Stochastic Generation of Storm Pattern

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Abstract: Lack of storm patterns (storm hyetograph) in many catchments is an important issue in hydrological analysis. So, in many studies various methods are developed to generate storm pattern. There are uncertainties in generated storm patterns due to uncertainty of generating method (model uncertainty) and uncertainty of the variables affecting the storm patterns such as the total depth of rainfall, rainfall duration and dimensionless hyetograph (inherent uncertainty). This study developed the Rain Data Processor (RDP) and the Rain Pattern Generator (RPG) models to generate storm patterns based on Mass curve method with considering inherent and model uncertainty in ungauge catchments by using the Monte Carlo simulation and Bootstrap resampling. Methodology of this study is applied in Iran (Seymareh catchment).According to the statistics of generated peak intensity by the RPG model; there is an acceptable agreement between observed and generated hyetographs. Also, the RPG model is more accurate than triangular hyetograph model in generation of storm pattern.
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Key words: generation, Storm pattern, Seymareh catchment, RDP, RPG

Introduction

The storm pattern (storm hyetograph) is one of the most important variables in flood hydrographs simulation and peak discharge estimation. The storm pattern includes duration, depth and time distribution in a storm event and it's recorded by synoptic and rain gauge station. Hence, there is no any storm pattern in many catchments. Therefore, many researchers and designers use the Soil Conservation Service (SCS) or storm pattern of other catchments for flood modeling in Iran. These approaches cause many errors in flood modeling.

Many studies have pointed out various methods to establish storm pattern in the following four categories (Ellouze and Abida 2009):

(I) Generation of storm pattern by using a single point of IDF curves for the specified duration (Chow et al. 1988).

(II) Generation of storm pattern by using the entire IDF curve(USAE 1948, Keifer and Chu 1957, Bandyopadhyay 1972, Chen 1983, Veneziano and Villani 1999, Alfieri 2007).

(III) Generation of non-dimensional storm pattern(Hershfield 1962, Huff 1967, Eagleson 1970, SCS 1972, Pilgrim and Cordery 1975, Tsubo et al. 2005, Powell et al. 2007).

(IV) Generation of storm pattern by using stochastic models (Koutsoyiannis et al. 1993, Zarris et al. 1998, Cheng et al. 2001, Koutsoyiannis and Mamassis 2001, Lin et al. 2005, Wu et al. 2006, Grimaldi and Serinaldi 2006).

In the first category; storm pattern is generated based on a specified return period, rainfall duration and an average value of rainfall intensity from the IDF curve.

In the second category; whole set of duration-intensity values are used for a specified return period.

In the third category (mass curve methods); observed storm events are converted to the dimensionless curves with cumulative fraction of rainfall duration on the horizontal axis, and cumulative fraction of total rainfall depth on the vertical axis.

Comprehensive information of the above categories for establishing storm patterns can be found also in other papers (Yen and Chow 1983).

In mass curve generation method, uncertainty in generated hyetograph is a main issue. Mass curve method has highly uncertainty because of the inherent uncertainty and randomness of the observed storm events (Veneziano and Villani 1999).

Wu et al. (2006) used the Monte Carlo simulation and cluster analysis to quantify inherent variability of the observed storm events for generating probabilistically rainfall hyetographs of a particular pattern in Hong Kong Territory. Wu et al. (2006) classified all observed storm events in four basic types of storm patterns: advanced type, central-peaked type, delayed type, and uniform type. These categories have same concept as Huff rainfall mass curves.

Another source of uncertainty in this method is incorrect connection between rainfall duration, total rainfall depth and generated dimensionless storm pattern and can be named model uncertainty(Yen et al. 1986). Uncertainty of storm event can strongly affect the flood generation and quantification of hydrograph variability has strong relation to quantify uncertainty of rainfall (Kusumastuti et al. 2007, Hong et al. 2006, Habib et al.

2007, Mascaro et al. 2010).So, the important issues in flood modeling are identification and uncertainty analysis of effective variables on storm pattern and considering inherent and model uncertainty in generation of storm pattern.

In this study, the main goal is developing a new probabilistically storm pattern generator based on mass curve method. This generator considers inherent and model uncertainty to generation of storm pattern by using the Monte Carlo simulation and bootstrap resampling. The Rain Pattern Generator"RPG" model is developed for the main goal of this study as above statements. Other features of RPG model makes it possible to generate storm pattern in ungauged catchments.

In the RPG model, Probability distribution of variables affecting the storm patterns such as rainfall duration, storm pattern type and dimensionless rainfall hyetograph ordinates are required for the Monte Carlo simulation and considering inherent and model uncertainty in storm pattern generation. Hence, the Rain Data Processor "RDP" model is developed to prepare required probability distributions for the RPG model. These proposed models are applied to Seymareh catchment.

In this study, Firstly, the proposed models are presented, then the study catchment and data are described, and, finally, results are summarized and discussed.

1. MATERIAL AND METHODS

1.1. RDP model

The RDP model is developed as a storm event processor. Uncertainty of storm patterns is quantified by using outputs of this model. The main outputs of the RDP model are probability distribution of the variables affecting the storm patterns such as rainfall duration, storm pattern type and the dimensionless rainfall hyetograph. The main steps in the RDP model before determination of probability distributions are, events filtering, events classification and determination of dimensionless matrix.

Events filtering

According to the two constraints, observed storm events are stored and filtered in the RDP data base. The minimum rainfall depth is the first constraint which is equal 2 mm. The minimum duration of storm event is the second constraint which is equal 100 minutes. For any storm events, if the gap between two time intervals (rainfall duration ordinates) is greater than 1 hour, then the rainfall before the gap is selected as an event rainfall. The observed rainfall is evaluated and filtered based on these constraints. The algorithm of event filtering in the RDP model is presented in Figure.1.

Events classification

After events filtering, storm events are categorized in three main groups and other subgroups based on duration, depth and type of storm pattern.

I- Group 1: duration of rainfall

Five categories for duration as D1, D2… D5 can be selected in the RDP model. The intervals [0-3], [3-6], [6-12], [12-24] and more than 24 hours are selected for duration of storm patterns. For example if duration of one observed storm event is 7 hours, this event belongs to the third category of Group 1(D3). The RDP model allocates each observed storm event to one category of Group 1.

II- Group 2: total depth of rainfall

Six categories for depth as H1, H2… H6can be selected in the RDP model. The intervals [0-2.62], [2.62-4.53], [4.53-6.6], [6.6-9.53], [9.53-14.95] and more than 14.95 mm are selected for the total depth of storm patterns. For example if total depth of one observed storm event is 8.2 mm, this event belongs to the forth category of Group 2 (H4). The RDP model allocates each observed storm event to one category of Group 2.

III-Group 3: type of storm pattern

If an observed storm event through the rainfall duration divided into four quarter, type of storm pattern determines which quarter has the biggest rainfall depth among others. For example Type (1) or T1 implies the biggest fraction of rainfall depth occur in the first quarter of the storm. This definition has same concept as "Huff curves"[10].In this study, all observed storm events are classified into four types as T1, T2, T4 depending on whether the heaviest rainfall occurred in the first, second, third, or fourth quarter of the storm period.

Addition of these three main groups, 120 subgroups are made in the RDP model by combining categories of groups. For example, observed events that have duration between 12 up to 24 hours, total depth between 9.53 up to 14.95 mm and type 1 storm pattern are stored in D4-H5-T1 subgroup.

Table 1. Classification of rainfall events

Definition	Category	Group No
Rainfall Duration	D1,D2,D3,D4,D5	1
Total Rainfall Depth	H1,H2,H3,H4,H5,H6	2
Type of Rainfall Pattern	T1,T2,T3,T4	3

Determination of dimensionless matrix

After classification of events in subgroups, all events have no dimensions in duration and depth. This process is illustrated in Figure 2.

In the RDP model, interval of X axis (dimensionless duration ordinates) and Y axis (dimensionless depth ordinates) can be adjusted by users. In this study, X axis has ordinates equal 0.1. After adjusting the dimensionless duration ordinates and event being non-dimensional in each subgroup, the RDP model makes one matrix with RxP array for each subgroup. R is the number of rows which are equal to the number of events and P is the number of columns which are equal to the dimensionless duration ordinates. In this study P is equal 10 because each ordinate is equal 0.1.

The sample of this matrix is presented in Table 2.

Table 2 Matrix of non-dimensional rainfall pattern

A(1,1)	A(1,2)	A(1,3)	…	A(1,P)
A(2,1)	⋱			A(2,P)
A(3,1)		⋱		A(3,P)
⋮			⋱	⋮
A(R,1)	A(R,2)	A(R,3)	…	A(R,P)

The condition of each array in storm pattern matrix is:

$$\begin{cases} A(i,1) = 0, & i = 1,2,....,R \\ A(i,P) = 1, & i = 1,2,....,R \\ 0 < A(i,j) < 1, & i = 1,2,....,R,\ j = 1,2,....,P \\ A(i,j) < A(i,j+1) \end{cases} \quad (1)$$

Where, R is the number of events in each subgroup of storm events and P is the number of dimensionless duration ordinates. A(i,j) is a dimensionless depth array of event (i) at the ordinate (j).

Determination of Probability distributions

The RDP model determines probability distribution of rainfall duration and storm pattern type categories for each category of Group 2 (H1, H2… H6) as below procedure:

1- All observed events are classified in the categories of Group 2(H1, H2… H6).
2- For each category of Group 2, duration and type categories of events are determined.
3- Occurrence probabilities of duration and type categories for each category of Group 2 are computed. For example if 100 events belong to H1 and among these events, 15 events belong to D1 and 35 events belong to T2, So occurrence probability of H1-D1 is equal 0.15 and occurrence probability of H1-T2 is equal 0.35.
4- Probability distribution of rainfall duration and storm pattern type categories for each categories of Group2 is determined according to occurrence probability of duration and type categories. Samples of these Probability distributions are illustrated in Figure 3.

Probability distributions of dimensionless hyetograph for each subgroup of storm events areanother output of RDP model. After determination of dimensionless matrix of hyetograph, uniform distribution is used for each dimensionless hyetograph ordinate. Algorithm of this procedure is shown in Figure 4. Triangular distribution is another alternative of probability distribution to quantified random properties of dimensionless hyetograph. For each subgroup 10 uniform distributions (equal 10 dimensionless duration ordinate) are used to quantify random property of dimensionless hyetograph ordinates.

1.2. RPG Model

The RPG is a stochastic model based on the Monte Carlo simulation and mass curve method and generate storm pattern for any specified rainfall depth. Storm pattern of any event can be extracted, if the total rainfall depth, the rainfall duration and the dimensionless hyetograph are specified. This concept is used in the RPG model to generate storm pattern. Furthermore, the RPG model uses the Monte Carlo simulation, bootstrap resampling and considers inherent and model uncertainty to generate storm pattern. The procedure of the storm pattern generation by the RPG model is illustrated as below steps:

1- The RDP model prepares Probability distributions of rainfall duration, storm pattern type and dimensionless hyetograph for each subgroup of storm events.
2- Total rainfall depth is specified by frequency analysis for a given return period or by user. Assume this rainfall depth belongs to H3group.
3- Monte Carlo simulation is initiated and number of simulation is specified by user.
4- Random occurrence probability (R1) is generated.
5- Duration of generated storm pattern is determined by using the R1 and probability distribution of rainfall duration for "H3-Di" subgroup of storm events (i=1, 2,.., 5). Assume generated rainfall duration belongs to D2category.
6- Random occurrence probability (R2) is generated.
7- Type of generated storm pattern is determined by using the R2 and probability distribution of storm pattern type for "H3-Ti" subgroup of storm events (i=1, 2,.., 4). Assume generated storm type belongs to T4category.
8- According to the step 4 up to 7 and those assumptions, generated storm pattern belongs to "H3-D2-T4" subgroup.
9- Bootstrap resampling is used to generate samples of dimensionless hyetograph matrix for determined subgroup of storm events in step 8.

10- Uniform probability distributions of each ordinate for sampled dimensionless hyetograph matrixes, are extracted by the RDP model.
11- Random occurrence probability (R3) is generated.
12- The value of each ordinate of dimensionless hyetograph is determined by using the R3 and uniform distribution of ordinate for any sample of dimensionless hyetograph matrix.
13- Average of sampled dimensionless hyetographs is computed as dimensionless hyetograph for the subgroup of storm events in step 8. In this step one Monte Carlo simulation is done. This procedureis repeated according to the numbers of Monte Carlo simulation. So, a specified rainfall depth has many samples of different storm pattern

At the end of Monte Carlo simulation, storm pattern (storm hyetograph) for a given rainfall depth is extracted from generated storm pattern according to the specified occurrence probability(for example 50%). Algorithm of storm pattern generation by the RPG model is shown in Figure.5.

1.3. The Study Catchment

Seymareh catchment is selected to test generation of storm pattern by the RPG model in ungauged catchments and uncertainty analysis of storm pattern. This catchment is located in west of Iran and its area is 29,244 square kilometer. The main Branches of Seymareh River are Gharaso and Gamasiyab rivers. 2658 storm events of Arak, Borojerd, Hamedan ,Kangavr, Khoramabad, Kermansha, Dezful and Holiailan stations are used with 10 minutes time interval. Information and location of these stations are presented in Table3 and Figure.6.

Table 3 Properties of station in Seymareh catchment

2. RESULT AND DISCUSSION

2.1. Strom pattern generation

The main capability of the RPG model is storm pattern generation in ungauge catchments. So, this capability is tested by preparing required probability distributions for RPG model without used the observed storm patterns (10 events) of Holiailan subcatchment (subcatchment of seymareh catchment) and the observed storm patterns(2648 events) of the other subcatchments are used. In other words, storm patterns in Holiailan subcatchment are generated without using itself data.

2.2. Validation of the RPG model

Validation of the RPG model is evaluated by using the 10 observed events of Holilan station in Holilan subcatchment. According to the total rainfall depth of each observed storm event, 1000 storm pattern generated by the RPG model. The performance of the RPG model is evaluated by comparing peak intensity of generated storm patterns (50% occurrence probability) with corresponding observed events (Ellouze and Abida 2009).

The scattergram of observed peak intensity versus generated values is shown in Figure.7. This scattergram indicates both generated high and low peak intensity are reasonably accurate. The statistics as Sum of Squares Due to Error (SSE) between the residuals (observed and generated values), Root Mean Squared Error (RMSE) and correlation coefficient (R^2) are considered to quantify the agreement between observed and generated hyetographs. The SSE and RMSE values closer to 0 indicate a model is more accurate for generation. The SEE, RMSE and correlation coefficient between observed and generated peak intensity by the RPG model are illustrated in Table 4. The SEE and RMSE are low and correlation coefficient is close to unity. So, there is an acceptable agreement between observed and generated hyetographs.

Table 4 Statistics of the agreement between observed and generated hyetographs (RPG results)

statistic	RPG model
SSE	2.67
RMSE	0.57
R^2	0.91

Furthermore, Storm pattern and duration with 95 and 5 percent occurrence probability are shown in Figure.8 and Figure.9. The results reveal 90 percent of duration and 98 percent of storm pattern steps of observed events fall in generated significant band of the RPG model.

3. CONCLUSION

Conclusion

This study has introduced two major innovations. Firstly, it has attempted to develop and use the RDP model to extract probability distribution of the variables affecting the storm pattern. Secondly, the RPG model is developed and used to generate storm pattern in ungauged catchments.

The results of comparing between generated and observed storm pattern reveal 90 percent of duration and 98 percent of dimensionless storm pattern of observed events fall in generated significant band of the RPG model. Also an acceptable agreement between observed and generated hyetographs by the RPG model is achieved based on the SSE, RMSE and R^2 statistics of generated and observed peak intensity.

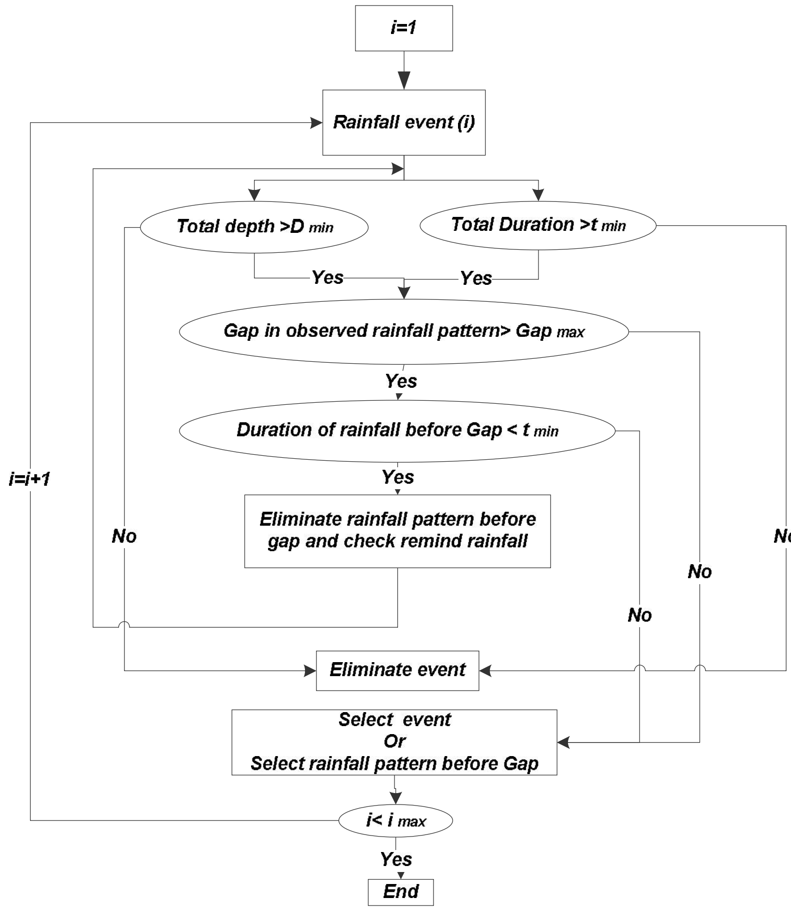


Figure 1. Algorithm of rainfall event filtering by the RDP model

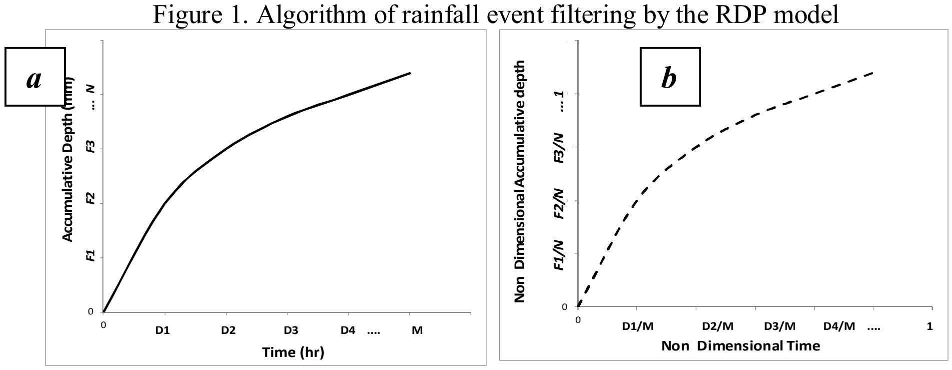


Figure2. Convert observed rainfall event into the dimensionless hyetograph, a- Observed rainfall pattern,

In the RDP model, interval of X axis (dimensionless duration ordinates) and Y axis (dimensionless depth ordinates) can be adjusted by users. In this study, X axis has ordinates equal 0.1. After adjusting the dimensionless duration ordinates and event being non-dimensional in each subgroup, the RDP model makes one matrix with RxP array for each subgroup. R is the number of rows which are equal to the number of events and P is the number of columns which are equal to the dimensionless duration ordinates. In this study P is equal 10 because each ordinate is equal 0.1.

The sample of this matrix is presented in Table 2.

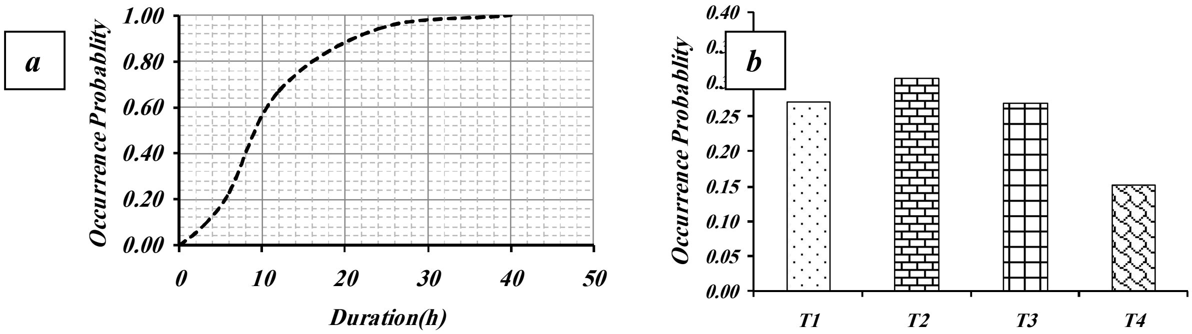


Figure3. Sample of probability distribution of duration and type of the rainfall event, a- probability distribution of rainfall duration, b- probability distribution of rainfall pattern type

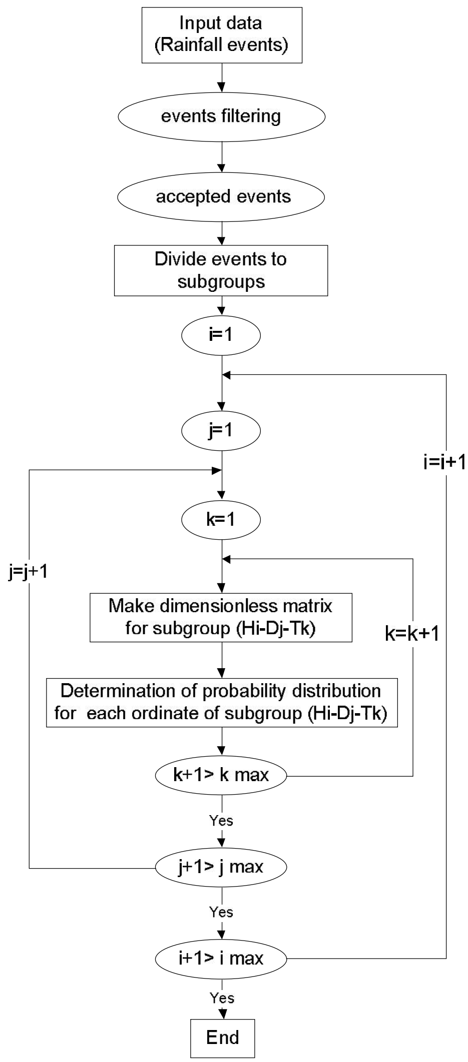


Figure4. Determination of probability distribution of dimensionless hyetograph

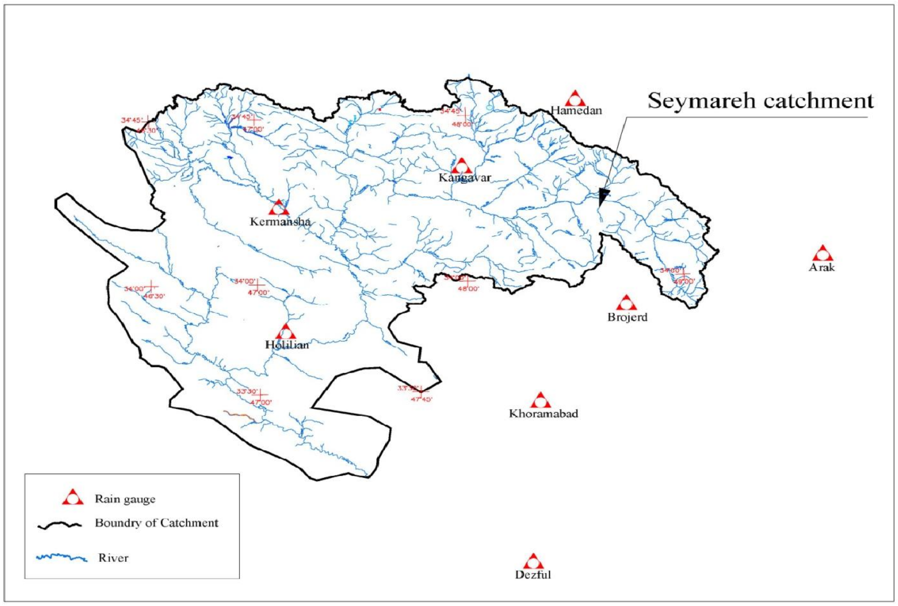


Figure 5. Algorithm of rainfall pattern generation by the RPG model

Table 3 Properties of station in Seymareh catchment

Station	Type	Longitude	Latitude	Number of events	application
Holiailan	Rain gauge	47-06	33-46	10	Validation
Arak	Synoptic	49-46	34-06	449	Train
Borojerd	Synoptic	48-45	33-55	324	Train
Hamedan	Synoptic	48-32	34-52	378	Train
Kangavr	Synoptic	47-59	34-30	762	Train
Khoramabad	Synoptic	48-17	33-26	365	Train
Kermansha	Synoptic	47-09	34-21	117	Train
Dezful	Synoptic	48-23	32-24	253	Train

Figure 6.Seymareh Catchment

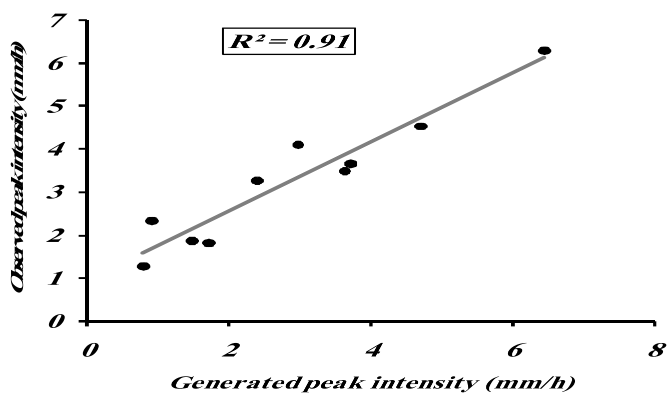


Figure 7. Compression of observed and generated (the RPG model) peak intensity

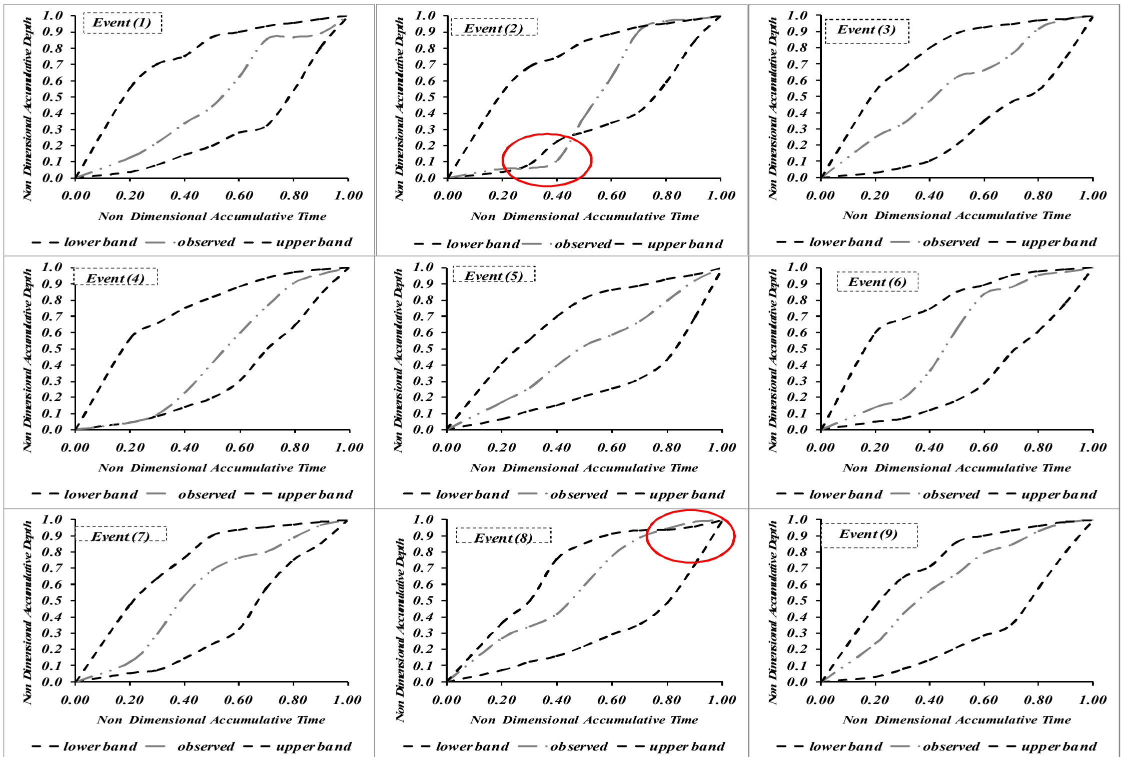
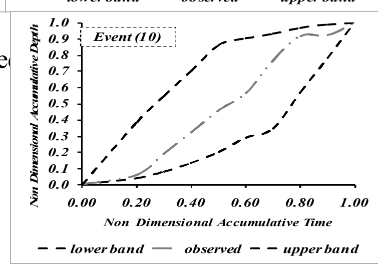


Figure8. Observe



nfidence band of RPG model

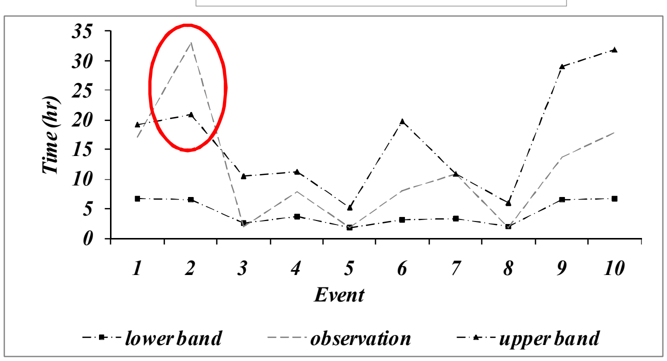


Figure 9. Duration of observed rainfall and generated confidence band of RPG model

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