 2011	8.5	9.4	0.6	0.9	9.6	11.0
20	4 November 2011	3.0	2.4	0.5	0.5	2.0	8.0
21	5 November 2011	8.0	13.2	3.1	1.6	1.5	8.0
22	11 April 2012	4.0	8.6	1.8	1.9	1.7	10.0
23	20 April 2012	3.0	4.6	1.1	1.3	1.2	6.5
Maximum		14.0	33.1	4.1	2.5	31.2	16.0
Minimum		3.0	2.4	0.1	0.5	1.2	5.5
Mean		6.0	9.5	1.2	1.4	8.8	9.1
CV (%)		43.1	68.2	98.7	42.9	97.4	28.8
Skewness		1.3	2.3	1.4	0.5	1.6	1.2
Kurtosis		2.8	7.4	1.0	-0.7	2.3	1.4

watershed in Arc GIS software environment (Dongquan et al. 2009; Sreedevi et al. 2012). The runoff producing rainfall events of varying intensities from 0.4 to 2.3 mm h^{-1} and durations from 3 to 14 h were used for the analyses, representing the most possible variations of intensities and durations. Twenty-three rainfall–runoff events were selected according to the available recorded dataset, based on the following criteria: (a) a runoff producing event with a minimum rainfall height 2 mm, (b) a minimum rainfall duration of 3 h, (c) the snowmelt contributed runoff events were excluded, (d) the consecutive rainfall events with 5-h dry periods were separated. Characteristics of the observed rainfall–runoff events have been shown in Table 1.

The direct runoff hydrograph (DRH) was separated from the base flow by the fixed base method (Chow et al. 1988; Kilgore 1997; Agirre et al. 2005; Liu et al. 2013; Ghasemizade and Schirmer 2013). The phi-index equals the total volume of storm period loss distributed uniformly across the storm's hydrograph. This method is very simple and straightforward in that the phi-index is matched up so that the amount of direct runoff from the hydrograph is equal to the amount of excess precipitation (McCuen 1989), According to Chow (1964), the best use of the phi-index is for runoff prediction due to major flood-producing storms. Thus, the excess rainfall was then determined using Phi-index method (Linsley et al. 1940; Sadeghi and Asadi 2010). The total runoff volume for each storm event was determined by integrating the direct runoff hydrograph. Once the volume of rainfall excess was determined, the corresponding Phi-index line was calculated for each storm and applied to the rainfall pattern (Das 2000; Subramanya 2000).

Model development

The storage attenuation coefficient, which represents the storage characteristic of stream channel, was calculated from recession part of observed flood hydrographs of the watershed (Eq. 1) (Subramanya 2000). As originally proposed by Clark (1945), the K parameter can be estimated by dividing the discharge at the point of inflection of the surface runoff hydrograph by the rate of change of discharge (slope of the hydrograph) at the inflection point. Although this procedure is simple, it requires an observed hydrograph with well-defined point of inflection which is usually not the case. The identification of inflection point on the recession limb of the observed hydrographs is an approximate procedure (Ahmad et al. 2009).

$$K = \frac{-Q}{dQ/dt} \tag{1}$$

To apply Clark's IUH model, the TAHs were developed based on Channel Profile (Linsley et al. 1940; Singh 1988; Bhawan 1998; Subramanya 2000; Mostafazadeh et al. 2009; Sadeghi and Asadi 2010), dimensionless TAH (Mostafazadeh and Sadeghi 2012), average velocity (SCS 1972; Singh 1988), spatially distributed travel time method (Maidment et al. 1996; Kilgore 1997; Hunukumbura et al. 2007; Karymbalis et al. 2011) for the study watershed and with the help of DEM data with 20 m grid digital map.

Channel profile method

In order to calculate time of concentration (Tc) and thus extracting TAH, the travel time from the most remote point on the hydrologic boundary of the watershed was required. The Kirpich equation has been used by various researchers for development of time area diagram (Jain et al. 2000; Kumar et al. 2002; Sahoo et al. 2006; Sarangi et al. 2007; Ahmad et al. 2009). Since the average slope of the total stream length was up to 10 %, we found that Kirpich equation was able to adequately describe the flow process in the study catchment. Also reasonably good agreements between observed Tc (from observed rainfall-runoff events) and calculated Tc values confirm the validity of the Kirpich formula in the current study. The Tc for the study area was computed using Kirpich formula (Eq. 2) and sub-areas for each hour of travel times were drawn to get isochronal areas (Kirpich 1940; Sadeghi and Dehghani 2006), with time interval of 15 minutes leading to enough numbers of isochrones.

$$Tc = 0.06628L^{0.77}S^{-0.385} \tag{2}$$

where Tc is time of concentration in hours, L is length of stream in km and S is representative slope. Isochrones were then constructed on the watershed map by plotting profile of the major tributaries and contour lines on the topographic map at spacing equal to the selected time interval. The isochrones were finally drawn by joining the points of intersections having the same time of interval and TAH was extracted using computed area between the isochrones.

Dimensionless TAH method

Considering large number of uniformly distributed points over the watershed, the distances from adjacent contours along the flow path were measured. The length and the slope of any reach were calculated and the corresponding travel time for any reach was approximately calculated as proportional to summation of $L/S^{1/2}$ (Singh 1988). Travel time of unity for the extreme upstream portion of the watershed was calculated according to the above procedure and the relative travel time for selected reach was assigned based on proportional summation of their length and the slope. Isochrones were then constructed on the watershed map by plotting length of the reaches along the flow path at spacing equal to the selected time interval. The base length of time–area diagram is the calculated travel time based on the extreme upstream portion of the watershed. Finally the drainage area within the isochrones corresponding to the selected time interval was determined using the ArcGIS 9.3 and was cumulated to generate the cumulative time–area histogram.

Average velocity method

Large numbers of points along the elevation contours were marked and the distances from the contributing channels were calculated. The corresponding average flow velocity by the SCS method and travel time was computed using divided distance by the velocity (Singh 1988). Construction of isochrones and TAH was the same as explained for previous methods.

Spatially distributed travel time method

The kinematic wave travel time equation, developed by Welle and Woodward (1986), was used to compute travel time for overland flow according to Eq. (3). (Overton and Meadows 1976; NRCS 2010; Froehlich 2011).

$$\mathrm{Tt} = \frac{\mathrm{Kc}}{I^{0.4}}\left(\frac{n\,L}{\sqrt{S}}\right)^{0.6} \tag{3}$$

where Tt is sheet flow travel time (min), Kc is a coefficient for unit conversion, equal to 6.943, n is roughness coefficient, L represents flow length (m), I is rainfall intensity (mmh^{-1}) with 2-years return period and 24-h rainfall duration and S is surface slope (mm^{-1}). The slope (SlGrid) and the flow direction (FldrGrid) were prepared using the DEM (Youssef et al. 2011). The land use data provided were derived from a vegetation map originally produced by the West Azarbaijan Province Major Office of Natural Resources, Iran, and has been improved by field survey. The spatially distributed travel time method uses Manning's roughness coefficient to calculate travel time. Thus, the Manning's n Grid was also prepared using the land use raster grid for the watershed (LuGrid) and the modified roughness coefficient table suggested by Engman (1986) and Chow et al. (1988). Then, according to the cell size of the raster data set, travel time and flow velocity of each grid cell was calculated using raster GIS. ArcMap 9.3 version and ArcHydro tools have been used to processing of the terrain layers. Finally, the inverse velocity grid and flow direction grids were used as a weight grid to compute flow length grid of the study watershed (Usul and Yilmaz 2002; Hunukumbura et al. 2007). The travel time grid of the watershed was then determined by multiplying watershed time of concentration and dividing by the maximum of the cell travel lengths (Kull and Feldman 1998).

The IUH of the study area was ultimately simulated by Clark's IUH model. Each simulated hydrograph was obtained from the application of the temporal distribution of excess rainfall to the time–area histogram. The final simulated hydrograph was calculated according to the superposition principle from the horizontal sum of the ordinates of the incremental flood hydrographs developed for each excess rainfall time interval. Runoff hydrograph prediction was done for 23 rainfall events. Sixteen randomly selected rainfall–runoff events were used for calibration of storage attenuation coefficient parameters of the Clark model. Many tests were conducted with various combinations of the parameter values to get simulated hydrographs as close as possible to the observed hydrographs. The model was then validated using the other seven rainfall–runoff events.

Model evaluation

The overall similarity between the observed and generated direct runoff hydrographs was visually assessed. Whereas the relative error (RE) was applied as an quantitative indicator of the model performance in predicting observed hydrographs properties such as peak flow, total runoff volume, time to peak and base time using Eq. (4) (Sadeghi and Singh 2005; Singh et al. 2007). The predicted hydrograph at both calibration and validation steps were plotted together with the observed flow for comparison. The performance of the Clark's time–area model was further evaluated in simulating observed hydrographs using coefficient of efficiency (CE), determination coefficient (R^2) and root mean squared error (RMSE) as shown in Eqs. (5)–(7) (ASCE 1993; Legates and McCabe 1999; Bardossy 2007; Moriasi et al. 2007; Sadeghi et al. 2009).

$$\mathrm{RE}\,(\%) = 100 \times \left|(\mathrm{Obs}_{\mathrm{value}} - \mathrm{Sim}_{\mathrm{value}})/(\mathrm{Obs}_{\mathrm{value}})\right| \tag{4}$$

$$\mathrm{CE} = 1 - \frac{\sum_{t=1}^{n}\left(Q_{\mathrm{Obs}(i)} - Q_{\mathrm{Sim}(i)}\right)^2}{\sum_{t=1}^{n}\left(Q_{\mathrm{Obs}(i)} - \overline{Q}_{\mathrm{Obs}}\right)^2} \tag{5}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(Q_{\mathrm{Sim}(i)} - \overline{Q_{\mathrm{Obs}}}\right)^2}{\sum_{i=1}^{n}\left(Q_{\mathrm{Obs}(i)} - \overline{Q_{\mathrm{Obs}}}\right)^2} \tag{6}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{t=1}^{n}\left(Q_{\mathrm{Sim}(i)} - Q_{\mathrm{Obs}(i)}\right)^2} \tag{7}$$

where $Q_{\mathrm{Obs}(i)}$, $Q_{\mathrm{Sim}(i)}$, $\overline{Q}_{\mathrm{Obs}}$ are observed, simulated and mean of the observed discharges at time i in m^{3}s^{-1} and n is the time horizon of the hydrographs, respectively. The model with higher CE and R^2, and smaller other criteria was supposed as the best performed model.

Results and discussion

The present study was conducted to assess the performance of Clark's IUH resulted from four different TAHs in the Galazchai small steep rangeland watershed in West Azarbaijan, Iran. To achieve the research purpose, isochrone maps were classified and intervals of 0.25 h were selected and the corresponding TAHs were developed for the study area and have been, respectively, shown in Fig. 3.

It is obvious that the major differences between TAHs in Fig. 3 include the distribution pattern of the isochrone areas. The further upstream areas away from the outlet have been allocated in more than 2 h time of concentration (Fig. 3a). The TAHs have a uniform distribution shape in the Fig. 3b. According to the shape of the study area, the presented TAHs in c and d parts have a better match with the pattern of the isochrone map of the study watershed; this distinction has been shown in the Fig. 4.

The results of comparison of cumulative area distribution for different time intervals and methods have been shown in Fig. 4. The pictorial comparison of the best and the worst performance hydrographs from different methods for the study storm events and at calibration stage has been made in Fig. 5 and the corresponding detailed results for the entire storm events and also statistical evaluations have been, respectively summarized in Tables 2 and 3.

As it is obvious in the observed and simulated hydrographs (Fig. 6), developed on TAH based on spatially distributed travel time method demonstrates slightly better performance in the estimation of the flow hydrograph.

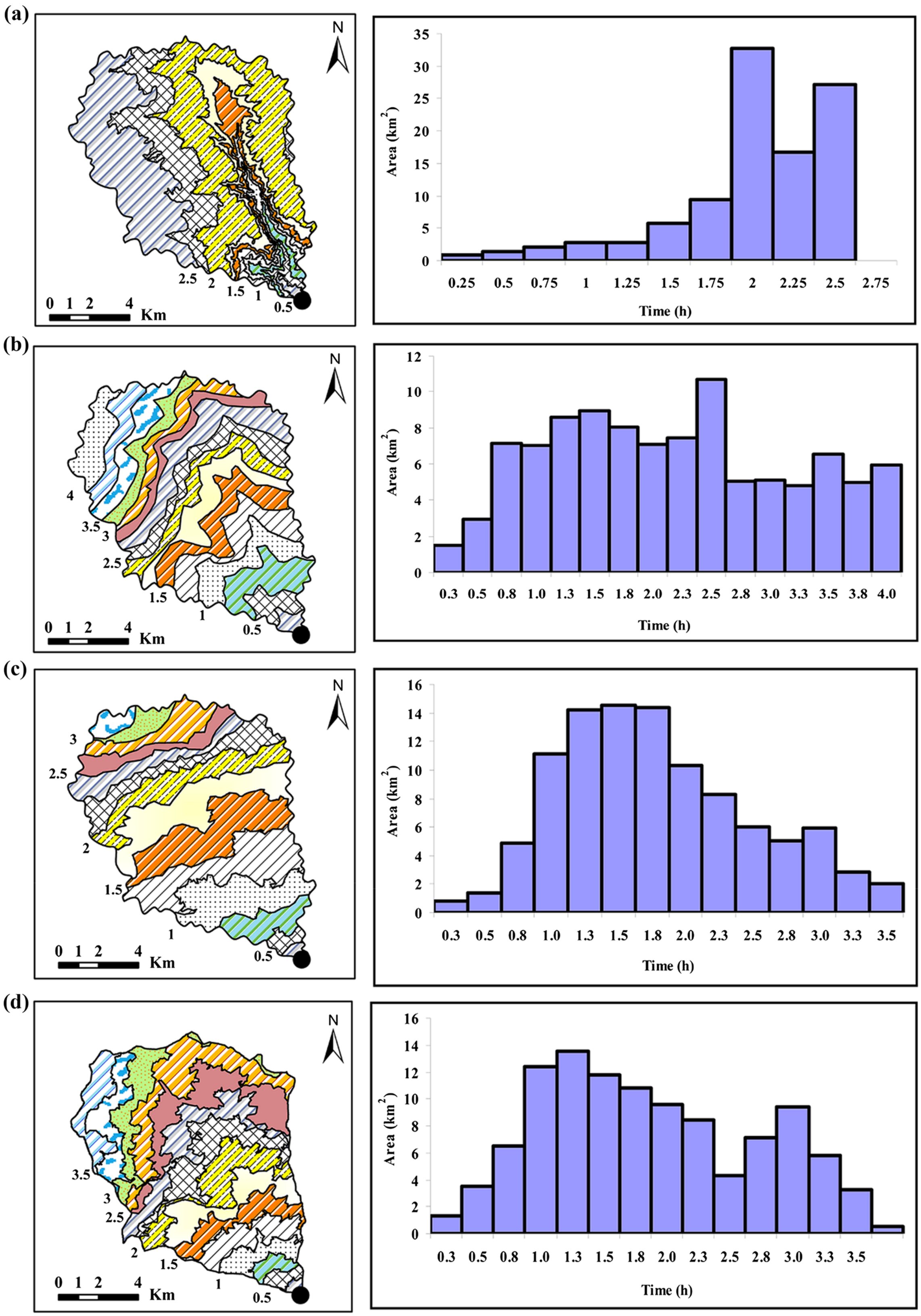

Fig. 3 Isochrones maps with 0.25 h intervals (*left*) and corresponding TAHs (*right*) of the Galazchai watershed resulted from applying linear profile (**a**), dimensionless TAH (**b**), average velocity (**c**) and spatially distributed travel time (**d**) methods

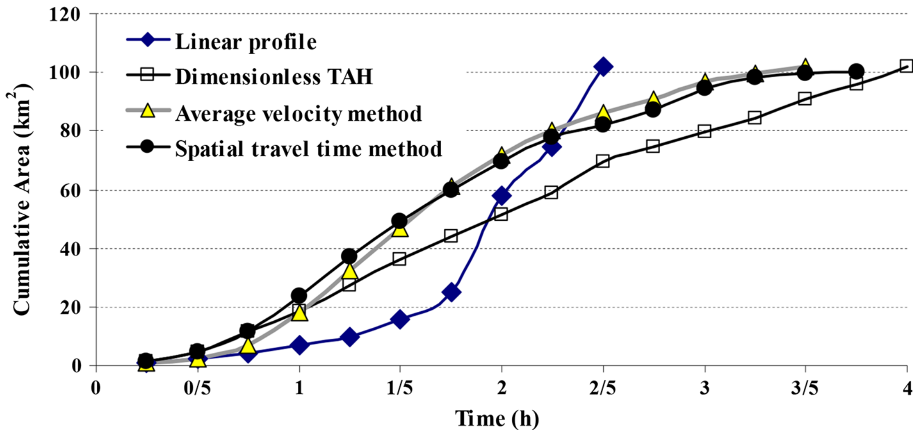

Fig. 4 Distribution of cumulative developed TAHs in different time intervals and methods for the Galazchai watershed, Iran

However, other methods could estimate flow discharge with a bit less accuracy. The error in falling limbs of simulated hydrographs is believed to be due to the reason that the recession limbs after the inflection point do carry indirect surface runoff resulting from recharge from stream banks, as also reported by Ahmad et al. (2009). It means that the simple time–area model has produced reasonable results. The accuracy of the Clark's IUH model has also been proved by Hunukumbura et al. (2007), Ahmad et al. (2009), Abid et al. (2010) and Sadeghi and Asadi (2010). Although the implemented model was applied to a watershed having observed rainfall and flow data, it can be used for ungauged watersheds by simulating hypothetical storms and analysing survey of flow variations at the outlet.

According to the simulation results (Table 2), the peak discharge, time to peak and time base of the observed and computed hydrographs match each other well enough, however, the falling limb of hydrograph is underestimated. It was verified that the Clark's time–area model poorly estimates the falling limb of the hydrographs as also mentioned by Kilgore (1997).

Relative error in estimation of time to peak in all models was the same and acceptable. The RMSE error was around 1.2–1.5 and the determination coefficient varied from 0.68 to 0.76. The RE in flow volume was lower than the RE in peak flow and time to peak. The results showed that the spatially distributed travel time method performed well with mean efficiency criteria of 0.75 and 0.69 in calibration and validation stages, respectively, and also had less RMSE among the other methods. The accuracy in the development of isochrones representing the spatial variability of surface water travel time over watersheds leads to an appropriate estimation of the direct runoff hydrograph (Sarangi et al. 2006).

The steep slope of the study watershed leads to distinguish the variations in the simulated hydrographs resulting from application of different approaches. According to the results, the four extracted TAHs form-employed methods represent different hydrologic response in the study area. It can be concluded that different set of input parameters influence the isochrone pattern and also leads to different level of accuracy in the simulated hydrographs. According to the results, the lower precision was obtained from the method which used dimensionless TAH and the most precise method was that which used spatially distributed travel time method for deriving the TAH. The amount of coefficient of efficiency varies from 0.41 to 0.93 for sixteen calibration events and average value of this criterion was 0.75, showing adequate model efficiency which is acceptable as unit hydrograph technique inherent itself with assumptions and approximations (Ahmad et al. 2009). Based on calibration and validation results, the simulated hydrographs resulted from all developed TAH models are in an acceptable range, that are in agreement with finding of Usul and Yilmaz (2002), Ammukutty and Nair (2009), Her (2011) and Matei (2012). The RMSE ranges from 0.24 to 5.1. The results indicated that, based on the most appropriate model for deriving TAH (spatially distributed travel time method), hydrograph times to peak were observed to be underestimated by 29.69 and 42.90 % in calibration and validation periods (Table 3). There was 1–5.8 % error in runoff volume computed from direct simulated hydrographs developed from Clark's time–area model showing that transformation model can define the response of the watershed if the input parameters of the model are estimated in a proper manner (Ahmad et al. 2009). The numerical values of the used criteria show that the results of the model based on spatially distributed travel time method for extracting TAH are able to provide good fits to the observed hydrographs at the Galazchai station. It can be attributed to considering the effects of land use on the generated runoff in the spatially distributed travel time method. This finding is similar to that found out by Melesse and Graham (2004). Similar results have also been reported by Kute and Stuart (2008). In this method, the resistance effect of Manning's roughness coefficient on the flow can be taken into account by isochrone mapping.

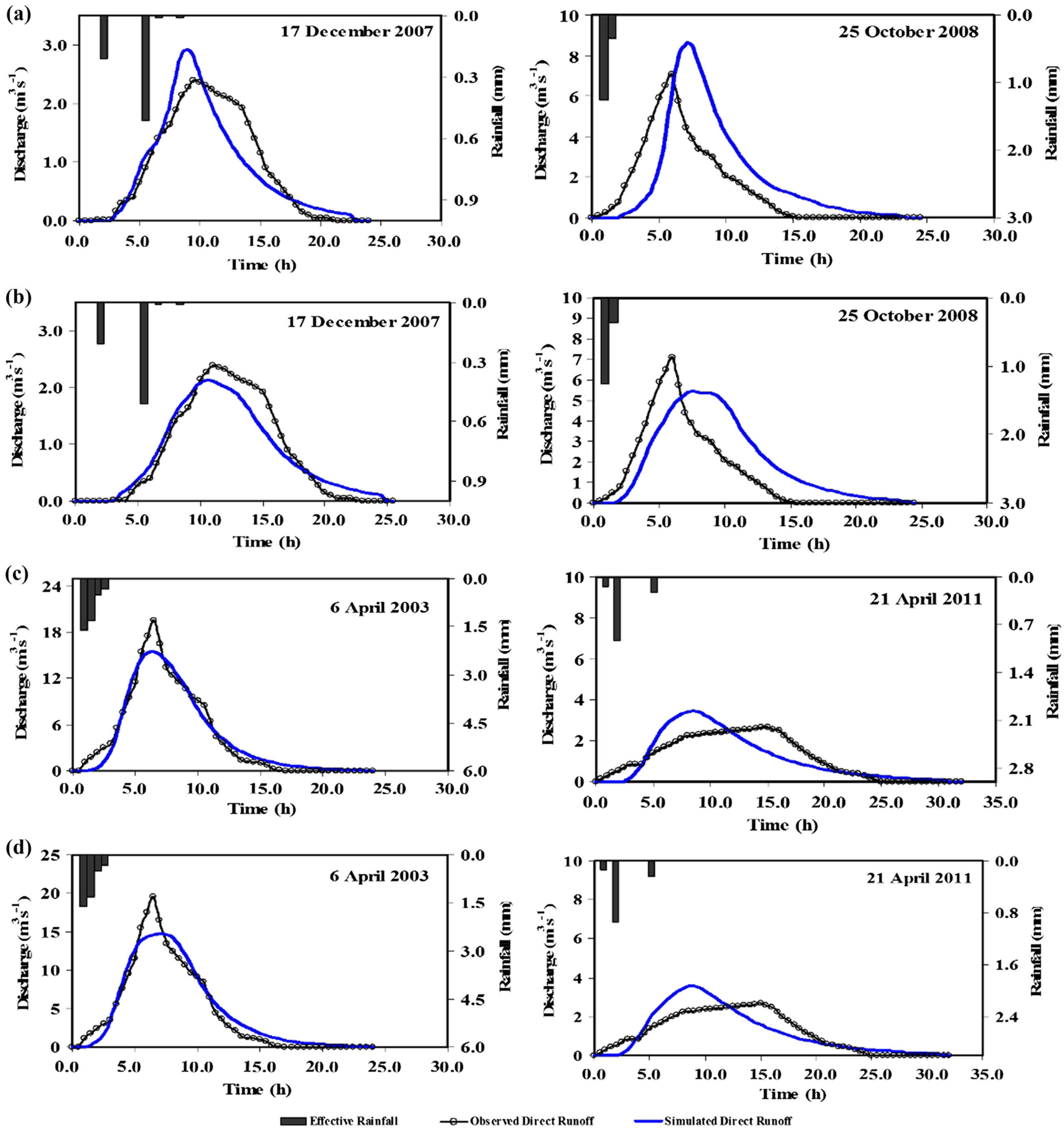

Fig. 5 Results of the best (*left*) and the worst (*right*) simulated storm events hydrographs resulted from different TAHs methods: linear profile (**a**), dimensionless TAH method (**b**), average velocity (**c**) and spatially distributed travel time (**d**) methods for the Galazchai watershed, Iran

Conclusions

Different TAHs were developed for simulating hydrologic response of the Galazchai small steep watershed in Iran. Considering arrangement of TAH sub-areas, the case where isochrones near the outlet are closer together gave the better result. The different TAHs had noticeable impacts on the estimated hydrographs. Based on the shape of the study area, the extracted TAH from SDUH method have a better match with the pattern of the isochrone map of the study watershed. The results reveal that the simulated hydrographs based on all developed TAH models are in an acceptable range, although spatially distributed travel time method performed slightly better due to

Table 2 Details of simulated hydrographs resulted from applying different TAHs and the Clark's time–area model in Galazcahi Watershed, Iran

No.	Stage	Variable date	Observed				Simulated															
			Qp	Qv	Tp	Tb	Qp				Qv				Tp				Tb			
							LP	DL	AV	SDTT	LP	DL	AV	SDTT	LP	DL	AV	SDTT	LP	DL	AV	SDTT
1	Calibration	2003 April 6	19.5	0.39	6.5	16.0	19.6	12.5	15.5	14.7	0.38	0.38	0.38	0.41	5.5	5.5	5.5	5.5	22.5	23.0	22.0	22.5
2		2003 December 9	9.2	0.14	5.5	14.5	9.2	5.4	7.1	6.5	0.14	0.14	0.14	0.15	4.5	4.5	4.5	4.5	13.5	15.0	13.5	14.0
3		2004 April 23	16.5	0.31	7.5	15.0	14.2	9.9	12.0	11.7	0.31	0.31	0.31	0.33	6.0	6.0	6.0	6.0	22.0	23.0	22.0	22.5
4		2004 May 29	31.2	1.44	16.0	26.5	38.9	32.7	35.6	36.4	1.42	1.42	1.42	1.50	9.5	9.5	9.5	9.5	42.0	43.0	42.0	42.5
5		2005 April 14	10.5	0.36	9.0	20.5	12.8	9.3	10.7	10.7	0.35	0.35	0.35	0.37	5.5	6.0	5.5	6.0	31.0	32.5	31.0	32.0
6		2007 December 17	2.4	0.08	11.0	21.0	2.9	2.1	2.5	2.4	0.07	0.07	0.07	0.08	5.5	6.5	6.0	6.5	20.0	21.5	20.0	21.0
7		2008 April 14	9.8	0.35	8.0	21.5	8.1	7.1	7.6	7.8	0.34	0.34	0.34	0.36	8.0	8.5	8.0	8.5	39.5	40.5	39.0	40.0
8		2008 April 23	12.4	0.46	8.0	21.5	14.6	11.3	12.7	12.9	0.45	0.45	0.45	0.48	6.5	7.0	7.0	7.0	34.5	35.5	34.5	35.0
9		2008 May 29	30.3	1.28	8.0	29.0	32.3	26.5	28.7	29.6	1.26	1.26	1.26	1.33	7.0	7.0	7.0	7.0	45.0	45.0	45.0	45.0
10		2008 October 1	5.7	0.17	8.0	15.5	6.0	4.3	4.9	4.9	0.16	0.16	0.16	0.17	5.0	5.0	5.0	5.0	27.5	28.0	27.0	27.5
11		2008 October 25	7.1	0.13	6.0	15.5	8.6	5.4	6.7	6.4	0.18	0.18	0.18	0.19	4.5	5.0	4.5	5.0	21.0	22.5	21.0	22.0
12		2009 March 10	2.6	0.05	8.5	15.5	2.0	1.3	1.6	1.5	0.04	0.04	0.04	0.05	3.5	4.5	4.0	4.5	16.5	18.0	16.5	17.5
13		2009 March 14	2.8	0.11	11.5	26.0	3.9	2.8	3.3	3.3	0.10	0.10	0.10	0.11	5.0	5.5	5.0	5.5	23.5	25.0	23.5	24.5
14		2009 May 17	5.3	0.12	9.0	17.5	5.5	3.5	4.3	4.2	0.12	0.12	0.12	0.12	4.5	5.0	4.5	5.0	20.5	21.5	20.0	21.0
15		2009 September 22	9.6	0.19	9.0	15.5	7.8	5.8	6.8	6.7	0.18	0.19	0.19	0.20	5.5	6.0	6.0	6.0	21.0	22.5	21.5	22.0
16		2011 April 21	2.7	0.13	15.0	24.5	3.8	3.2	3.4	3.6	0.13	0.13	0.13	0.14	6.0	6.5	6.0	6.5	28.5	29.5	28.0	29.0
17	Validation	2011 April 23	6.6	0.23	8.0	21.5	6.0	5.1	5.5	5.6	0.22	0.22	0.22	0.23	7.5	8.0	8.0	8.0	32.0	33.5	32.5	33.0
18		2011 October 29	1.4	0.03	12.0	14.5	1.6	1.0	1.2	1.2	0.03	0.03	0.03	0.03	3.5	4.0	4.0	4.0	13.5	14.5	13.5	14.0
19		2011 October 30	9.6	0.27	11.0	21.5	9.1	6.2	7.4	7.0	0.22	0.22	0.22	0.23	5.0	5.5	5.5	5.5	20.0	21.5	20.5	21.0
20		2011 November 4	2.0	0.02	8.0	9.5	1.5	0.8	1.1	1.0	0.02	0.02	0.02	0.02	3.0	4.0	3.5	4.0	9.0	11.5	9.5	10.5
21		2011 November 5	1.5	0.04	8.0	15.5	1.8	1.2	1.5	1.4	0.04	0.04	0.04	0.04	4.0	5.0	4.5	5.0	17.0	19.0	17.5	18.5
22		2012 April 11	1.7	0.05	10.0	16.5	2.1	1.4	1.6	1.6	0.05	0.05	0.05	0.05	4.0	5.0	4.5	5.0	17.0	18.5	17.0	18.0
23		2012 April 20	1.2	0.02	6.5	11.5	1.3	0.8	1.0	0.9	0.02	0.02	0.02	0.02	3.0	3.5	3.5	3.5	10.5	12.0	11.0	11.0

Qp is peak flow (m^3s^{-1}), Qv is total volume (m^3), Tp is time to peak (h), Tb is the base time (h), and LP, DL, AV and SDTT, respectively represents linear profile, dimensionless, average velocity, and spatially distributed travel time methods of TAH development

Table 3 Evaluation criteria for the assessment of model performance for calibration and validation steps

No.	Stage	Criteria	Determination coefficient				RE in Qp				RE in Qv			
		Method date	LP	DL	AV	SDTT	LP	DL	AV	SDTT	LP	DL	AV	SDTT
1	Calibration	2003 April 6	0.86	0.83	0.95	0.93	0.7	36.0	20.6	24.7	1.3	1.4	1.4	4.8
2		2003 December 9	0.70	0.68	0.91	0.85	0.2	41.4	22.8	29.3	1.8	1.8	1.8	3.9
3		2004 April 23	0.74	0.60	0.87	0.84	14.0	39.8	27.0	29.0	1.1	0.5	0.5	5.4
4		2004 May 29	0.66	0.77	0.62	0.65	24.6	4.8	14.1	16.5	1.2	1.2	1.2	4.5
5		2005 April 14	0.84	0.97	0.82	0.87	22.3	10.9	2.5	2.2	1.8	1.8	1.8	3.9
6		2007 December 17	0.80	0.93	0.74	0.79	3.9	3.8	4.0	1.9	3.9	3.8	4.0	1.9
7		2008 April 14	0.47	0.38	0.63	0.58	17.4	27.0	21.9	19.6	2.0	2.0	2.0	3.7
8		2008 April 23	0.51	0.49	0.68	0.66	18.1	8.3	2.3	4.5	1.6	1.7	1.7	4.0
9		2008 May 29	0.72	0.76	0.84	0.85	6.5	12.7	5.4	2.4	1.7	1.7	1.7	4.0
10		2008 October 1	0.76	0.78	0.86	0.89	5.0	25.2	14.4	13.9	2.3	2.4	2.4	3.3
11		2008 October 25	0.31	0.37	0.66	0.62	21.3	23.3	5.2	10.2	31.4	31.6	31.5	39.2
12		2009 March 10	0.82	0.79	0.70	0.76	23.1	49.5	39.3	40.9	5.2	4.9	5.1	0.8
13		2009 March 14	0.59	0.77	0.53	0.60	37.2	0.0	15.5	15.1	2.6	2.5	2.6	3.2
14		2009 May 17	0.65	0.60	0.88	0.85	4.4	32.7	18.1	21.2	2.2	2.2	2.3	3.5
15		2009 September 22	0.83	0.69	0.78	0.79	19.3	40.2	29.2	30.1	1.8	1.8	1.7	4.0
16		2011 April 21	0.56	0.71	0.54	0.59	41.9	19.0	29.0	34.2	2.7	2.7	2.8	3.0
Maximum			0.86	0.97	0.95	0.93	41.9	49.5	39.3	40.9	31.4	31.6	31.5	39.2
Minimum			0.31	0.37	0.53	0.58	0.2	0.0	2.3	1.9	1.1	0.5	0.5	0.8
Average			0.68	0.69	0.75	0.76	16.2	23.4	17.0	18.5	4.0	4.0	4.0	5.8
C.V (%)			23	25	18	16	76	66	66	66	183	187	184	154
17	Validation	2011 April 23	0.49	0.45	0.68	0.65	8.1	23.1	15.9	14.8	2.2	2.1	2.1	3.6
18		2011 October 29	0.56	0.86	0.55	0.66	14.0	28.3	11.6	16.3	5.4	5.7	5.3	0.1
19		2011 October 30	0.50	0.75	0.49	0.56	4.4	35.3	22.7	26.8	17.3	17.3	17.3	12.5
20		2011 November 4	0.12	0.43	0.02	0.14	25.7	59.0	44.9	50.0	6.0	4.6	5.4	0.8
21		2011 November 5	0.49	0.59	0.82	0.82	24.4	15.7	0.6	2.0	4.8	4.1	4.3	1.6
22		2012 April 11	0.76	0.73	0.90	0.87	19.5	20.3	5.3	7.1	5.7	5.3	5.6	0.3
23		2012 April 20	0.83	0.92	0.89	0.93	7.3	36.6	17.9	24.8	8.1	8.0	7.4	2.9
Maximum			0.83	0.92	0.90	0.93	25.7	59.0	44.9	50.0	17.3	17.3	17.3	12.5
Minimum			0.12	0.43	0.02	0.14	4.4	15.7	0.6	2.0	2.2	2.1	2.1	0.1
Average			0.54	0.67	0.62	0.66	14.8	31.2	17.0	20.3	7.1	6.7	6.8	3.1
C.V (%)			43	29	50	40	58	46	85	78	69	74	72	138

Table 3 continued

No.	Stage	Criteria	RE in Tp				RMSE				Coefficient of efficiency			
		Method date	LP	DL	AV	SDTT	LP	DL	AV	SDTT	LP	DL	AV	SDTT
1	Calibration	2003 April 6	7.7	15.4	0.0	0.0	1.4	1.5	0.8	0.9	0.85	0.82	0.95	0.93
2		2003 December 9	27.3	36.4	9.1	9.1	0.9	0.9	0.5	0.6	0.70	0.69	0.92	0.85
3		2004 April 23	6.7	13.3	6.7	6.7	1.5	2.0	1.2	1.4	0.76	0.60	0.84	0.81
4		2004 May 29	25.0	25.0	31.3	31.3	5.2	3.8	5.3	5.1	0.52	0.74	0.51	0.53
5		2005 April 14	16.7	5.6	16.7	16.7	1.0	0.6	1.0	0.9	0.82	0.93	0.83	0.88
6		2007 December 17	0.0	4.5	13.6	13.6	0.2	0.2	0.3	0.3	0.86	0.93	0.82	0.85
7		2008 April 14	43.8	37.5	31.3	31.3	1.6	1.7	1.4	1.4	0.45	0.37	0.59	0.57
8		2008 April 23	18.8	37.5	18.8	18.8	2.3	2.1	1.7	1.8	0.37	0.46	0.63	0.61
9		2008 May 29	0.0	25.0	6.3	6.3	4.4	4.2	3.4	3.4	0.72	0.75	0.84	0.84
10		2008 October 1	12.5	6.3	18.8	18.8	0.6	0.6	0.5	0.4	0.68	0.68	0.79	0.82
11		2008 October 25	16.7	25.0	8.3	8.3	1.3	1.0	0.8	0.9	−0.14	0.29	0.54	0.45
12		2009 March 10	11.8	11.8	17.6	17.6	0.2	0.3	0.3	0.2	0.83	0.71	0.72	0.75
13		2009 March 14	21.7	8.7	26.1	26.1	0.6	0.3	0.6	0.5	0.40	0.78	0.43	0.49
14		2009 May 17	0.0	5.6	5.6	5.6	0.6	0.7	0.5	0.5	0.69	0.62	0.85	0.82
15		2009 September 22	5.6	0.0	16.7	16.7	0.7	1.0	0.9	0.8	0.81	0.64	0.75	0.76
16		2011 April 21	46.7	33.3	43.3	43.3	0.6	0.4	0.5	0.5	0.29	0.66	0.37	0.41
Maximum			46.7	37.5	43.3	43.3	5.2	4.2	5.3	5.1	0.86	0.93	0.95	0.93
Minimum			0.0	0.0	0.0	0.0	0.2	0.2	0.3	0.2	−0.14	0.29	0.37	0.41
Average			16.3	18.2	16.9	16.9	1.5	1.3	1.2	1.2	0.60	0.67	0.71	0.75
C.V (%)			87	72	68	68	99	90	109	105	45	27	25	24
17	Validation	2011 April 23	31.3	31.3	25.0	25.0	1.0	1.0	0.8	0.8	0.51	0.48	0.69	0.67
18		2011 October 29	20.8	16.7	25.0	25.0	0.2	0.1	0.1	0.1	0.62	0.85	0.71	0.79
19		2011 October 30	22.7	9.1	31.8	31.8	1.5	1.2	1.5	1.4	0.46	0.69	0.47	0.55
20		2011 November 4	25.0	18.8	31.3	31.3	0.3	0.2	0.3	0.3	0.23	0.44	0.11	0.25
21		2011 November 5	18.8	43.8	18.8	18.8	0.2	0.2	0.1	0.1	0.58	0.71	0.86	0.87
22		2012 April 11	0.0	10.0	5.0	5.0	0.2	0.2	0.2	0.2	0.65	0.72	0.82	0.83
23		2012 April 20	0.0	7.7	15.4	15.4	0.1	0.1	0.1	0.1	0.87	0.79	0.89	0.90
Maximum			31.3	43.8	31.8	31.8	1.5	1.2	1.5	1.4	0.87	0.85	0.89	0.90
Minimum			0.0	7.7	5.0	5.0	0.1	0.1	0.1	0.1	0.23	0.44	0.11	0.25
Average			16.9	19.6	21.7	21.7	0.5	0.4	0.4	0.4	0.56	0.67	0.65	0.69
C.V (%)			72	68	44	44	110	106	121	119	35	23	43	33

LP, DL, AV and SDTT, respectively represent linear profile, dimensionless, average velocity, and spatially distributed travel time methods of TAH development (Modified from Fang et al. 2005)

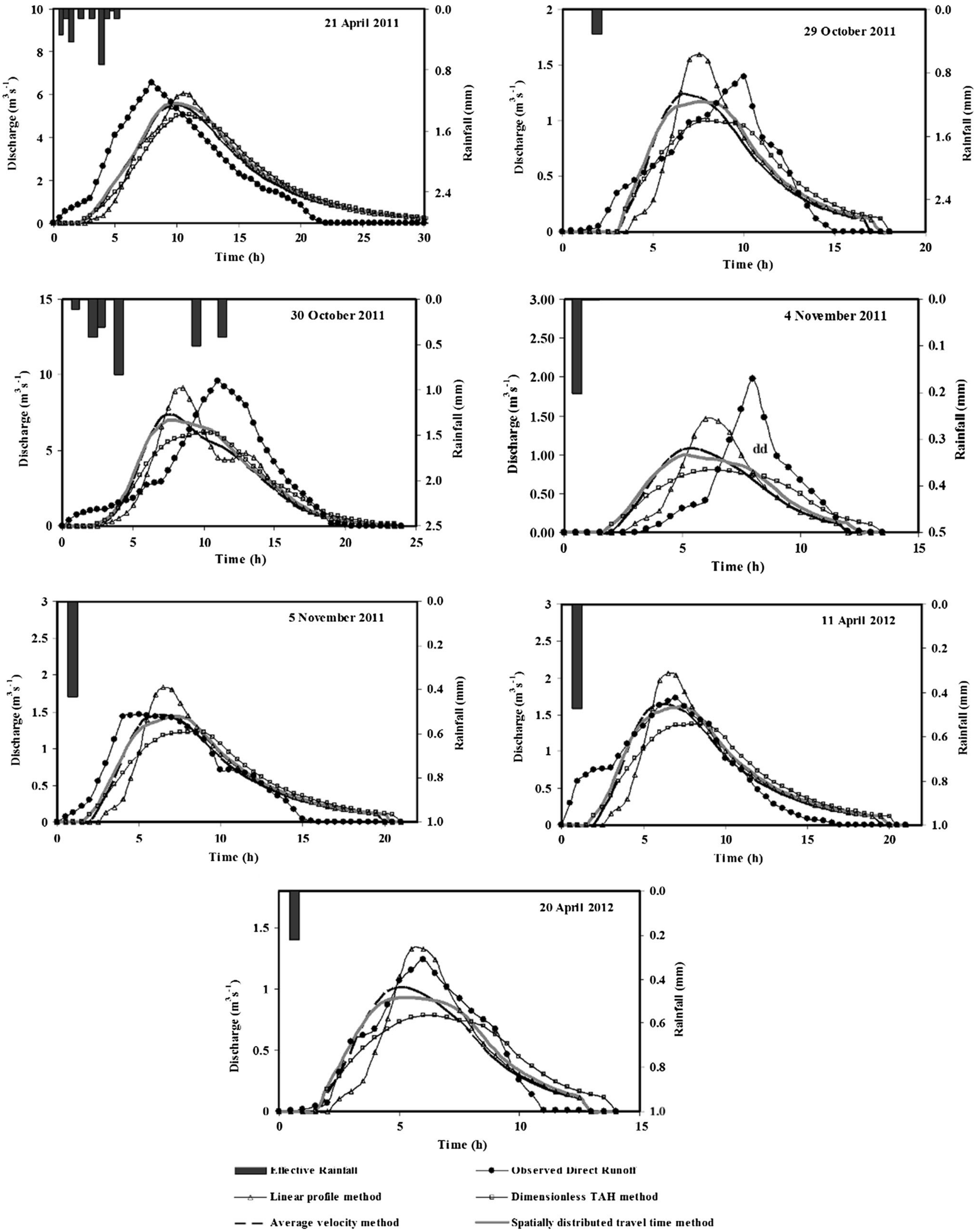

Fig. 6 Simulated hydrographs resulted in validation stage from different TAHs methods for the Galazchai watershed, Iran

considering spatial variability of computed travel times. The spatially distributed unit hydrograph model predicts direct runoff hydrographs with good accuracy, 75 and 69 % according to the coefficient of efficiency criterion. The weight grid reflects the resistances of each cell in the watershed to flow according to topographic and land use conditions, thus results a retardation in the flow. So, it is concluded that resistance effect of Manning's roughness coefficient on the flow can reflect the actual watershed conditions in generation of runoff. Similar findings have been reported by Usul and Yilmaz (2002) and Hunukumbura et al. (2007). The spatially distributed unit hydrograph model will take into account the changes in different land use area in the different parts of the watershed. The land use pattern and variability are well analysed by the isochrones mapping as an input for the Clark model. The variations in the simulated discharge values based on the spatially distributed travel time TAH can be minimized by adjusting the roughness coefficients. The distributed parameter estimation capability of the SDUH model helps to understand how the vegetation management alternatives in the different parts are affecting the response of the event runoff in the watershed. To better assess the performance of the runoff routing technique, it is recommended that the model has to be tested on different watersheds of varying topography and land uses in different parts of Iran.

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