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Flood frequency analysis using density function of wavelet (Case study: Polroud River)

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ABSTRACT

In this paper, we present a method to perform flood frequency analysis (FFA) when the assumption of stationary is not important (or not valid). A wavelet transform model was developed to FFA. A full series was applied to FFA using two different wavelet functions, and then a combined method was investigated. In the combined method, all discharge data which were less than the lowest value of annual maximum (AM) discharge were removed. Furthermore, energy function of wavelet was used for FFA. The data was decomposed into some details and an approximation through different wavelet functions and decomposition levels. The approximation series was employed to FFA. This was performed using discharge data from of the Polroud River in Iran. This analysis was performed on the daily maximum discharge data from the Tollat station in the north of Iran. Data from 1975 to 2007 was evaluated by the wavelet analysis. The study shows that the wavelet full series model results (density function) are too small in compared with the results of combined method and they are both lesser than traditional methods (AM and PD). On the other hand, the results of energy function method were closed to the combined method when they are compared with the full series data results. These wavelet models were assessed with the AM and PD methods. The concrete result of this paper is that, the basin hydrologic conditions and data's nature are very important parameters to improve FFA and to select the best method of analysis.

1. Introduction

Despite over half a century of research on flood frequency analysis (FFA), the new methods continuously are being presented in this important branch of hydrology, which indicates its importance. Hence, increasing the accuracy in this area has been considered by many researchers. Stationary data is used in most of traditional methods such as annual maximum (AM) and partial duration (PD).

Hydrologic systems are sometimes impacted by extreme events as severe storms, floods and droughts. The magnitude of an extreme event is inversely related to its occurrence frequency; very severe events occur less frequently than more moderate events. The objective of frequency analysis of hydrologic data is to relate magnitude of extreme events to their frequency of occurrence through the use of probability distributions. The hydrologic data analyzed are assumed to be independent and identically distributed; and the hydrologic system producing them (e.g., a storm rainfall system) is considered to be stochastic space independent, and time independent in the classification scheme. The hydrologic data employed should be carefully selected so that the assumptions of independence and identical distribution are satisfied. In practice, this is often achieved by selecting the annual maximum (AM) of the variable being analyzed (e.g., the AM discharges, which is the largest instantaneous peak flow occurring at any time during the year) with the expectation that the successive observations of this variable from year to year will be independent (Chow et al. 1988).

The main aim of the FFA in hydrology is to determine the relationship hydrograph-return period. Until now, most of literatures investigated the flood peak univariate statistical procedures. However, concerning hydraulic works above all for flooding and inundation management, it is not enough to know information about flood peak only, but it is also useful to statistically estimate flood volume and duration. In order to have this information, joint cumulative distribution function (CDF) and probability density function (PDF) of involved variables is needed, and so multivariate statistical analysis has to be applied (Box et al. 1964).

Flood frequency analysis (FFA) has a major role to prevent from damages to establishment. Considering the irreparable damages of inattention to FFA, in last half of century, many different methods were presented in this branch of hydrology studies. Most of these approaches are based on statistical distributions. Such as these approaches was presented by Chow and his colleagues in applied hydrology.

A major shift in approaches to the management of flooding is now underway in many countries worldwide. This shift has been simulated by severe floods, for example on the Oder (Odra. 1997), Yangtze (1998), Elbe (Labe. 2002), Rhone (2003), in New Orleans (2005), on the Danube (2006) and in the UK (2000, 2007 and 2009) (Rossi et al. 2011).

Flood risk management is the process of decision making under uncertainty. It involves the purposeful choice of flood risk management that are intended to reduce flood risk (Rossi et al. 2011).

Traditional approaches to flood forecasting involve multi-dimensional mathematical models extensively based on underlying physical principles. In contrast, machine learning algorithms are data-driven methods whereby models are inferred directly from a database

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of training examples. Consequently, the incorporation of background knowledge, in the form of an understanding of the hydrology of the system being studied, only takes place indirectly through, for example, the choice of input variables to the artificial intelligence (AI) algorithm, or through the identification of an appropriate lead time for prediction. For this reason, data-driven models are sometimes referred to as being 'black box' (Abu and Sung. 2011).

Post-event analysis of any particular flood event will reveal that both the rainfall and snowmelt inputs that caused it and the effects in terms of areas flooded and damaged caused will be spatially variable or distributed in nature. The hydrology and hydraulics of the event will reflect the heterogeneities in the driving variables and catchment and channel characteristics. The distributed nature of the process is important, and the logical consequence is that in trying to predict flood events for flood management we should use distributed models whenever local distributed inputs interact with local nonlinear processes to produce responses where the distributed impacts might be significant (Petersen Olivier et al. 2009).

In recent 6 decades, many researches and studies were performed on FFA and its related branches. These researches and studies include several different methods from traditional methods, such as using AM and PD data, index flood, etc. to newer methods such as self-organization feature map, fuzzy clustering, regional FFA (RFFA), etc. The last subject is most considered in last decades. Below, previous researches and studies about these methods are presented.

Different types of probability distributions are one of the most usage and popular method in FFA. Most of researchers were working on developing this approach. In most of experimental projects, this method of FFA is used, in past and today. Some of researches are reviewed types of this method and was discussed about them (Jim and Edmund. 2011).

FFA in urban watersheds is complicated by non-stationary of annual peak records associated with land use change and evolving urban stormwater infrastructure. A framework for FFA is developed based on Generalized Adaptive Models for Location, Scale and Shape parameters (GAMLSS), a tool for modeling time series under non-stationary conditions. GAMLSS is applied to AM peak discharge records for Little Sugar Greek, a highly urbanized watershed which drains the urban core of Charlotte, North Carolina. It is shown that GAMLSS is able to describe the variability in the mean and variance of the AM peak discharge by modeling the parameters of the selected parametric distribution as a smooth function of time via cubic splines (Shu et al. 2008).

In another paper the joint impact of sample variability and rating curve impression in at-site FFA was considered. A novel likelihood-based framework is developed for this purpose, amusing the power-law model for the stage-discharge measurement and generalized extreme value (EV) model for the AM discharges. It shows that the two models can be pooled into one likelihood function (Guilan Regional Water Company, Research Committee. 2011).

Kale provided a synoptic view of extreme monsoon floods on all the nine large rivers of South Asia and their association with the excess (above-normal) monsoon rainfall periods. Simple techniques such as the Cramer's t-test, regression and Mann-Kendall (MK) tests and Hurst method were used to evaluate the trends and patterns of the flood and rainfall series (Adamowski. 2008, Heo et al. 2001).

At other study, the gradients of trends in the mean and the standard deviation (SD) are estimated by the weighted least squares method and the best fitting linear model of trend is with the aid of the Akaike Information Criterion (AIC). It shows that for every time series, a trend in the variance has a considerable effect on the trend estimators of the mean value. The analysis also includes seasonal peak flow series in order to obtain further insight into the detected non-stationary of the peak flows series (Adamowski and Fung Chan. 2011).

In other research, was examined the methods and approaches available in long-term flood seasonality analysis and applies them to the river Ouse (Yorkshire) in Northern England Since AD 1600. A detailed historical flood record is available for the city of York Considering of annual maximal flood level since AD 1877, with documentary accounts prior to this (Ravnik et al. 2004; Lawry et al. 2011).

RFFA has become a standard practice for determining flood quantiles at ungagged locations or at sites with short records. RFFA is the most popular method in FFA for watersheds that have not enough data for FFA. This method was used frequently and developed in last decades. Some of studies about this branch of FFA were presented below.

At first part of a study with 2 parts, a two parameter Weibull distribution with independence in both time and space was selected as a RF model and analyzed based on an index flood assumption. The method of maximum Likelihood (ML), the method of Moment (MOM), and the method of probability weighted moments (PWMs) were used to estimate flood quantiles at a site of interest (Zhang et al. 2006). In the second part of this study, flood quantile estimates determined from flood data at a single site have limited precision because ordinarily the available sample size is small. To improve the precision of such quantile estimates, an index flood technique has been employed enabling one to use available flood data at several sites in a region computer simulation experiments were performed in order to compare the sample properties of quantile estimates obtained based on the ML, MOM, and PWM methods and to determine the probability of the asymptotic variances obtained for each method for finite samples (Ozger et al. 2010).

In another study of RFFA, was compared Bayesian Generalized Least Squares (BGLS) regression approaches using a fixed and region-of-influence (ROI) framework that seeks to minimize the Bayesian model error variance (predictive uncertainty) (Haddad et al. 2012).

Shu and Ouarda presented the methodology of using adaptive neuro-fuzzy interface systems (ANFIS) for flood quantile estimation at ungagged sites (Macdonald et al. 2012). A regionalized relationship to estimate flood magnitudes for ungagged and poorly gauged catchments can be established using RFFA. RFFA was performed in this study using fuzzy c-mean, L-moment and artificial Neural network (ANN) (Lecrec and Ouarda. 2007).

Some of the other researchers performed RFFA using different methods and approaches, such as index- flood, combining self-organizing feature map and fuzzy clustering, GEV model (Pellegrini et al. 2012; Heo et al. 2001; Beven. 2011).

Up to now, we were considered to several common methods in FFA, but some other methods are being used in analysis, one of these methods is fuzzy expert system (FES). In Shu and Burn paper, the performance of the FES is improved by tuning of the membership functions of the fuzzy sets using a genetic algorithm (GA) (Quiroz et al. 2011).

We couldn't find any study in FFA by wavelet transform, but many studies have been done using wavelet transform in different branches of sciences involve hydrology and others (Patral et al. 2007; Shrinivas et al. 2008; Nourani et al. 2009; Chow et al. 2013; Vishwas et al. 2011; Strupczewski et al. 2001). One of these studies in hydrology is a large set of monthly precipitation data from 43 stations throughout Texas that was employed to investigate the spatial variability in the multi-scaling properties of wet and dry spells. Rainfall data from stations scattered across a very large size of data are analyzed by using a multi-scaling approach. Wavelet spectrum maps are interpreted considering different scale behavior of stations. It is found that stations show different scaling properties in terms of their wet and dry spells (Golizadeh et al. 2011).

Many studies and researches in FFA indicate the importance of this very important branch of hydrology. Damages of recent huge floods in the world indicate the result of inattention to this nature phenomena or mistakes in estimate of flood risk. So that many researchers were tried to make the better estimation of flood risk in last decades.

2. Case Study (Polroud basin)

FFA was performed on Polroud River in north of Iran (Guilan province). Polroud is located in the east of Guilan and it is the most important river in this region as sometimes east of Guilan basin was called Polroud basin. Fig. 1 shows the satellite picture of Polroud basin with two hydrometric stations (note: this picture is rotated about 45 deg. clockwise). Table 1 shows a summary of Polroud river characters.

Although the Manjil (Sefidroud) dam on Sefidroud River is the main source of Guilan water demand, but so it is distance to east of Guilan lands is far that so using Polroud River for supply of water demand is inevitable. In Polroud basin two main stations on two branch of this river has been established. Fig. 1 shows these two stations, Haratbar and Tollat. Table 2 shows the characters of these stations (Shu et al. 2004; Villarini et al. 2009; The Math Works. 2009.

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MATLAB, Version 7.8.0.347). In this paper, 52 years discharge data of Tollat station was used.

3. Wavelet transform

The wavelet transform has increased in usage and popularity in recent years since its inception in the early 1980s, yet scientists still do not enjoy the widespread usage of the Fourier transform (Subramanya et al. 2008).

Fig. 2 shows a schematic form of wavelet transform (Gubareva et al. 2011). The time-scale wavelet transforms of a continuous-time signal, x(t), is defined as:

$$T(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} g^{*}\left(\frac{t-b}{a}\right)x(t)dt \quad (1)$$

Table 1. Characters of Polroud river and its basin (GRWC. 2011).

Features	quantity/quality
Length	51 km
basin area	1765 km^2
origin	south of Alborz mountains
River delta	Caspian sea
River annual stream flow	$472*10^6$ m^3

Table 2. Characters of stations on Polroud river (GRWC. 2011).

River (branch)	Station	Height(m)	establishing date	Basin area (km^2)	Longitude	Latitude
Polroud	Tollat	113	1335	1574	50°17'30"	36°59'41"
Samoush	Haratbar	123	1336	115	50°18'11"	36°59'53"

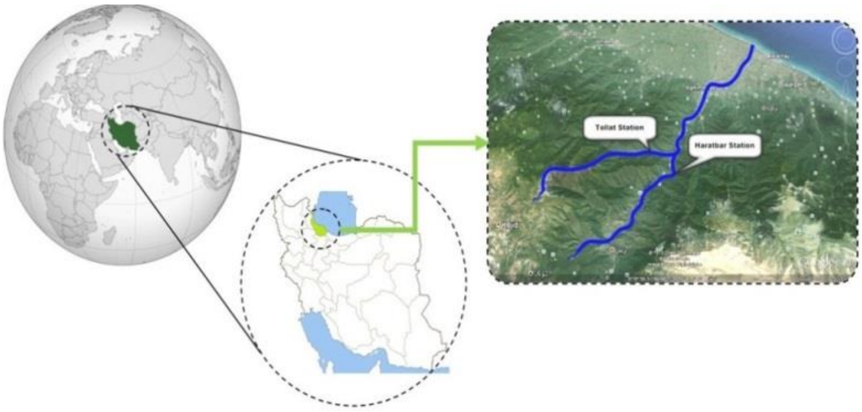

Fig. 1. The position of Polroud River.

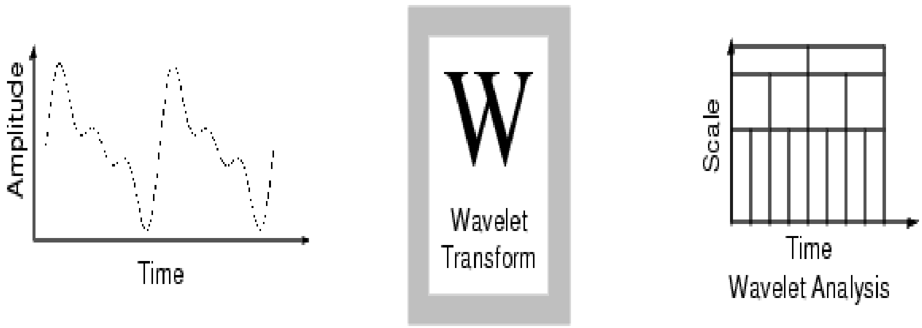

Fig. 2. Schematic showing of wavelet transform.

where, * corresponds to the complex conjugate and g(t) is called wavelet function or mother wavelet. The parameter "a" acts as adilation factor, while "b" corresponds to a temporal translation of the function g(t), which allows the study of the signal around "b". The characters of wavelet transform are to provide a time-scale localization of processes, which derives from the compact support of its basic function. This is opposed to the classical trigonometric function of Fourier analysis. The wavelet transform searches for correlations between the signal and wavelet function. This calculation is done at different scales of "a" and locally around the time of "b". The result is a wavelet coefficient (T(a, b)) contour map known as a scalogram. In order to be classified as a wavelet, a function must have finite energy, and it must satisfy the following ''admissibility conditions'':

$$\int_{-\infty}^{+\infty} g(t)dt=0,\quad C_g=\int_{-\infty}^{+\infty}\frac{\left|\hat{g}(w)\right|^2}{|w|}dw<\infty \quad (2)$$

where, g^(w) is Fourier transform of g(t); i.e. the wavelet must have no zero frequency component. In order to obtain a reconstruction formula for the studied signal, it is necessary to add ''regularity conditions'' to the previous ones.

$$\int_{-\infty}^{+\infty} t^k g(t)dt=0,\quad where\ k=1,2,...,n-1 \quad (3)$$

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So the original signal may be reconstructed using the inverse wavelet transform as (Subramanya. 2008):

$$x(t)=\frac{1}{C_g}\int_{-\infty}^{+\infty}\int_{0}^{+\infty}\frac{1}{\sqrt{a}}g\left(\frac{t-b}{a}\right)T(a,b)\frac{dadb}{a^2} \quad (4)$$

Two functions were existed that have main role in wavelet analysis: scale function (φ) and wave function (ψ). These two functions are produced a collection of functions that is used in decomposition or reconstruction of a signal. φ and ψ called father and mother wavelet, respectively (Kjeldsen et al. 2002). Two wavelet functions that used in this study were introduced briefly.

3.1. Haar

Any discussion of wavelets begins with Haar wavelet, the first and simplest. Haar wavelet is discontinuous, and resembles a step function. It represents the same wavelet as Daubechies db1 (Gubareva et al. 2011). The simplest wavelet analysis is based on Haar scale function. The Haar scale function is shows as:

$$\varphi(x)=1 \qquad if \quad x\in[0,1] \quad (5)$$

$$\varphi(x)=0 \qquad if \quad x\notin[0,1] \quad (6)$$

Haar wavelet is discontinuous and similar step function. Haar function is like Daubechies1 function. The (7) to (9) show Haar wave function:

$$\psi(x)=1 \qquad x\in[0,0.5] \quad (7)$$

$$\psi(x)=-1 \qquad x\in[0.5,1] \quad (8)$$

$$\psi(x)=0 \qquad x\notin[0,1] \quad (9)$$

Fig. 3 and Fig. 4 show the Haar wave and scale functions, respectively.

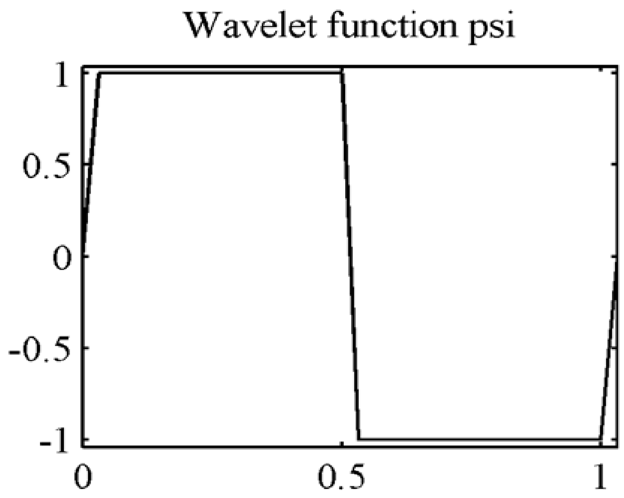

Fig. 3. Haar wave function.

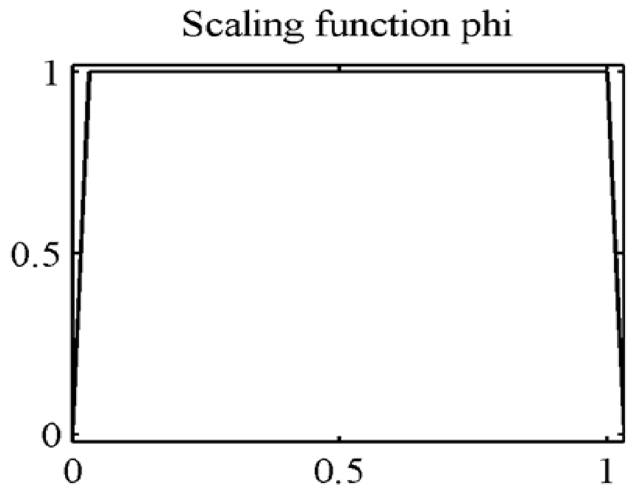

Fig. 4. Haar scaling function

3.2. Daubechies10

At first of using wavelet, Daubechies wavelets with some other by similar characteristics were only available wavelets. The simplest is Haar wavelet exactly that only discontinues wavelet in all of them. The other wavelets in this family are continues (Kjeldsen et al. 2002).

Ingrid Daubechies, one of the brightest stars in the world of wavelet research, invented what is called compactly supported orthonormal wavelet, thus making discrete wavelet analysis practicable.

The names of the Daubechies family wavelets are written dbN, where N is the order, and db is the "surname" of the wavelet. The db1 wavelet, as mentioned above, is the same as Haar wavelet (Gubareva et al. 2011).

The most of these family functions are not symmetric but dissymmetric of some these are deterministic. Functions regularity of this family is increased with increasing their orders. This family is orthogonal also (Gubareva et al. 2011).

Many researchers and scientist were believed Daubechies is the most exact functions in wavelet functions for analyzing of natural phenomena. Fig. 5 and Fig. 6 show the Daubechies10 wave and scale functions, respectively.

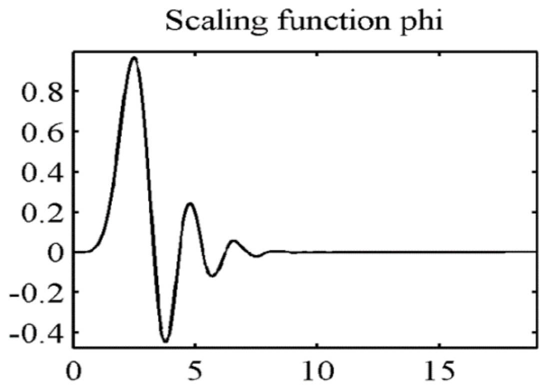

Fig. 5. Dubechies10 wave function.

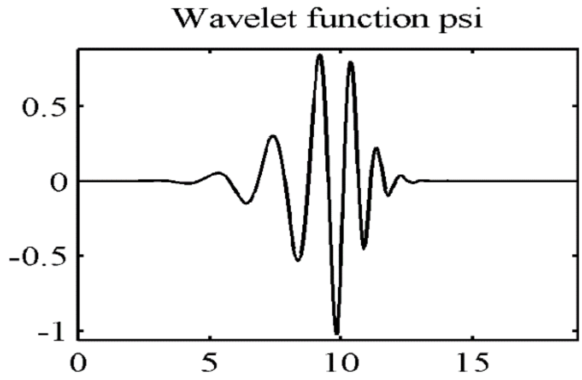

Fig. 6. Daubechies10 scaling function.

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4. Materials and methods

In this study FFA using wavelet transform has been considered. For this purpose a full series of Tollat discharge data was used for making wavelet model. For this purpose, time period of study has been reduced from 52 years to about 33 years. Fig. 7 shows this signal, it contained more than 12000 data.

After making signal, next step is selection of wavelet function and its decomposition level. When is used wavelet transform, selection of wavelet function and decomposition optimized level is so important. One of the important and base points is choosing mother wavelet based on phenomena natural and series type. So each mother wavelet function pattern that make a better set adaption in geometry aspect to time series, gets better results. In this paper furthermore this important case, density function form of wavelet modeling was also considered. After choosing wavelet function, next important step is selection of decomposition level.

In theory decomposition process can continue infinitely, but really decomposition process cans perform to signal details involve one pixel only. In a signal decomposition using maximum decomposition is not correct because although it improves computations accuracy in network training have inverse result on simulated data, because over training of network pattern to training data.

In this paper the simplest and first wavelet function was used, Haar. Also Daubechies function was used in two levels.

At the end of this study, the wavelet results were compared with some traditional methods, such as AM and PD.

4.1. Analysis and investigation of data

In this part of study was investigated used data for different methods. In AM method 52 year data of Tollat station on Polroud River was used. In all of study period, the smallest data is 0.4 m^3/sec and the largest data is 537 m^3/sec. The mean and standard deviation (Std) of AM data are 119.42 and 93.84 m^3/sec, respectively.

When normal distribution was used in AM and PD methods, data have to fitness to normal distribution, this subject was investigated drawing data on normal paper (Fig. 8).

Fig. 8 clearly shows that Polroud data is not normal, so for using these data in normal distribution, must become normal. This can be done by different methods, that in this paper Box-Cox formula was used for normalization of data (Golizadeh et al. 2011). This normalization results are showed in Fig. 9. This picture clearly shows that data was normalized well. Used data in AM and PD methods was investigated for stationary, stability and homogeneity and station, stable and homogenous data was used finally.

For many days in 52 years period has not recorded any discharge and this make an incomplete series, for solving this problem two ways: at first, reproduce artificial data for no discharge days that have a special problems and mistakes. And second, used a period of time that has complete discharge data. Second method was selected because an about 33 years period was distinguished in studying period, in other hand from many researchers point a minimum 30 years period is enough (Grimaldi et al. 2006).

In this study for FFA using wavelet transform 3 TS were used: first series is almost 33 years period that contain all the data, mean and standard deviation of data are 15.75 m^3/sec and 17.85 m^3/sec, respectively. This series called 100 % or full series in this paper. Second series is produced from omitting of all the data smaller than 80 % of the least AM discharge, mean and standard deviation of this series are 40.17 m^3/sec and 26.02 m^3/sec, respectively. This series called 80 % series. And the last series produced like second series but in this case the criteria for omitting the data is the data smaller than 95 % of the least AM discharge or 25.8 m^3/sec (called 95% series). Fig. 7 shows the full series (100 %).

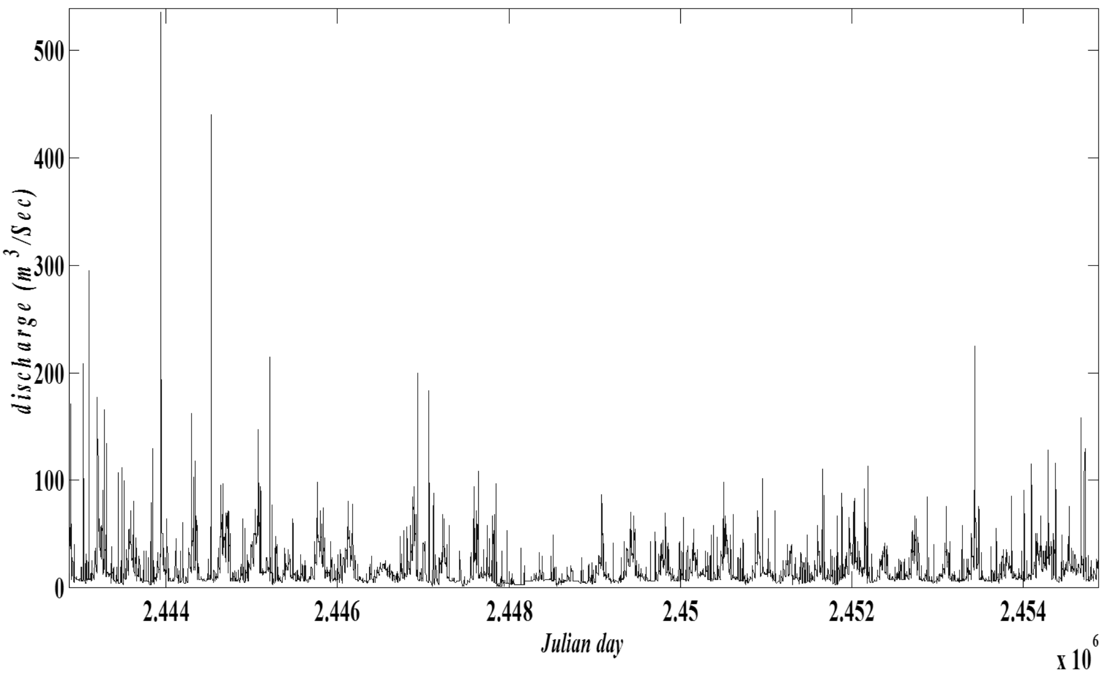

Fig. 7. Full time series for 32years period (100 % of data).

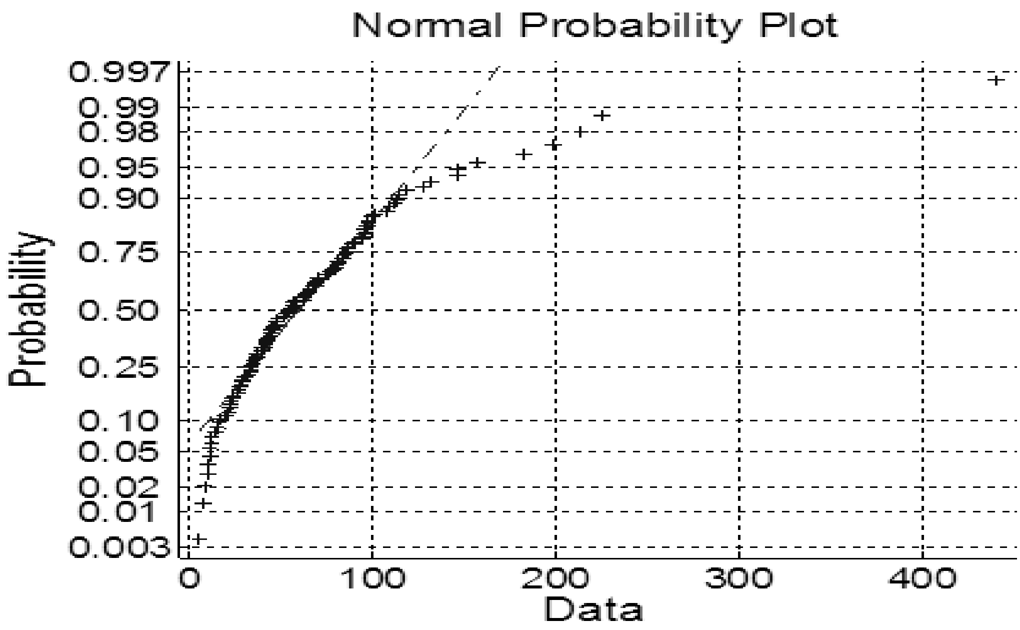

Fig. 8. Polroud discharges data on normal paper.

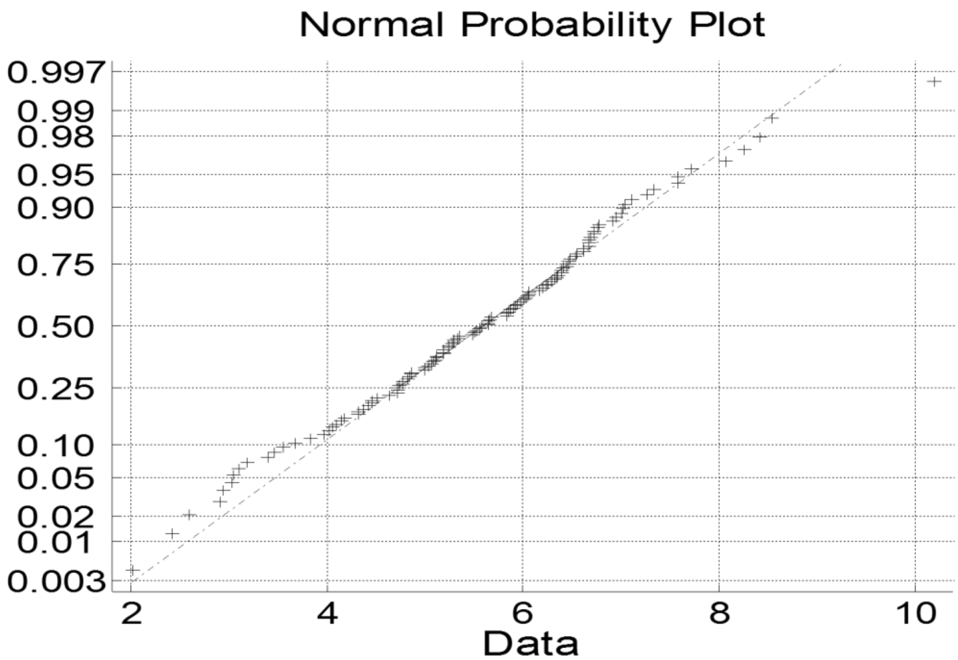

Fig. 9. Polroud normalized data on normal paper.

5. Results and discussion

In this section, we present flood frequency analyses for Polroud Basin, focusing on wavelet transform method. Fig. 10 shows the probability density distribution function related to TS that shows in Fig. 7. Also Fig. 11 shows Daubechies10 in second level of decomposition.

Table 3 shows the FFA results on full TS (100 % of data) using Haar1 and Daubechies10 with determined decomposition levels for different return periods. Table 4 and Table 5 show the results for TS 80 % and TS 95 %, respectively.

Table 3. Flood frequency analysis using haar and Duabechies10 with full series (100 % of data).

Return period	Probability	Discharge (m^3/s) Haar	Discharge (m^3/s) Dubechies10
2	0.5	6.63	8.13
10	0.1	32.49	31.85
25	0.04	48.38	48.32
50	0.02	61.58	60.93
100	0.01	76.44	75.63
1000	0.001	189.9	189.02

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FFA results on Polroud River presented using two wavelet functions, Haar and Daubechies10, with full and combined series. Now FFA results compute using Tollat station AM and PD data.

For FFA using methods that data fitted to a special distribution, investigation of stationary, stability and homogeneity is necessary. All of these computations were performed on AM data and PD daily maximum discharge. Table 6 and Table 7 show these results, respectively. Investigation of these conditions was performed using Mann-Witeny and Wald-Wolfowitz, furthermore stationary was investigated in both cases.

Table 4. Flood frequency analysis using haar and Duabechies10 with 80 % time series.

Return period	Probability	Discharge (m^3/s) Haar	Discharge (m^3/s) Dubechies10
2	0.5	31.3	31.6
10	0.1	60.4	60.2
25	0.04	81.8	81.4
50	0.02	101.5	102.6
100	0.01	138.4	138.6
1000	0.001	293.7	293.7

Table 5. Flood frequency analysis using haar and Duabechies10 with 95 % time series.

Return period (year)	Probability	Discharge (m^3/s) Haar	Discharge (m^3/s) Dubechies10
2	0.5	36.2	36.0
10	0.1	65.5	65.3
25	0.04	89.2	89.3
50	0.02	111.2	111.5
100	0.01	160.2	159.5
1000	0.001	436.1	297.5

Table 6. Flood frequency analysis using annual maximum data and fit to LP3 and exponential distribution.

Return period (year)	Probability of occurrence	Discharge (m^3/s) LP3	Discharge (m^3/s) Exponential
2	0.5	92.3	90.6
10	0.1	215.7	241.6
25	0.04	311.6	327.6
50	0.02	400.5	392.7
100	0.01	508.5	457.7

Table 7. Flood frequency analysis using partial series and fit to normal distribution.

Return period (year)	Probability of occurrence	Discharge (m^3/s)
2	0.5	66.9
10	0.1	136.5
25	0.04	162.0
50	0.02	178.5
100	0.01	192.3
1000	0.001	234.9

5.1. Comparison of results

At the end of this section, a general comparison between results of all methods was presented. Graphical results of all presented methods in this paper are showed in Fig. 12. In this figure, AM results was presented using Log-Pearson 3 (LP3) and wavelet results in two different type: full series and TS 5 % and also mean of 5 different wavelet functions (Haar, Daubechies3, Daubechies10, Symlet4 and Coiflet2). The time axis (horizontal axis) is logarithmic.

An exact investigation of Fig. 12 shows that:

a) AM result is the most overestimating method. This overestimation about Polroud data is clearer, because its distribution is exponential and in its AM data time series only 0.06 % of data is more than 200 m^3/sec and these numbers of data distributed in different years.

b) In PD series, used data is about three times larger than AM series and almost all the added data is smaller than AM series data, so that results of this method is smaller than AM results as predicted.

c) Above trend is continued in wavelet analysis, means with using a larger size of small data, results are becoming smaller and more accurate.

d) When 5 % series is used estimations are much larger than full series is used.

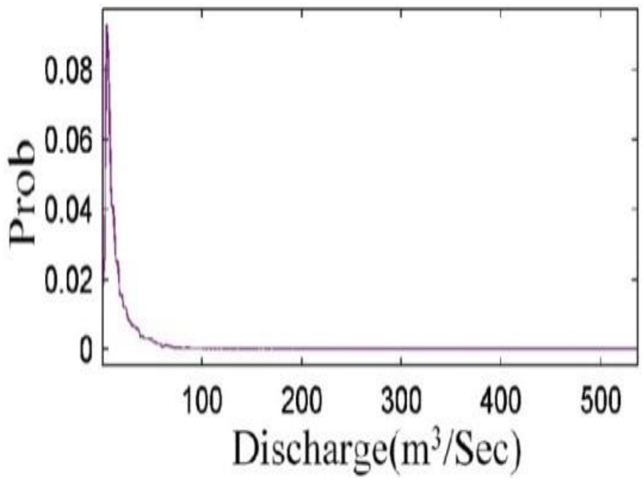

Fig.10. Probability distribution function of wavelet analysis time series (Haar1).

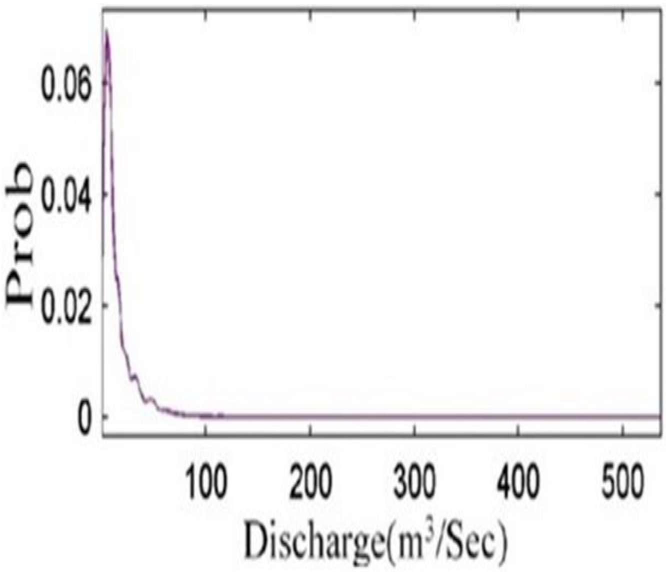

Fig. 11. Probability distribution function of wavelet analysis time series (daubechies10).

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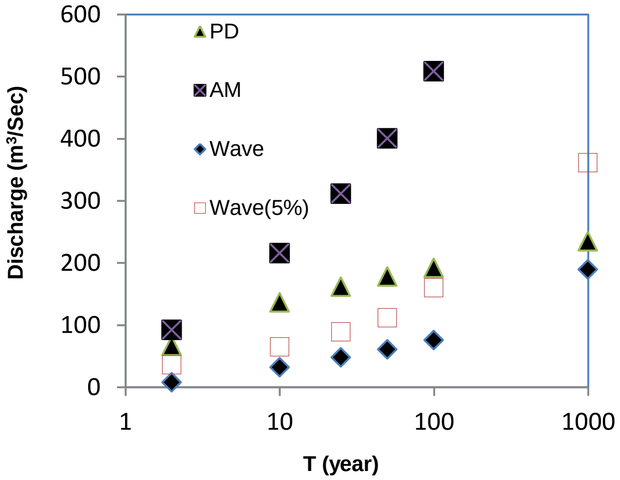

Fig. 12. Graphical comparison for diffrent methods of flood frequency analysis on Polroud river.

6. Conclusion

Presentation of variety of methods of FFA in more than last half century can't cause less consideration by researchers to this branch of hydrology, which shows the importance of FFA. Results collection of this paper shows that when numerous of small data are so going up, the model is prepared smaller analysis results. Briefly, when frequently of small data is too much and large data is occurred rarely, dependence of study aim different method can use. But when data distribution almost is uniform or has a collection of too small data only, wavelet can present the very exact results. According to last studies, statistical methods are contained too mistake hypothesis and although their large results, those ones are not closed to accurate results. In general, for every project, researcher must select the best method based on the hydrological studying of watershed and available data.

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