Effects and consideration of storm movement in rainfall-runoff modelling at the basin scale

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Abstract: A number of studies have emphasized the effects of rainfall movement on runoff simulation; nevertheless, due to the lack of rain gauges inside sub-basins, a method using a hyetograph of the nearest gauges to a sub-basin is usually employed. This study investigated the effects of neglecting rainfall movement on overland simulation results in even a middle-sized basin. Simulations were carried out under two conditions: (1) stationary conditions where the nearest gauge hyetograph was used and rainfall movement was ignored, which is quite common in case of a lack of data; (2) moving conditions where a shifted hyetograph based on hyetograph timing recorded in the basin was used. The simulation results were compared with the measured discharge at the outlets. The results revealed that using the shifted hyetograph, which could consider the rainfall movement over sub-basins, decreased the mismatches between the simulated and observed hydrograph. In some of the cases, the shifted hyetograph reduced the relative difference more than 20%. The study provided a useful method to cope with rainfall movement in runoff modeling of sparsely gauged large watersheds.

1. Introduction

Since the first reports in the 1960s (Maksimov, 1964: Yen and Chow 1969) emphasized that higher peak flows are generated whenever the precipitation moves from upstream toward downstream, and conversely, rainfalls passing from down to upstream result in a rounded hydrograph, a great deal of research has investigated the effects of rainfall movement on the shape of the runoff hydrograph in the past half century. Most studies (Ngirane et al., 1985; Singh, 1997, 1998) have applied mathematical approaches to obtain a better understanding of the effects of storm speed and direction characteristics on the hydrograph shape. Their results showed that hyetograph characteristics, such as rainfall pattern, duration, intensity, direction and speed, significantly affected the hydrograph shape, and they emphasized that downward storm movement cause to increase the peak flow. Some researchers (Singh, 1998; Mizumura, 2011) adopted a kinematic wave equation to model the hydrograph in the case of a moving rainstorm. Their results showed that the maximum flow depth was generated when the rainstorm speed equalled the flood movement toward the outlet, and the speed of the storm had a greater impact for larger Manning's roughness coefficients. Recent studies have preferred dynamic wave models based on Saint Venant equations to obtain flexible results under varying conditions (Costabile, 2012). Kim and Seo (2013) applied a dynamic wave model base on shallow water equations to study the effects of storm movement on runoff generation in a V-shaped watershed experimentation system. The results revealed that storm movement could generate a loop in the stage-discharge curve, and changes in storm movement direction could invert the rotation of the loop. In addition, they revealed that the characteristics of rating curve depended on basin characteristic rather than functions of storm movement in V-shaped basin. In addition, there has been some research (De Lima et al. 2002) using rainfall simulators at laboratory scale to investigate the effects of storm movement. Laboratory portable rainfall simulators and flumes were used to simulate the hydrograph response to moving storms and subsequently soil erosion (De Lima et al. 2003). They applied different hyetograph patterns to study the effects of rainfall characteristics on the runoff hydrograph. The simulation outputs of hypothetical storms moving upward and downward over a laboratory impervious plane revealed that the peak discharges and hydrograph shape were highly affected by storm movement. In particular, they highlighted that runoff under moving rainfall is a non-linear process, essentially different from stationary rainfalls. Saghafian et al. (1995) used a two-dimensional runoff model and a Monte Carlo method to investigate storm movement effects on runoff. The results indicated that when storm movement is slow, a stationary rainstorm could be used in simulations; while when storm movement is fast, a stationary rainstorm was not acceptable. Ogden et al. (1995) showed that the runoff hydrograph was more sensitive to storm speed than direction in two-dimensional basin topography. Base on Manning's equation, the peak maximum occurred when the storm moved toward downstream at a critical speed equalling half the flow velocity.

Although there is well-known background on the effects of moving storms on overland flow generation, most of the interest has focused on laboratory experiments (Singh, 1997, 1998; De Lima et al. 2002, 2003) or mathematical approaches (Costabile, 2012; Kim and Seo 2013; Saghafian et al., 1995, Ogden et al., 1995). These studies emphasized the effects of movement on runoff generation via a synthetic hyetograph whose direction, speed and intensity were well-controlled by the researchers. However, few studies are available about rainstorm movement effects on runoff in natural environments of real basins, especially in the case of data deficiency. Therefore, it is essential to develop an approach that supports hydrologists bridging the gap between mathematical model and real condition. The objective of this study was to (1) precisely examine the effects of moving storms on hydrograph simulation at the basin scale using real recorded rainfall-runoff; (2) provide an approach to consider storm movement under the conditions of data shortage in sparsely gauged basins.

2. Materials and methods

2.1 Study area and data availability

Barandoozchay basin, one of the Urmia Lake sub-catchments, is located in the northwest of Iran. The study area lies in between Urmia Lake and the Iran-Iraq-Turkey international border from 44° 45' E to 45° 14' E and 37° 06' N to 37° 29' N. The area of the basin is about 1146 km^2.

The basin is divided into 7 sub-basins (B1 to B7), based on the river branches and topographic futures. Fig. 1 shows the Barandoozchay map and hydrometeorological gauges. This mountainous basin is mostly covered by grasslands, followed by farmland and orchard land. The humid air often (not always) comes from the west, originating from the Mediterranean Sea.

There are 6 daily rain gauges and 4 stream gauges inside the basin (Fig. 1), and 3 hourly rain gauges (35010, 34013 and 34019) around the basin.

[Fig. 1 is here]

Seven storm events, which were recorded in all rain gauges during 1995 to 2014, were selected. These events have recorded rain data (daily and hourly) available from the nearby rain gauges and the hydrometric runoff data from the stream gauges.

2.2 Estimation of sub-basin hyetograph

When the cloud is stationary, most of sub-basins that are covered by the cloud react to the rainfall simultaneously, implying that the start time and end time of the rainfall event is approximately the same for all sub-basins; while in the case of a moving cloud, the sub-basins that are located in the wind direction start to generate runoff earlier than the others (Fig. 2).

[Fig. 2 is here]

Since there is no record from the rain gauge inside the basin, the start and end time of the events were unknown. Therefore, the residence time of the storm cloud over each sub-basin and its role in outlet runoff generation were estimated and examined.

As the first step, the total daily rainfall of each sub-basin was estimated using Kriging and IDW (Inverse Distance Weighted) methods, based on the rain gauges inside the basin. Fig. 3 shows the raster map of generated rainfall for the event on May 12th, 2010.

[Fig. 3 is here]

The total daily rainfall was then disaggregated into hourly rainfall. Since there is no hourly recording gauge inside the basin, the nearest recording gauges at Urmia, Oshnavieh and Naghadeh (35010, 34013 and 34019) were used. The hourly rainfalls for sub-basins were obtained through following steps:

Determine the best hyetograph from one of the stations for disaggregation. The best hyetograph was selected based on daily rainfall amounts in stations and sub-basins.

Calculate the ratio of total rainfall in a sub-basin to the total daily rainfall recorded in the selected station with the best hyetograph.

Multiply the calculated ratio to the best hyetograph to obtain hourly rainfalls of a sub-basin (Choi, 2008; Gyasi-Agyei et al. 2005, 2007). Fig. 4 illustrates the procedures to disaggregate the daily rainfall into each sub-basin's hyetograph.

[Fig. 4 is here]

Due to dynamic motion of the cloud, the rainfall duration, start and end time, and intensity as well as other characteristics change. These parameters are known for the gauge locations, but unknown in other locations as well as sub-basins. To determine the cloud arrival time of each sub-basin and the time of rainfall occurrence (start, end and duration), the recorded hyetograph was concentrated to a unique time named the Time of Gravity Centre of

Hyetograph (TGCH) (Khalighi 2009). Since the TGCH is specified in gauge locations, it can be calculated for sub-basins through the following procedures:

(1) TGCH for recorded rainfall was calculated as a momentum of the rainfall component around the horizontal and vertical axis. The Fig. 5 shows that the recorded event in station 35010 started at 4:00 am and ended at 2:30 pm, and the calculated TGCH was at 9:00 am (8.981).

(2) When cloud moves over a basin, the rainfall time at a point depends on the point location and cloud speed and direction. At least 3 gauges are necessary to determine the occurrence time of rainfall at a point, although more gauges could increase the accuracy. As there are only 3 recording gauges around the study basin, a flat plane passes through the stations (Fig. 6). Therefore, the equation of the plane (TGCH=aX+bY+c) was applied to calculate the TGCH at each point. The UTM coordinates of the stations (X, Y) are considered as independent variables and the TGCH are considered as dependent variable, and then the coefficients (a, b and c) of the flat plane are calculated using algebraic functions (Howard 2010).

(3) The coordinates of the sub-basin centroids were placed in the above equations to determine the TGCH of each sub-basin.

(4) The previously derived hyetograph was shifted as its gravity centre conformed to the TGCH of each sub-basin centroid (Fig. 7).

[Fig. 5 is here]

[Fig. 6 is here]

[Fig. 7 is here]

For example, the TGCH for event 95/04/22 was recorded at 8.98, 6.48 and 5.33 at the stations 35010, 34019 and 34013 respectively (table 2), then the equation of the TGCH plane of this event was: TGCH=0.000077×X+0.000069+Y-317.457. Based on this equation and the coordinates of the B1 sub-basin centroid, the TGCH was 8:00 am, implying that the TGCH at B1 occurred almost one hour earlier than at station 35010, which was 8:59 am.

2.3 Rainfall-runoff modelling

The HEC-HMS model (TR-55, 1986) was used to investigate the effects of storm movement on hydrograph simulations. The model was calibrated using 5 events (1995/04/22, 2002/04/21, 2003/04/03, 2006/04/18 and 2008/04/07). Based on sensitive analysis, the relative initial abstraction (R_a = I_a/S) is the most sensitive parameter among the other parameters such as curve number (*CN*), lag time (T_l), total storage (*S*) and initial abstraction (I_a). Table 1 showed the primary and optimized parameters in sub-basins. The validation was conducted using the events 2010/05/12 and 2014/04/22. The results of peak discharges were shown in Table 2.

[Table 1 here]

[Table 2 here]

After the calibration and validation, the simulations were carried out for all events using two hypotheses: (1) stationary cloud where the sub-basin hyetograph timing is equal to the nearest recording gauge; (2) moving cloud where the sub-basin rainfall hyetograph shifted base on cloud movement direction and sub-basin location.

A Taylor diagram (Taylor, 2001, 2005; Sigaroodi et al., 2014) and root mean squared of relative difference (RD) were used to compare the results of two hypothesized conditions.

$$\mathrm{RD} = \sqrt{\left(\frac{(P_O - P_S)}{P_O}\right)^2} \times 100$$

where the P_O and P_S are observed and simulated peak discharge respectively.

3. Results

Fig. 8 shows the planes of TGCH for different events. Although the basin is mainly affected by the eastern humid Mediterranean air, the results indicated that each selected rainfall event had different directions and speeds.

[Fig. 8 is here]

Based on the gauge locations and TGCH of each event, a plane equation $TGCH = aX + bY + c$ was obtained for each event. Table 3 shows the equation coefficients.

[Table 3 is here]

The gravity centre coordinate of each sub-basin is used in the equations to calculate the TGCH for the sub-basin centroid of each event. Fig. 9 shows how the sub-basin hyetograph is shifted to obtain the TGCH for the event on April 3rd, 2003. The measured TGCH at the gauges and the calculated TGCH for sub-basins are shown in Table 4.

[Fig. 9 is here]

[Table 4 is here]

Fig. 10 presents the HEC-HMS modeled results for the event on April 22nd, 2014 at the gauge 35005. The right part shows the model performance under stationary conditions where all sub-basins react to the hyetograph simultaneously. The gray and brown lines are the modeled outputs for upper sub-basins, which make the simulated total output (blue line). The hydrograph is sharp and the time to peak is quite different compared to the observed hydrograph (red line). The left part presents the modeled result using a shifted hyetograph, which matches better with the observed hydrograph.

[Fig. 10 is here]

For comparison, the modeled peak discharges of the 7 selected events under the two conditions are presented together with the observations in Table 5.

[Table 5 is here]

Fig.11 displays the standard deviation (SD) and correlation coefficient R^2 of the modeled results under stationary and moving conditions on the Taylor diagram. It is clearly seen that the moving condition results are closer to the observation points than the stationary condition results.

[Fig. 11is here]

4. Discussion

To achieve accurate hydrological modeling, high quality and spatially-explicit rainfall data should be accessible; however, in many cases uniform hyetographs are used for all sub-basins due to lack of sufficient gauges. If the cloud motion is neglected, it means that the differences between the times of runoff generated by sub-basins are ignored. In this case, to compensate for the difference and achieve better matching between simulated and observed runoff, other basin factors such as curve number (*CN*) or time-lag have to be modified, which most probably cause artifacts in the coefficients (Khalighi et al., 2006, 2009).

Some researchers used portable rainfall simulators or flumes in laboratory scales (Yen 1969, Singh, 1997, De Lima et al. 2002, 2003), while others preferred mathematical models to detect the effects of rainfall movement on runoff generation (Saghafian et al., 1995, Ogden et al., 1995, Kim and Seo 2013). Synthetic or artificial rainfalls are used in the laboratory or mathematical simulations. In contrast to previous studies, this research investigated the effects in a real basin under natural conditions, where the rainfall characteristics cannot be controlled. If there are sufficient rain gauges in basin, at least one gauge in the middle of each sub-basin, accurate runoff simulations can be achieved. However, this is not true in most cases, where sparse gauges or no gauge is available. This study provided an approach that the rainfall time in ungauged sub-basins could be determined using the recorded rainfalls in around gauges. Although more rain gauges can obtain better results, at least 3 gauges are necessary to record the rainfall event for determining the cloud direction and speed, which is reflected in the TGCH plane.

When the cloud movement is slow, consideration of movement is more important compared to fast movement conditions. In the event of April 22nd, 2014, the time difference between gauges 35010 and 34019 (Table 4) shows that the cloud movement is very low, thus the sub-basin B1 generates runoff much earlier than B7. This result was not consistent with the findings of Saghafian (1995), who stated that a stationary rainstorm could be used in low speed storms. This study showed that for small basins or laboratory scales where the cloud covers the whole basin, the storm motion effect could be ignored; while in the case of middle-size to large basins, the runoff of low speed storms passing over the basin has an obvious role in determining hydrograph shape. It can then be concluded that when the time difference between the recorded rainfalls around the area is small, the differences between stationary and moving runoff simulations are slight. These results were consistent with the findings of previous studies, which showed the impacts of cloud motion on hydrographs by using rainfall simulators at different laboratory scales (Sing, 1997, 1998; de Lima and Singh, 2002; de Lima et al., 2003; Marzen, 2015) or the kinematic wave method (Mizumura, 2011).

The results of this study also revealed that longer rainfalls are less affected by cloud movement. In other words, for rapid and short rains, the runoff hydrograph is more strongly affected by cloud movement speed and direction. These results were consistent with the findings of previous studies (de Lima and Singh, 2002; Khalighi, 2009; Dae-Hong Kim, 2013) in laboratory, which emphasized the effects of rainfall duration on runoff generations.

It should be noted that the effects of cloud movement on hydrograph modeling become visible only when the study area is divided into sub-basins. In addition, lack of gauges in this study caused to use a flat plane to calculate the TGCH for the sub-basins; other interpolation methods such as IDW and Kriging could be more appropriate to obtain surface data from the point data. Despite of these, the similarity between recorded and simulated hydrograph shapes as well as peak discharges indicated that the proposed method could significantly improve runoff modeling accuracy in sparsely gauged large basins..

In conclusion, although there are many laboratory experiments on the effects of rainfall movement on runoff simulation, this study developed an important method to determine how the spatial-temporal dynamics of rainfall can be considered at the real watershed scale, in particular for large areas without sufficient gauges.

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Tables

Table 1. Optimized parameter in sub-basins

Sub-basin	$R_a = I_a/S$		CN	T_l (h)
	Primary	Optimized		
B1	0.2	0.197	68	7.6
B2	0.2	0.18	71	6.2
B3	0.2	0.23	78	3.7
B4	0.2	0.23	80	2.3
B5	0.2	0.23	78	3.1
B6	0.2	0.23	82	2.7
B7	0.2	0.164	77	5.9

Table 2. Comparison of observed and simulated peak discharge in validation step

Hydrological Station	2010/05/12		2014/04/22	
	Observed	Simulated	Observed	Simulated
35003	12.2	14.4	--	--
35005	34.8	31.5	297.9	352

Table 3. Obtained coefficients for the TGCH flat plane

Coefficient / Time	95/04/22	02/04/21	03/04/03	06/04/18	08/04/07	10/05/12	14/04/22
a	0.000077	0.000256	0.000222	0.000244	0.000047	-7.3E-05	-8.9E-05
b	0.000069	0.000008	0.000095	-3.4E-05	-0.00003	0.000074	-0.00019
c	-317.457	-144.736	-485.298	30.743	127.119	-236.65	855.542

Table 4. TGCH measured at the gauges and calculated for the sub-basins

Location		UTM		Precipitation Events						
		X	Y	95/04/22	02/04/21	03/04/03	06/04/18	08/04/07	10/05/12	14/04/22
Gauges	35010	507361	4155960	8.98	20.4	7.3	14.7	3.0	8.3	15.9
Gauges	34019	534124	4091310	6.48	26.7 [a]	6.2	23.4	6.2	1.6	25.5
Gauges	34013	510374	4100492	5.33	20.7	1.1	17.3	4.8	4.0	25.9
Sub-basins	B1	510820 [b]	4139365	8.0	21.1	6.3	16.1	3.7	6.8	18.7
Sub-basins	B2	495670	4134355	6.5	17.2	4.5	12.6	3.1	7.6	20.9
Sub-basins	B3	493644	4123015	5.6	16.6	3.7	12.5	3.3	6.9	23.2
Sub-basins	B4	483585	4118992	4.5	14	2.8	10.1	3	7.3	24.9
Sub-basins	B5	486806	4113932	4.4	14.8	2.9	11.1	3.3	6.7	25.5
Sub-basins	B6	493217	4112538	4.8	16.4	3.2	12.7	3.6	6.1	25.2
Sub-basins	B7	508969	4120830	6.6	20.5	5.1	16.3	4.1	5.6	22.3

a: The numbers over 24 refer to the next day.

b: Coordinate of centroid of sub-basin.

Table 5. Modelled peak discharges under two conditions and differences

		Peak Discharge			Difference (%)	
Date	Hydrological Station	Obs.	Stationary	Moving	Stationary	Moving
2014/04/22	35005	297.9	352	315.3	18.2	5.8
2010/05/12		34.8	31.5	34.4	9.5	1.1
2008/04/07		61.4	70.15	65.6	14.3	6.8
2006/04/18		96.15	100.5	100.13	4.5	4.1
2003/04/03		20.1	20.4	20.3	1.5	1
2002/04/21		65.9	42.9	41.6	34.9	36.9
1995/04/22		37.45	51.2	42.58	36.7	13.7
2010/05/12	35003	12.2	14.4	13.4	18	9.8
2008/04/07		51.9	65.16	63.4	25.5	22.2
2006/04/18		85.4	93.8	93.57	9.8	9.6
2003/04/03		3.7	3.5	3.8	5.4	2.7
2002/04/21		24.3	28.8	26.1	18.5	7.4
1995/04/22		113.2	127.7	127.3	12.8	12.5
1995/04/22	35001	83	83.3	83.3	0.4	0.4

Figure captions

Figure 1. Barandoozchay basin and hydrometeorological gauges

Figure 2. Schematic of rainfall movement effect on runoff formation

Figure 3. Spatial distribution of rainfall event 2010/05/12

Figure 4. Schematic of rainfall hyetograph determination in sub-basin centroid. a) Hourly hyetograph at nearest gauge, b) Daily precipitation at nearest gauge, c) Daily precipitation in sub-basin centroid, d) Derived hyetograph for sub-basin

Figure 5. HYGC output for calculation of hyetograph centroid at 95/04/22 in station 35010 (Gx: Temporal coordinates of concentrated event, Gy: Average of incremental rainfall)

Figure 6. Flat plane passing through the TGCH for the event 1995/04/22

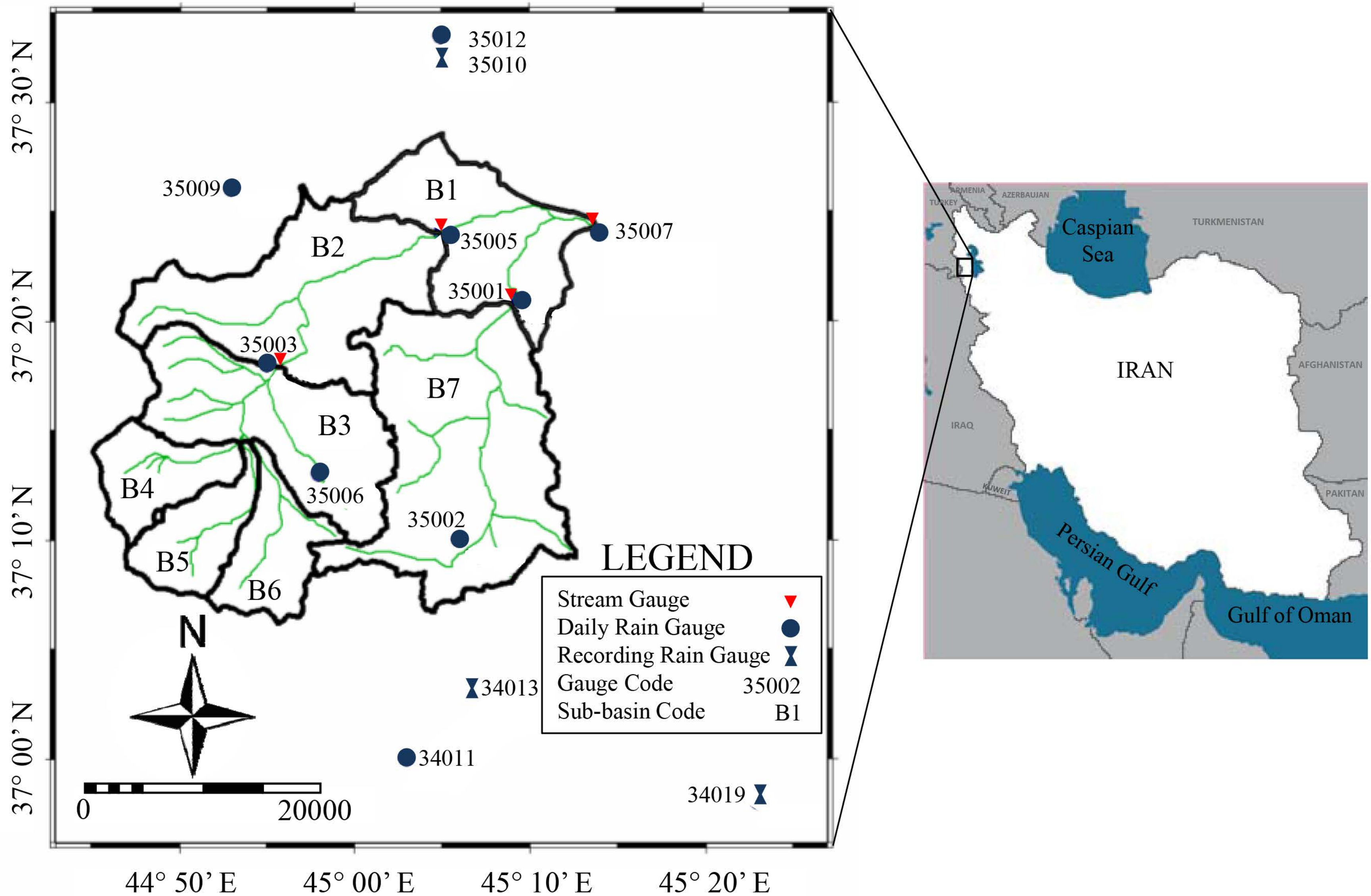
Figure 7. Shifting the hyetograph to the estimated TGCH

Figure 8. Precipitation time occurrence plane in different events

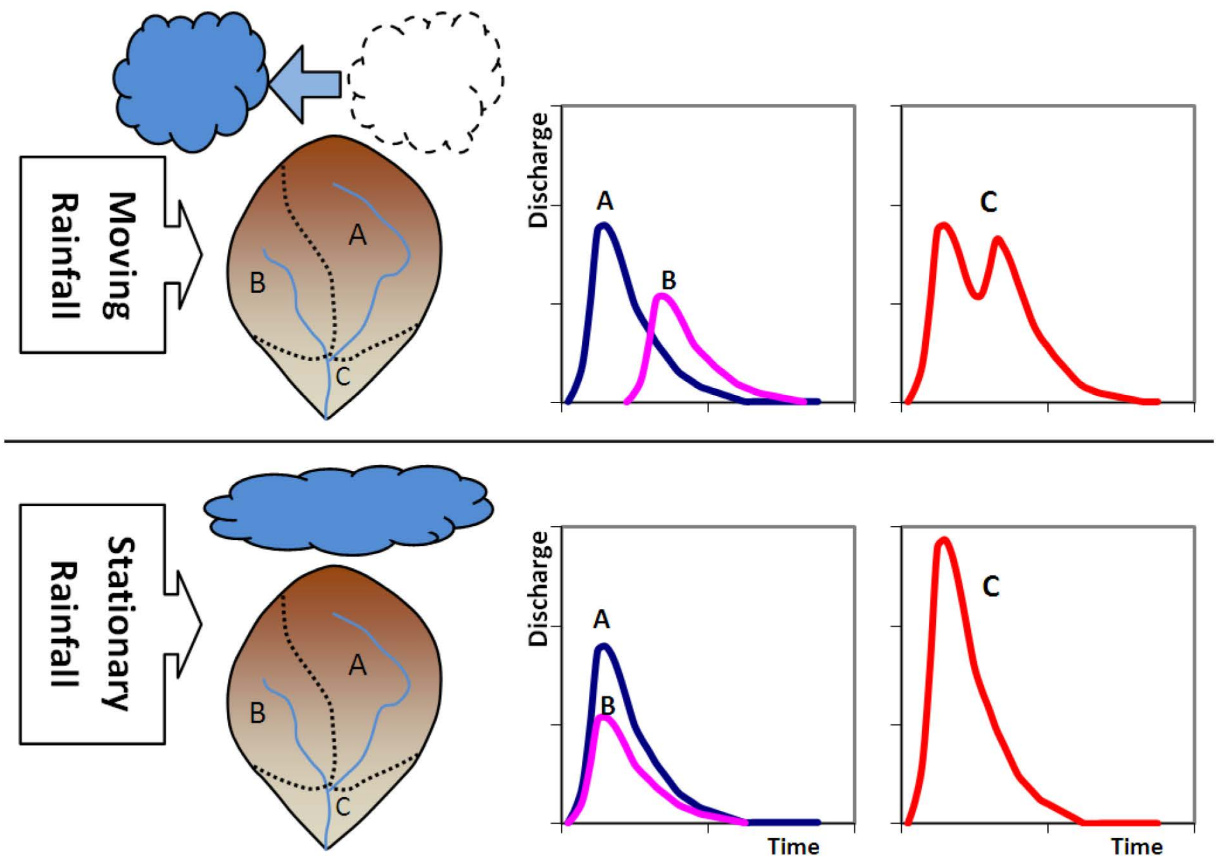
Figure 9. Hyetograph of sub-basins before shift (left) and after shift (right). (Red arrows show the timing position of TGCH before and after shifting)

Figure 10. HEC-HMS output for rainfall event 2014/04/22, under two different conditions, moving simulation (left) and stationary simulation (right)

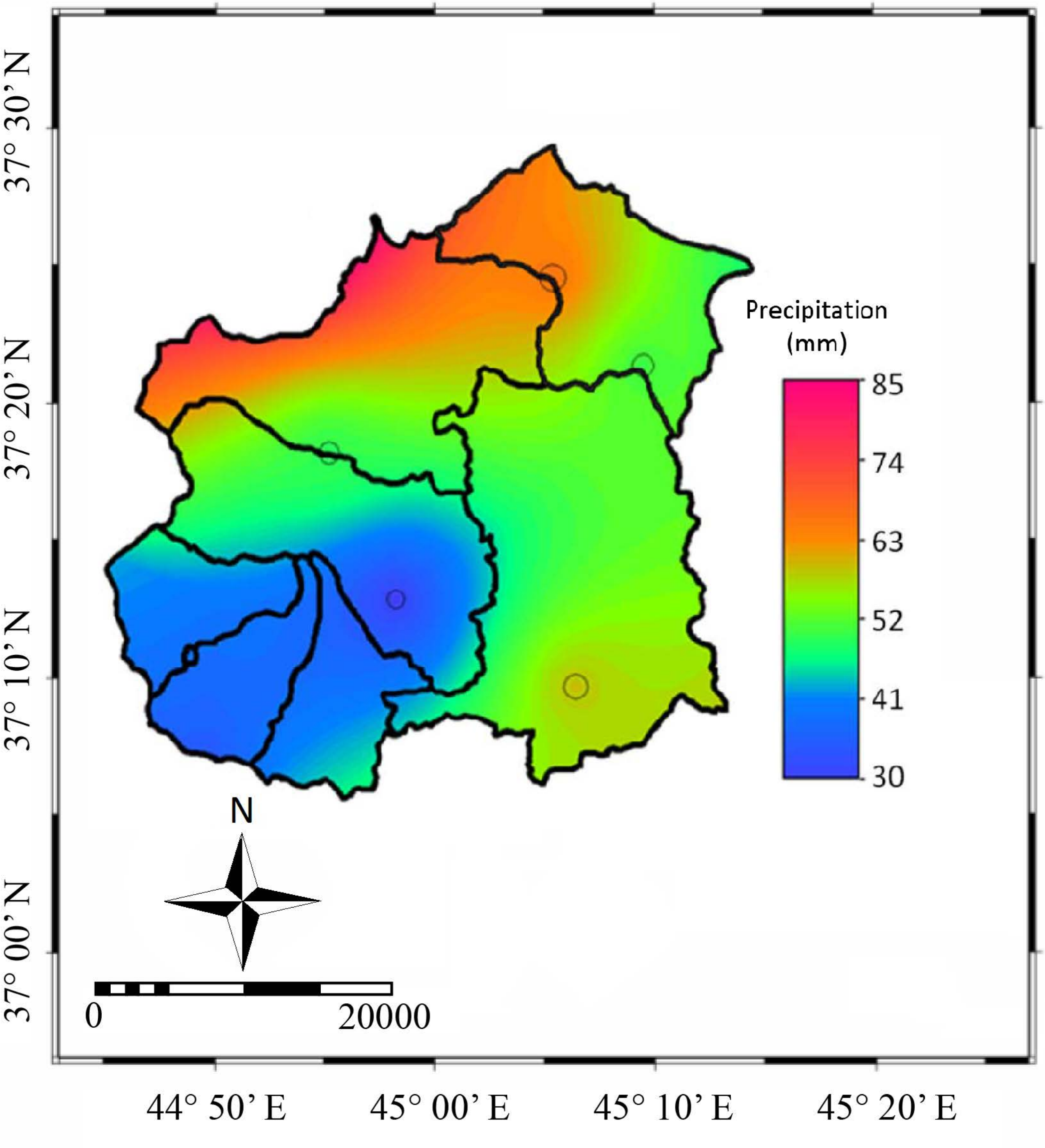
Figure 11. Scatter plot of the simulated peak discharge for stationary and moving conditions on a Taylor diagram



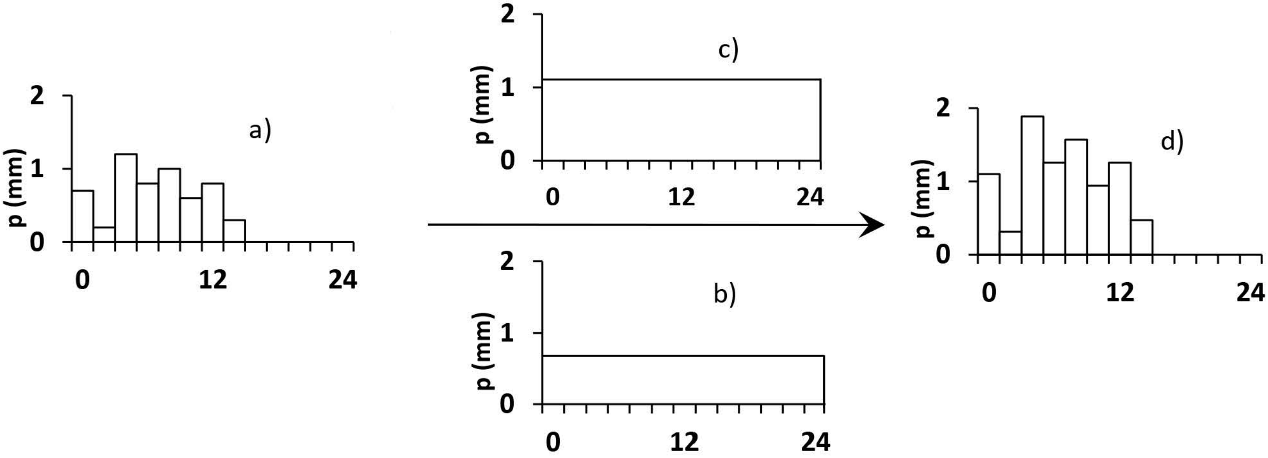
35012
35010
35009
B1
35005
35007
B2
35001
35003
B7
B3
B4
35006
35002
B5
B6
LEGEND
Stream Gauge
Daily Rain Gauge
Recording Rain Gauge
Gauge Code 35002
Sub-basin Code B1
N
34013
34011
34019
0
20000
37° 30' N
37° 20' N
37° 10' N
37° 00' N
44° 50' E
45° 00' E
45° 10' E
45° 20' E
ARMENIA
AZERBAIJAN
TURKEY
Caspian Sea
TURKMENISTAN
IRAN
AFGHANISTAN
IRAQ
KUWEIT
PAKITAN
Persian Gulf
Gulf of Oman



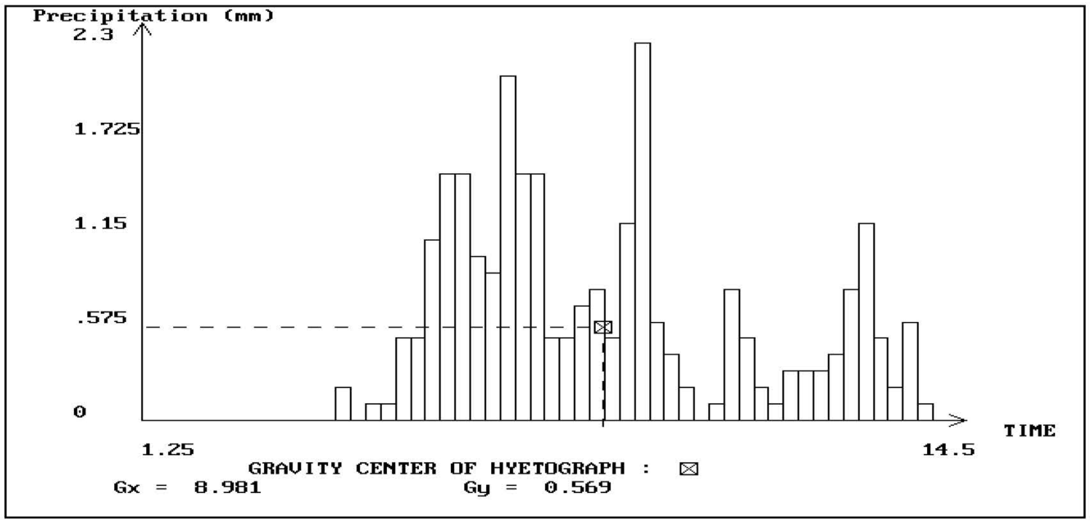
Moving Rainfall
A
B
C
Discharge
A
B
C
Stationary Rainfall
A
B
C
Discharge
A
B
Time
C
Time

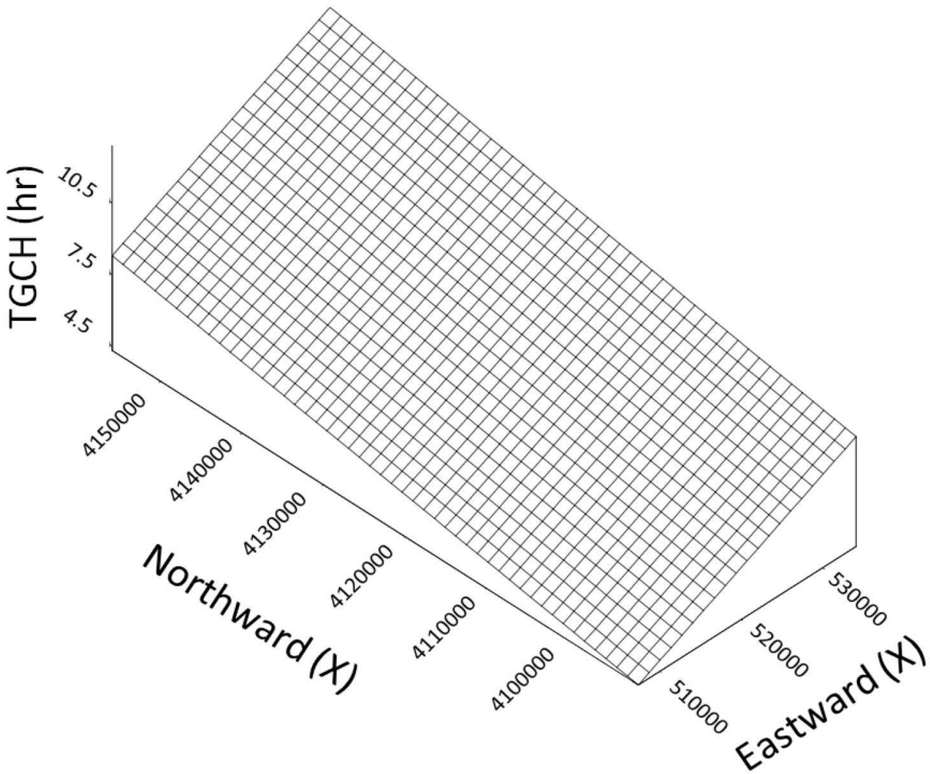


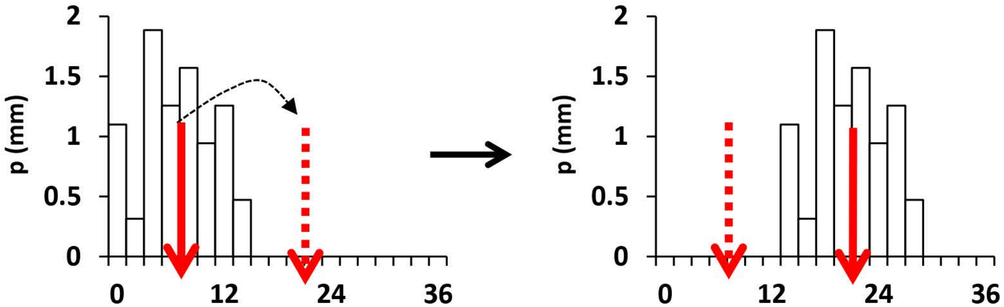
37° 30’ N
37° 20’ N
37° 10’ N
37° 00’ N
Precipitation
(mm)
85
74
63
52
41
30
N
0
20000
44° 50’ E
45° 00’ E
45° 10’ E
45° 20’ E

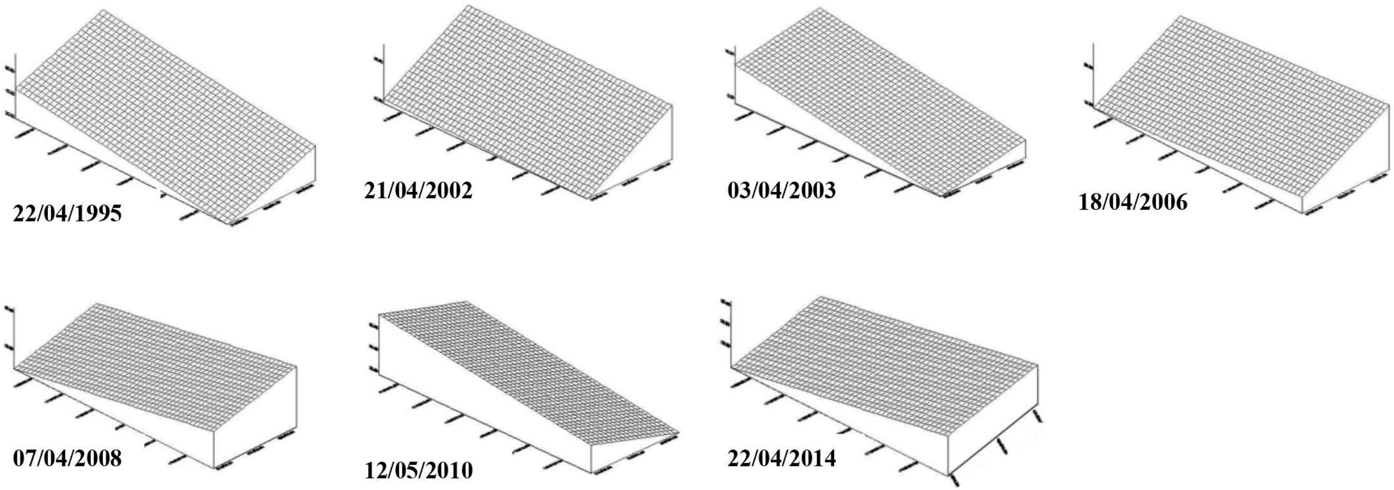


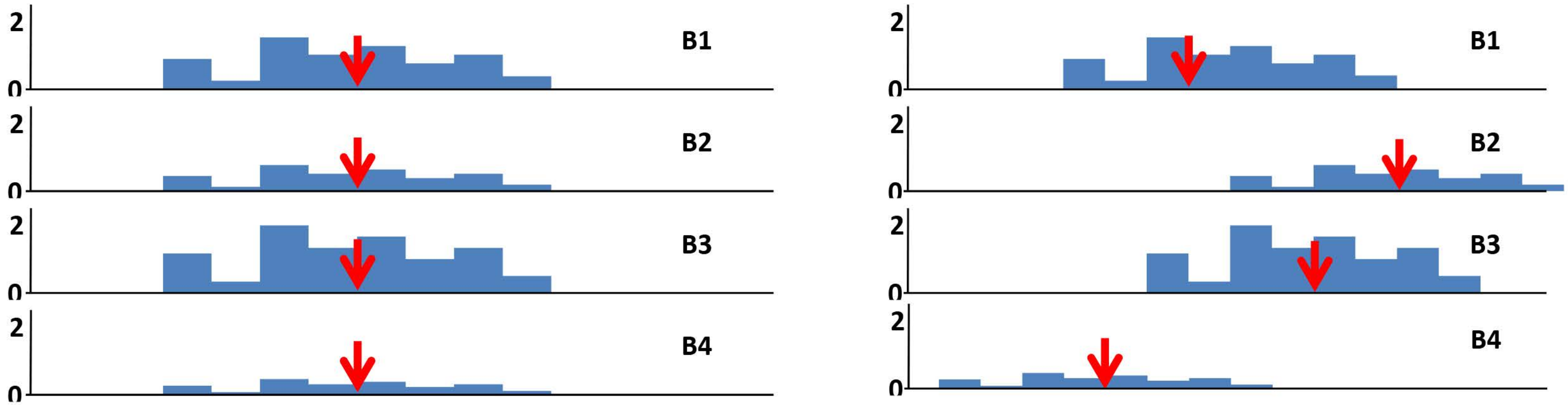
a)
b)
c)
d)
p (mm)
0
1
2
0
12
24


Precipitation (mm)
2.3
1.725
1.15
.575
0
TIME
1.25
14.5
GRAVITY CENTER OF HYETOGRAPH :
Gx = 8.981
Gy = 0.569


TGCH (hr)
10.5
7.5
4.5
4150000
4140000
4130000
4120000
4110000
4100000
Northward (X)
510000
520000
530000
Eastward (X)

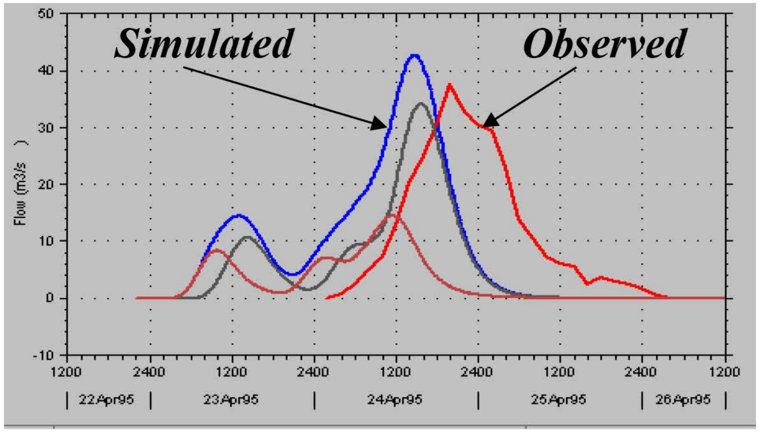

2
1.5
1
0.5
0
p (mm)
0
12
24
36
2
1.5
1
0.5
0
p (mm)
0
12
24
36


22/04/1995
21/04/2002
03/04/2003
18/04/2006
07/04/2008
12/05/2010
22/04/2014

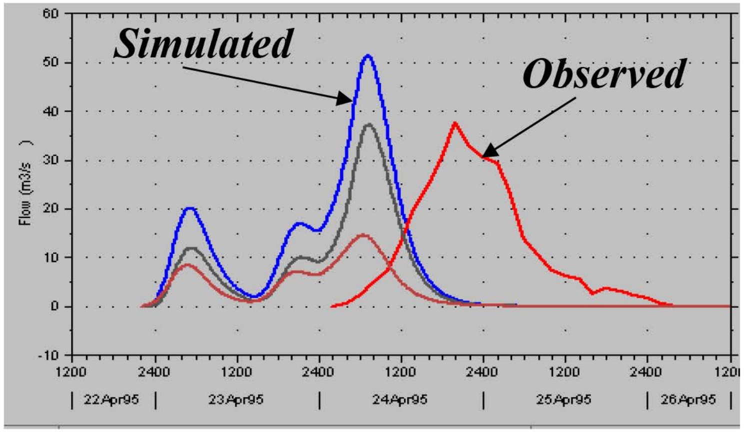


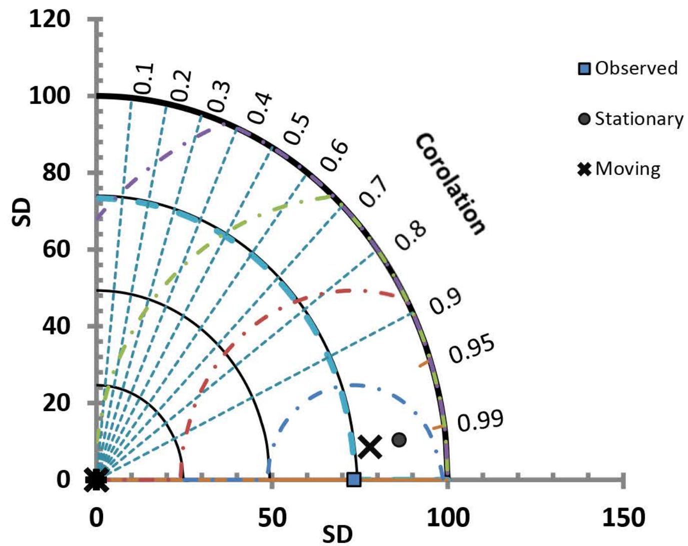
2
0
B1
2
0
B2
2
0
B3
2
0
B4
2
0
B1
2
0
B2
2
0
B3
2
0
B4

Moving Simulation



Stationary Simulation




120
100
80
60
40
20
0
SD
0
50
100
150
SD
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.95
0.99
Corolation
Observed
Stationary
Moving