Utilizing the Recursive Digital Filters based on the isotopic tracers in flood hydrograph simulation (case study: abolabas river basin)

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Abstract
Environmental conditions of the basin and the relationship between groundwater and river play an important role in selecting the appropriate method for separating the base flow from flood hydrograph. This is of great importance in Abolabas karstic basin. Straight line, variable slope and recursive digital filters optimized with isotopic tracers were used to separate the base flow. Runoff was simulated by geomorphological instantaneous unit hydrograph model. GIUH model was calculated as a function of geomorphologic parameters including bifurcation ratio, area ratio, length ratio, the peak flow velocity in the outlet and the stream length of last order. In this study, two rainfall-runoff events with isotopic tracer data were studied under wet antecedent moisture conditions. RMSE, R^2, PEP% and PETP% showed the superiority of RDFs optimized with isotopic tracers in the flow simulation. However, two rainfall-runoff events lacking isotopic tracer data were studied under wet antecedent moisture conditions to evaluate the performance of this method. The statistical measures approved the performance of RDFs with isotopic tracers in flood hydrograph simulation.

Key words: IUH, Geomorphology, RDFs, Trace, Isotope, Base Flow.

1. Introduction

Extreme weather events have increased significantly in recent decades due to global warming(Wasko, Westra et al. 2021). Iran's climate is generally semi-arid, with frequent flooding causing significant damage to people and society (Zoratipour and Hydari 2022).
Adib, Salarijazi et al. (2011) compared four validations of the CLARK model as well as the calculated flood hydrographs resulted from the GCIUH-CLARK model and observational hydrographs. Their findings reflected the satisfactory responses of the two models, but the lack of need for calibration and use of historical rainfall data were the advantages of the GCIUH-CLARK model over the other model.

Eidipour, Akhond-Ali et al. (2016) used GIUH model to simulate runoff in the Abolabas basin. To evaluate excess rainfall in the Abolabas karstic basin, they used initial-proportional and initial-constant losses. The results showed the superiority of initial-proportional losses in simulating flood hydrograph. One of the important components of runoff hydrograph modeling is estimating the base flow which is associated with subsurface flows and groundwater reserves. Since field observation data are not available in most cases, different methods are used to estimate the base flow. This can strongly affect the accuracy of runoff hydrograph simulation. So far, several methods have been provided for separating flow components. These methods are classified into two groups of analytical and non-analytical methods. Non-analytical methods include the use of chemical or isotopic tracers to determine the ratios of surface flow, subsurface flow, and groundwater. Much effort has been made to use natural and synthetic tracers for hydrograph separation including the use of the chemical data of groundwater and runoff. But it soon became apparent that none of these parameters are suitable because of instability or unspecified source. However, environmental isotopes are suitable because of high stability (Mu, Wu et al. 2021, Qin, Han et al. 2021).
Stable isotopes are used for the separation of hydrographs based on the difference between the isotopic composition of groundwater and rain. The isotopic composition of groundwater indicates the long-term average isotope input, while storms have a different isotopic composition. If there is no difference between the isotopic content of groundwater and storm, hydrograph separation by isotopes is impossible. Since a combination of chemical and isotopic tracers identify the flow path in a small catchment in the east of France, (Ladouche, Probst et al. 2001) determined flow components using chemical and isotopic tracers with a focus on time and spatial variability of resources for a 40 mm precipitation. Isotopic hydrograph separation showed that the peak flow accounts only for 2 to 13 percent of the flow in any event and the rest belongs to other delayed resources. In fact, this study showed that a combination of different types of hydrometric data and geochemical and isotopic tracing will be helpful in identifying flow components.
Yang, Xiao et al. (2021) with using The two-parameter recursive digital filter method (Eckhardt) and the conductivity mass balance (CMB) method solved this disagreement by analyzing the effectiveness of the CMB method for correcting the Eckhardt method through application of the methods to 26 basins in the United States by comparison of the biases between the generated daily baseflow series.
Zarei, Akhond-Ali et al. (2014) studied the runoff production process in Abolabas karstic basin with an arid and semi-arid climate using hydrometric data in combination with isotopic tracers. In the rainy season, they sampled three rainfall events considering the role of antecedent moisture and their corresponding floods. Their results showed that the share of groundwater in the Abolabas karstic basin is greater than that of runoff from rainfall. In addition, the share of surface runoff and flow components before and after the rain was very sensitive to antecedent moisture.
Analytical methods are classified according to different views about changes in the base flow during surface runoff. Scientists like Lyne and Hollick (1979), Nathan and McMahon (1990), Chapman (1991) were pioneers in the use of a recursive digital filter in hydrology. He considered the daily discharge time series as a combination of base flow corresponding to low-frequency sound waves and fast flow corresponding to high-frequency sound waves. Nathan and McMahon (1990) defined a general framework for the base flow and indicated that base flow separation is quick and purposeful using a filter parameter of 0.925.

Eckhardt (2005) assumed a linear relationship between outflow from an unconfined aquifer and groundwater reserves. He proposed a filtering algorithm for separating the base flow using two constant parameters of recursion and maximum base flow index (BFI_{max}).

According to Mason-Deese (2013) the path flow defined by the recursive digital filter can be used as the base flow in ungauged basins. Flood and base flow in the Panola basin were separated by geochemical separation. Recursive digital filter parameters were optimized using the base flow values obtained from geochemical techniques and the results were compared with those obtained from the geochemical base flow.

Literature shows the need for estimating runoff hydrograph in ungauged basins. This is why in this study, Abolabas runoff hydrograph was estimated using geomorphological instantaneous unit hydrograph model. Abolabas basin is a karstic basin with a complex reaction to the entry of precipitation. Due to the significant impact of base flow separation method on runoff hydrograph simulation, three base flow separation methods including straight line (SL), variable slope (VS) and recursive digital filters (RDFs) optimized with isotopic tracers were compared to show the effect of base flow separation methods on runoff hydrograph modeling quantitatively.

2. Material & Methods

2.1 Case study

In this research, the data provided by the Pol Manjaniq hydrometry station, which is located on the outlet of Abolabas Basin in the Southwest of Iran, East of Khuzestan Province, and Northeast of Baqmalek City, was used. This station is established over the Abolabas River, with geographical coordinates of $49^{\circ}53'31''$ eastern longitude and $31^{\circ}31'07''$ northern latitude. The spread of lime formations with large thicknesses, the weather suitable for karst development, and active tectonics have set the scene for the formation and spread of karst in the study area. Infiltration of rainfall water through fractured porous spaces during consecutive years, and development of joints and dissolution ducts in lime masses have provided for formation of karst water resources in this region (Zarei, Akhond-Ali et al. 2014).

2.2 Non tracer based base flow separation

In the Straight Line (SL) method, the starting and end points are simply connected by a straight line and the corresponding discharge is assumed to be the base flow discharge In the Variable Slope (VS) method, the base flow curve is extrapolated forward before the surface runoff. The flow curve after stopping the surface runoff, i.e. the inflection point on the Ression curve is extrapolated and is connected by a straight (Chow *et al.*, 1988). This method is used when the groundwater level is high and the flow in streams is directly related to groundwater. As a result, after flow Ression in the stream, groundwater storage is immediately discharged to the stream (Gonzales, Nonner et al. 2009).

2.3 RDFs optimized with isotopic tracers based base flow separation

RDF is a numerical algorithm used in signal processing and analysis first developed by (Lyne and Hollick 1979). This algorithm is used in hydrology for separating river hydrograph to high-frequency (direct runoff) and low- frequency (base flow) components as follows (Nathan and McMahon 1990):

$$b_k = \alpha b_{k-1} + \frac{(1+\alpha)}{2}(y_k - y_{k-1}) \qquad b_k \le y_k \qquad (1)$$

Where y is the entire flow, b the base flow, α the filter parameter and k is the time step counter. (Eckhardt 2005) proposed the following algorithm:

$$b_k = \frac{(1 - BF\,\mathrm{Im}\,ax)\alpha b_{k-1} + (1-\alpha)BF\,\mathrm{Im}\,ax}{1 - \alpha BF\,\mathrm{Im}\,ax} \qquad b_k \le y_k \qquad (2)$$

Where BFImax is the maximum base flow index. By optimizing the recursive digital filters with chemical or isotopic tracer data, the base flow can be estimated in single flood events(Abebe, Endalie et al. 2022, Zhong, Li et al. 2022).

2-3 Determinig Excess Rainfall Using the Initial-proportional loss Method

As long as the cumulative rainfall over the permeable region does not exceed the initial losses, no surface flow emerges. In this method, value of rainfall from the beginning of rainfall to the emergence of runoffs is considered the initial loss and is subtracted from the total rainfall value (Cordery 1987). In this method, values of the proportional loss model are constant depending on the portion of rainfall that transforms into excess rainfall in each Δt interval (Fig. 2).

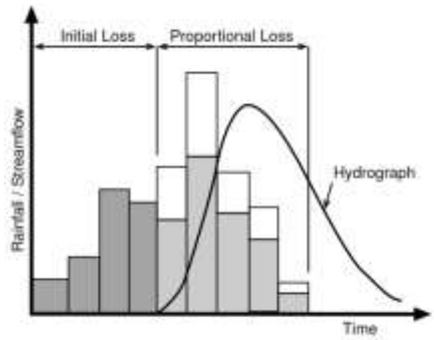

Figure 2: Initial-proportional loss method (Hill, Mein et al. 1998)

In this model, loss rate is not constant and depends on the depth of rainfall in the time interval.
To determine that percentage of rainfall that turns into loss, the notion of surface flow is used. In a very common definition, the runoff coefficient is equal to the ratio of direct peak runoff rate to the mean rainfall intensity in an event. Due to the considerable changes in intensity of rainfall, it is hard to determine the runoff coefficient based on observational data (Kaboli and Akhond-Ali 2015). The runoff coefficient may be expressed as the ratio of runoff to rainfall in an event.

2-4 Geomorphological Instantaneous Unit Hydrograph Model

In the theory of Geomorphological Instantaneous Unit Hydrograph (GIUH), it was tried to link the hydrograph with the geomorphological specifications of a basin so as to assess the hydrologic response of that basin to surface runoffs. Based on hydrodynamic parameters, it is possible to calculate the peak flood velocity. Using the basin geomorphological parameters, such as branch ratio (R_B), area ratio

(R_A), length ratio (R_L) (Horton 1945, Strahler 1957), and length of the watercourse with the highest level (L_Ω), it is possible to obtain the GIUH hydrograph (Table 1).

Table (1): Geomorphological parameters of Abolabas Basin used in the GIUH model)

Value	Unit	Parameter
3.63	Dimensionless	R_B
4.1	Dimensionless	R_A
1.91	Dimensionless	R_L
10.86	Kilometer	L_Ω

(Rodriguez-Iturbe and Valdes 1979) proposed relations (3) and (4) for estimation of peak discharge and peak time in GIUH.

$$q_p = \frac{1.31}{L_\Omega} R_L^{0.43} v \tag{3}$$

$$t_p = 0.44\left(\frac{L_\Omega}{V}\right).\left(\frac{R_B}{R_A}\right)^{0.55} R_L^{-0.38} \tag{4}$$

If values of peak discharge and time to peak of a GIUH hydrograph are determined accurately, the precise and perfect shape of the hydrograph do not matter significantly and a triangular approximation suffices (Rodriguez-Iturbe and Rinaldo 1997). Hence,

$$q_p.t_b = 2 \tag{5}$$

2-5 Comparing and Assessing Model Performances

In this study, two statistical criteria, namely the coefficient of determination (R^2) and Root Mean Square Error (RMSE), were used to assess the simulations of hydrograph shapes (Relations 6 and 7).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Q_o - Q_c)^2}{n}} \tag{6}$$

$$R^2 = \frac{\left[\sum(Q_o - \overline{Q_o})(Q_c - \overline{Q_c})\right]^2}{\sum(Q_o - \overline{Q_o})^2 \sum(Q_c - \overline{Q_c})^2} \tag{7}$$

Moreover, to assess the specifications of the calculated hydrograph, peak discharge estimation error (%) and time to peak estimation error (%) were calculated via relations (8) and (9).

$$PEP = \left(\frac{Q_{pc}}{Q_{po}} - 1\right) \times 100 \tag{8}$$

$$PETP = \left(\frac{T_{pc}}{T_{po}} - 1\right) \times 100 \tag{9}$$

Where, Q_0 is the observed discharge, Q_c is the calculated discharge, $\overline{Q_o}$ is the mean observed discharge, $\overline{Q_c}$ is the mean calculated discharge, Q_{pc} is the calculated peak discharge, Q_{po} is the observed peak discharge, T_{pc} is the calculated time to peak, and T_{po} is the observed time to peak.

3. Results

separated the base flow in 15.01.2011 and 01.30.2011 events using isotopic tracers. The base flow obtained by isotopic tracers was used for optimizing the recursive digital filters. Eckardt and Lyne–Hollick filter parameters were calculated by RMSE minimization. The resulting Eckardt filter optimized with isotopic tracer (EFOIT) and Lyne-Hollick filter optimized with isotopic tracer (LFOIT) are respectively shown in Tables 2 and 3.

Table 2: EFOIT parameters

EVENTS	RMSE	BFImax	α
15.01.2011	0.57	0.77	0.32
30.01. 2011	0.79	0.80	0.47
AVE	-	0.785	0.395

Table 3: LFOIT parameters

EVENTS	RMSE	α
15.01. 2011	0.95	0.96
30.01 2011	1.13	0.98
AVE	-	0.97

3.1. Flood hydrograph simulation

To investigate the effect of base flow on GIUH-simulated flood hydrograph, the straight line (SL), Variable slope (VS) and Eckardt filter optimized with isotopic tracer (EFOIT) were used. Statistical values of storm events with isotopic tracer data are shown in Table 4. Events lacking isotopic tracer data are presented in Table 5.

Table 4: Statistical criteria of events with isotopic tracer data

NUMBER	DATE	BASE FLOW MODELS	RMSE	R^2	PEP%	PETP%
1	15.01.2011	SL	0.51	0.8	-26.24	0
		VS	2.62	0.27	-15.71	-6.25
		EFOIT	0.22	0.92	-4.79	0
2	30.01. 2011	SL	4.07	0.14	-57.18	-19.35
		VS	7.09	0.02	-39.2	-25.8
		EFOIT	0.49	0.90	-15.69	0

Table 5: Statistical criteria of events lacking isotopic tracer data

NUMBER	DATE	BASE FLOW MODELS	RMSE	R^2	PEP%	PETP%
1	03.03.1996	SL	6.01	0.53	-2.70	4.16
		VS	6.73	0.83	33.64	0
		EFOIT	1.96	0.93	-10.96	0
2	11.12.2000	SL	0.84	0.79	-27.5	0
		VS	0.46	0.97	16.88	0
		EFOIT	0.44	0.94	-10.41	0

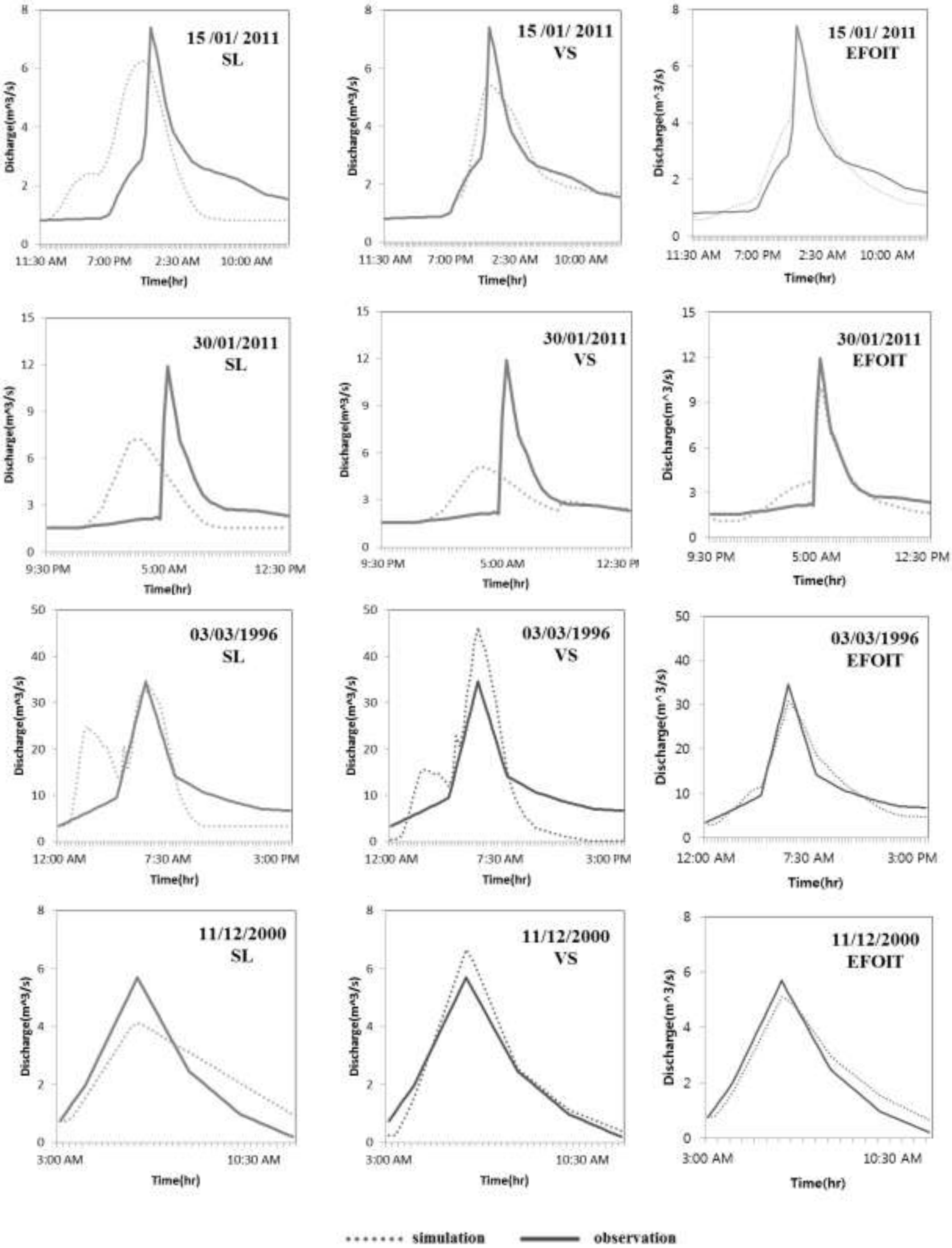

Figure 5: The effect of base flow separation method on flood hydrograph simulation

4. Discussion

RMSE values (Tables 2 and 3) show that Eckardt filter outperforms Lyne-Hollick filter. It seems that the two-parameter Eckardt filter leads to greater adaptation of the base flow obtained by isotopic tracers. Hence, Eckardt filter was selected for base flow separation. The base flow was separated by Eckardt filter optimized by an isotopic tracer.

Events on 03.03.1996 and 11.12.2000 under wet antecedent moisture conditions (ACM) are similar to those with isotopic tracer data. The parameter *a* equals 0.395 and BFI_{max} is equal to 0.785. These are the mean values of EFOIT parameters in Table 3. RMSE and R^2 values (Table 4) show the superiority of EFOIT model in base flow separation compared to straight line and variable slope methods. Between conventional methods of base flow separation, straight-line method outperforms variable slope method.

Percentage error in peak (PEP %) and percentage error in time to peak (PETP %) in EFOIT method are less than those in straight-line and variable slope methods. PEP% as the most important parameter in the design of hydraulic structures is improved in base flow separation by the variable slope as compared to straight-line method. In contrast, straight line outperforms the variable slope method in estimating the time to reach the peak discharge.

Considering the two events on 03.03.1996 and 11.12.2000 to assess the generalizability of the model in wet antecedent moisture conditions, statistical criteria were analyzed (Table 5). According to RMSE and R^2 values, EFOIT model outperforms straight line and variable slope methods in base flow separation. In addition, variable slope method clearly outperforms the straight line base flow separation. In the event on 0.3.03.1996, straight line method showed a lower percentage error peak (PEP %) than other methods. But the simulated hydrograph clearly shows two peaks indicating unsuitability of the straight line method (Figure 5).

5. Conclusions

Effective rainfall was estimated by initial-proportional losses. Runoff was simulated by geomorphological instantaneous unit hydrograph model. Since calibration process is not required, According to the research of (Andrieu, Moussa et al. 2021) GIUH is a good model to evaluate the impact of flow components on flood hydrograph simulation. Because of the complexity of rainfall-runoff in karstic basins, river base flow should be estimated more accurately. Accordingly, flood hydrograph simulation in ungauged karstic basins deals with more restrictions than other ungauged basins. Hence, straight-line, variable slope and recursive digital filter optimized with isotopic tracers were used for base flow separation.

Hydrographs simulated by GIUH model using different base flow separation methods showed that EFOIT outperforms straight line and variable slope methods in simulating flood hydrograph, although it slightly underestimates the peak discharge. According to the results, the coefficient of determination (R^2) in the EFOIT method was higher than 0.9 in all events. But R^2 was not constant in the straight line and variable slope methods. RMSE and PEP% were minimum in the EFOIT method. PETP% in the EFOIT method was equal to zero for all events.

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