



**Runoff generation processes during the wet-up phase in asemi-arid basin**

H. Zarei et al.

# Runoff generation processes during the wet-up phase in a semi-arid basin in Iran

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[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



## Abstract

Understanding the hydrological processes in catchments is important for water resources management, particularly in semi-arid regions of the world. To contribute to this field, dominant runoff generation processes in a semi-arid basin (283 km<sup>2</sup>) in Southwestern Iran were investigated using analysis of hydrometric data in combination with natural isotopic tracers through the wet-up phase of a rainy season. The analysis of seven rainfall–runoff events during the rainfall dominated period illustrated the role of antecedent base flow and cumulative rainfall for explaining the hydrological response. Three distinct storm events and the corresponding discharge were collected and analyzed for oxygen-18 and deuterium isotope composition. The results show that during the wetting-up cycle, the runoff ratio during storm events increased progressively from 1 to 10 %. Higher event runoff ratios following catchment wet-up were shown to be directly linked to changes in soil moisture, which in turn controlled the runoff generation processes. In line with the hydrometric results, the two-component hydrograph separation using  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  demonstrated a clear connection to the antecedent wetness conditions. The results suggest that the runoff ratios during storms and the partitioning of event and pre-event water fractions are sensitive to the amount of catchment wet-up and could hence be strongly impacted by changes in the timing, duration and amount of precipitation in the future.

## 1 Introduction

Improving the understanding of hydrological processes in catchments is important for water management and the availability of surface water and groundwater resources, both in terms of quality and quantity (Hrachowitz et al., 2011). This is especially true in arid to semi-arid regions of the world where the lack of water often is a major limitation for the livelihood of humans. Gaining better insight into the hydrological functioning in these regions is therefore urgently needed especially in the light of climate change

## Runoff generation processes during the wet-up phase in a semi-arid basin

H. Zarei et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

that risks to further restrict the water availability in the future (Abbaspour et al., 2009; Hemadi et al., 2011; Zohrabi et al., 2011; Roshan and Grab, 2012). Hydrometric data and environmental isotopes are important tools that can be used to quantify the contributions of runoff components during different hydrological conditions and provide direct insights into the dominating hydrological processes (Didszun and Uhlenbrook, 2008; Lyon et al., 2008; Munyaneza et al., 2012).

The use of isotopic hydrograph separation (IHS) is one of the most powerful methodologies to understand hydrological processes. IHS is commonly used to determine the fractions of event (new) water and pre-event (old) water contributions to streamflow during hydrological episodes (Hooper and Shoemaker, 1986; Laudon and Slaymaker, 1997; Richey et al., 1998; Chen et al., 2008). Most previous work using IHS has been carried out in small basins in humid/boreal region (e.g. Uhlenbrook et al., 2002; Laudon et al., 2007; Blume et al., 2008; Wenninger et al., 2008). The general finding from most of these studies have been that the contributions from pre-event water during rain storms and snowmelt events are dominating. The dominance of pre-event water means that most water during the rain (or snowmelt) event comes from water already in the catchment prior to the precipitation event started, and hence only a small fraction of the stream water originates from the recent rainfall (or snowmelt). This finding has important implications for our understanding on how water is routed through the catchment and can provide valuable knowledge that can help maintain both the quality and quantity of our water resources.

Less research has been conducted in more water limited regions of the world using IHS (Mul et al., 2008; Bohté et al., 2010). This is especially true for the large parts of the Middle East which generally is characterized by an arid to semiarid climate with a strong seasonality in precipitation, including relatively wet winters and dry summers (Alijani and Harman, 1985; Ballato et al., 2010). This region is sensitive to climate change as an alteration in the water balance could affect the existence of millions of people. In populated regions with semi-arid climate, understanding hydrological

processes are even more essential since droughts can result in drinking water deficiency and severe crop loss.

In order to better understand the hydrological functioning of a semi-arid region we studied the hydrological response over one rain-season in the mountainous meso-scale

Abolabas basin in Iran. The objective of this work was to improve the basic understanding of (1) the hydrological response to rain episodes as the catchment is wetting up after almost six months of drought, and (2) the contribution of event/pre-event water change over this transition period. To answer these questions, seven events and corresponding discharge during one hydrologic year were monitored, of which three episodes were sampled for oxygen-18 and deuterium isotopes to quantify old and new water contributions to the total runoff.

## 2 Material and methods

### 2.1 Site description

This study was carried out in the meso-scale Abolabas karst basin, with an approximate catchment area of 283 km<sup>2</sup>, located in the Zagros Mountains in southwestern Iran (Fig. 1). The population of the city of Baghmalek and its vicinity that depend on the water from the catchment is approximately 65 000. Several small villages exist within the study catchment, generally living from subsistence agriculture. The basin is also of more general interest as it is an important headwater source for downstream cities and has therefore become one of the most investigated catchments in the country for hydrological research due to its importance as a drink water resource in the region and nationally (Saghafian and Ghermez Cheshmeh, 2008; Rezaei Sadr et al., 2012). Karst formations cover about 64 % of the total surface area of the basin. Elevation ranges from 691 to 3283 m.a.s.l., with an average elevation of 1885 m; where the higher regions are characterized by steep slopes, often with shallow soil coverage and the lower parts mainly consist of deep alluvial deposits.

## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The long term mean annual precipitation and temperature is 825 mm and 21 °C, respectively. The annual average potential evapotranspiration at Baghmalek station is estimated to be 1457 mm. The majority of precipitation falls in the rainy season (November till April) in the form of rain and partly as snow at higher elevations. Runoff is dominated by rainfall between November and February, after that, snow melt from higher elevations become dominating.

## 2.2 Sampling and field measurements

The rainfall and discharge data were obtained from the hydrological database of Khuzestan Water and Power Authority, Ahvaz. There are two long-term monitored rain gauges in the catchment, Baghmalek station at lower elevation (720 m a.s.l.) is a continuously recording rain gauge and Malagha at an intermediate elevation (1080 m a.s.l.) is monitored manually on a daily basis (Fig. 1). Runoff was monitored at the Pole Manjeniq hydrological station continuously (Fig. 1) using an established relationship between the stage and discharge.

Three distinct storm events and the corresponding discharge response were sampled for stable isotope composition of oxygen-18 ( $\delta^{18}\text{O}$ ) and deuterium ( $\delta^2\text{H}$ ) during the rainy season of December 2010 to February 2011. For each event spatially distributed temporary rain gauges were used to collect rain water in the basin. Precipitation was collected at six sites for each event (Fig. 1) using simple devices consisting of a collection area of 0.04 m<sup>2</sup>. The funnel shaped collection device was connected to the sample bottle by a U-shaped trap designed to remain filled with water after the precipitation event, thus protecting the water sample from evaporation and associated isotopic fractionation. Water samples from the main channel of Abolabas River at Pole Manjeniq station were collected manually every 30 min during the three events. The water samples were collected into 60 mL polyethylene wide-mouth round bottles. Prior to sampling, new bottles were treated with 10 % HCl, washed with deionized water at least three times, and rewashed three times in-situ using stream water. Water samples were hand-dipped along the shore at a water depth of 10–15 cm at a turbulent section

## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



of the river. Sample bottles were filled to the brim without trapping any air bubbles and kept refrigerated at the water quality laboratory of Ahvaz University. Finally based on the discharge fluctuations, a total of 60 samples (42 stream, and 18 rain) were analyzed for isotopic content.

### 5 2.3 Laboratory analysis

The analyses were performed on an Isotope Ratio Mass Spectrometer (IRMS) Delta Plus XP (Thermo, Germany) interfaced with a Gas Bench II in G.G. Hatch stable isotope laboratory at University of Ottawa, Canada.

10 Oxygen-18 Analysis: samples and internal standards were flushed with a gas mixture of 2% CO<sub>2</sub> in helium off-line. The closed exetainers were left to equilibrate at room temperature for a minimum of 18 h.

15 Deuterium Analysis: to the samples and internal standards Hokko beads were added to the exetainer vials before being flushed with a gas mixture of 2% H<sub>2</sub> in helium off-line. The exetainers were left to equilibrate at 25.0 C for 1.5 h minimum (De Groot, 2008).

All data is reported in Delta notation  $\delta$ , the units are per mil (‰) and defined as

$$\delta = \frac{R_x - R_{\text{std}}}{R_{\text{std}}} \times 1000 \quad (1)$$

20 where  $R$  is the ratio of the abundance of the heavy to the light isotope,  $x$  denotes sample and std is an abbreviation for standard. The measurement precision for  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  were  $\pm 0.15$  and  $\pm 2\%$ , respectively. All  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values are reported as per mill (‰) and normalized to internal standards calibrated to International standards VSMOW.

## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## 2.4 Isotopic Hydrograph Separation (IHS) technique

For a conservative tracer, a simple mixing equation for a two-component hydrograph separation model is described as follows (see Buttle, 1994 for a review):

$$Q_t C_t = Q_p C_p + Q_e C_e \quad (2)$$

where  $C$  is the concentration of each solution,  $Q$  is the flow, and the subscripts  $t$ ,  $p$ , and  $e$  refer to pre-event water (old previously stored water as soil and groundwater), event water (new recently derived precipitation water), and total flow, respectively, together with a mass constrain.

$$Q_t = Q_p + Q_e \quad (3)$$

Following Eqs. (2) and (3), the proportion of flow that arises from pre-event may be written as

$$Q_p = \left( \frac{C_t - C_e}{C_p - C_e} \right) Q_t \quad (4)$$

This two-component mixing model was first used by Pinder and Jones (1969) for a variety of chemical tracers to quantify groundwater and direct runoff contributions to total runoff and has since been widely used. The details and assumptions of the hydrograph separation method are discussed in several previous studies (Sklash and Farvolden, 1979; Wels et al., 1991; Buttle, 1994). The basic assumption is that the isotopic composition of baseflow at the sampling point is representative for the pre-event water in the catchment and that composition of collected precipitation describes the event water (Buttle, 1994; Mul et al., 2008).

Due to spatial variation, hydrograph separation was in this paper performed using weighted mean values for each event, based on all collected rainfall samples (Mcdonnell et al., 1990):

### Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



$$\delta^{18}O = \frac{\sum_{i=1}^n P_i \delta_i}{\sum_{i=1}^n P_i} \quad (5)$$

where  $P_i$  and  $\delta_i$  denote fractionally collected rainfall depth and isotope content, respectively.

## 3 Results

### 3.1 Rainfall–runoff observations

Following a period of six months of drought conditions resulting in the annual low flow, the rainy season began in the beginning of December with several consecutive storm events (Fig. 2). The discharges at the outlet of the Abolabas catchment measured at the Pole Manjeniq gauging station, for data recorded from November 2010 till May 2011, ranged from low flow  $0.04 \text{ mm d}^{-1}$  to maximum flow of  $5.7 \text{ mm d}^{-1}$ . Total rainfall during the study period, from November 2010 to April 2011, was 393 mm which generated total a runoff of 107 mm, of which 27 % came during high flow events.

During the 2010/11 rainy season a total of eleven events were recorded of which seven events occurred during the rainfall dominated period, while the remaining four events occurred during the snowmelt period. Due to the lack of sufficient information about the isotopic composition of snowmelt, only the rainfall dominated period is discussed further. The characteristics of the rainfall–runoff events are presented in Table 1. The range of the runoff ratio (P/R) for the basin for seven storms ranged from below 1 to 10 %. The runoff ratio was at the start of the rainy season (below 1 %) but steadily increased (to approximately 10 %) as the wet season progressed.

To improve the understanding of hydrological processes in the catchment, strength of regression between runoff ratio and characteristics of the rainfall–runoff events are discussed and presented in Table 2. The results reveal a significant ( $P < 0.001$ ) exponential relationship between runoff ratio and base flow of the events (Fig. 3a) with





the 21.0 mm of rain was  $3.6 \text{ mm d}^{-1}$ . The rainfall had a mean  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  content of  $-3.73\text{‰}$  (SD  $0.43\text{‰}$ ) and  $-17.55\text{‰}$  (SD  $3.36\text{‰}$ ), respectively (Table 3). The initial  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  amount in stream water (pre-event water) was  $-4.83$  and  $-25.20\text{‰}$ , respectively. The episodic stream response was large small compared to event 1 but small compared to event 2 (Fig. 4e and f).

### 3.3 Results of isotopic hydrograph separation

A significant difference in the isotopic composition is necessary to perform a two-component hydrograph separation. This method limitation was fulfilled for the three events, with the lightest isotopic content (for both  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$ ) observed in the pre-event water, and the heaviest during rainfall.

Using the isotopic content of baseflow (pre-event), rainfall (event) and river water, the pre-event water fraction was calculated (Eq. 4). Results from the two-component hydrograph separations for the events 1, 2 and 4 are presented in Fig. 5. The two-component hydrograph separation model using  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  led to a dominance of pre-event water contribution for the investigated events at Pole Manjeniq station. Percentages of pre-event fraction, separated using  $\delta^{18}\text{O}$  for the peak flows and total event were 94 and 96 % (event 1), 56 and 72 % (event 2) and 53 and 92 % (event 4), respectively. Percentages of pre-event water, separated by  $\delta^2\text{H}$  at the peak flows and total event were similar with 100 and 99 % (event 1), 57 and 72 % (event 2) as well as 33 and 88 % (event 4), respectively.

## 4 Discussion

Improving the understanding of hydrological response in catchments is essential for water resources management. Numerous isotopic studies have focused on evaluating hydrological response in karst landscapes in humid regions around the world (e.g. Katz et al., 1997; Jones et al., 2000; Aquilina et al., 2006), often with the intention to improve

**Runoff generation processes during the wet-up phase in asemi-arid basin**

H. Zarei et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

the understanding of hydrological responses during episodes. However, few hydrograph separation studies have been conducted in semi-arid regions. Here we focus on a meso-scale karst basin during a wet-up period that began after six months of drought conditions. In order to improve the basic understanding of the hydrological response to rain episodes and to calculate the partitioning between event/pre-event water, a number of hydrological events during one hydrologic year were monitored and sampled for stable isotope composition of oxygen-18 ( $\delta^{18}\text{O}$ ) and deuterium ( $\delta^2\text{H}$ ).

The rainfall–runoff transformation is a complex and non-linear process. However the most important cause of non-linearity is likely represented by the effect of antecedent conditions (Rallison and Miller, 1981; Singh, 1988). The observed low runoff ratios (from  $< 1\%$  to  $\sim 10\%$ ) indicate that only a small fraction of the rainfall was directly translated to stream flow during individual events, especially during the first phase of the wet season. Two reasons can contribute to this pattern. The first is that precipitation at elevations above 2500 m.a.s.l arrives, and accumulate, as snow and hence approximately 30% of the catchment does not contribute to stream water during the period considered. This area is largest/smallest during January/April, respectively. However, even if the snow accumulation part of the catchment is significant, it is not large enough to explain the observed pattern.

The second factor is that following the six months of drought conditions most of the early precipitation results in a recharge of the catchment soil and result in that only a small fraction of the riparian areas closest to the river will contribute to stream flow. As the soils in the study catchment overlying the bedrock are porous with relatively high infiltration rates, most of the precipitation will infiltrate the soils resulting in little overland flow. As the catchment wets-up higher runoff ratios results, indicating an increased hillslope contribution. According to water level fluctuations of piezometer wells in the basin ground water level can increase by up to 16 m, during the rainy season (Anonymous, 2007). This suggests a large soil recharge potential and that the storm flow reaches the stream largely through the soil by subsurface runoff mechanisms. New rainwater is able to recharge the aquifer, possibly through fractures, and mobilizes older water that has

**Runoff generation processes during the wet-up phase in asemi-arid basin**

H. Zarei et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

been residing in smaller fractures and pores within the catchment soil and bedrock. This runoff generation mechanisms was supported by observed isotopic contents in stream water which are closer to the content of pre-event water for the three events (Table 2). The result is also in line with the results from other studies (Wenninger et al., 2008; Hrachowitz et al., 2011; Munyaneza et al., 2012) who found that event runoff ratios were low for most catchments with comparable semi-arid conditions.

In line with the hydrometric results, the two-component hydrograph separation using  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  demonstrated a clear connection to the antecedent wetness conditions. During event 1, which occurred during the driest conditions, the runoff consisted of close to 100 % pre-event water. As the catchment wetted up after some progressive rain storms, the portion of event water during events 2 and 4 became larger. Consistent with the increase in antecedent moisture, the amount of event water contribution increased during peak flow, suggesting a more direct link between rainfall and runoff. Still however, it can be concluded from the rainfall–runoff response analysis and the isotopic content of the stream water that the runoff generation was dominated by subsurface flows (Fig. 5). Similar findings have been reported from several other isotopic studies in humid regions (e.g. Sklash and Farvolden, 1979; Kennedy et al., 1986; Uhlenbrook et al., 2008) demonstrating that pre-event water and subsurface water contributions during episodes is a dominant process. Also the results fall well into the range of what was reported by others for catchments with similar climatic conditions (Hrachowitz et al., 2011; Munyaneza et al., 2012). Although generally in line with these previous studies, few have previously addressed the role of catchment wetting-up for runoff generation. While, groundwater sustained the flow during dry periods, more rapid runoff generation processes with larger event water fractions was observed as the catchment became successively wetter.

## 5 Conclusions

This study focused on the use of hydrometric measurements in combination with natural isotopic tracer methods for identifying the dominant runoff generation processes in a semi-arid karst basin. The results illustrate that runoff ratio generally is low indicating that only a small proportion of rainfall is translated into stream water during events, especially during the first phase of the wet season. Higher runoff ratios and larger event water fractions following catchment wet-up, were shown to be directly linked to changes in soil moisture, which in turn controlled the runoff generation processes. Over all, the results suggest that the storm event hydrology are sensitive the amount of catchment wet-up and hence could be strongly impacted if the timing, duration and amount of precipitation change in the future.

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# HESSD

11, 3787–3810, 2014

## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Runoff generation processes during the wet-up phase in asemi-arid basin**

H. Zarei et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

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## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.

**Table 1.** Characteristics of the rainfall–runoff events ( $P$ , amount of precipitation;  $I_p$ , intensity of precipitation;  $Q_0$ , initial stream flow;  $Q_{\max}$ , peak flow; RR, Runoff Ratio of event).

Event	Date	Antecedent moistures mm	$P$ mm	Cumulative rainfall mm	$I_p$ mm h <sup>-1</sup>	$Q_0$ m <sup>3</sup> s <sup>-1</sup>	$Q_{\max}$ m <sup>3</sup> s <sup>-1</sup>	RR (%)
1*	13 Dec 2010	1.0	12.0	15.3	21.35	0.36	2.23	0.8
2*	15 Jan 2011	31.0	25.2	88.7	9.63	0.81	7.41	2.6
3	27 Jan 2011	2.5	29.5	131.3	9.60	1.11	4.12	2.9
4*	31 Jan 2011	35.0	21.0	155.6	10.87	1.50	11.90	4.2
5	8 Feb 2011	9.0	19.0	190.0	6.0	1.50	3.31	5.3
6	10 Feb 2011	28.0	14.5	214.0	6.0	1.64	6.64	8.3
7	11 Feb 2011	25.0	15.5	242.0	8.1	2.00	11.20	10.5

\* The three isotopic sampled events.

Antecedent Moistures was calculated based on the accumulative rainfall in the 5 days ago.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.

**Table 2.** Strength of regression (adjusted  $R$ ) between Runoff Ratio and Characteristics of the rainfall–runoff events.

	Antecedent Moistures	Cumulative Rainfall	$Q_0$	$Q_{\max}$	$I_p$	$P$
Regression type	Ascending Power	Exponential	Exponential	Power	Descending Exponential	Linear
$R$	0.74	0.99	0.97	0.66	0.88	0.34
$P$ value	0.05	0.001	0.001	0.1	0.01	0.1

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.

**Table 3.** Isotopic contents observed in the study catchment during the investigated events.

	Parameter	Event 1		Event 2		Event 4	
		$\delta^{18}\text{O}$	$\delta^2\text{H}$	$\delta^{18}\text{O}$	$\delta^2\text{H}$	$\delta^{18}\text{O}$	$\delta^2\text{H}$
		(‰VSMOW)					
pre-event water	Mean	-4.77	-21.19	-4.85	-24.00	-4.83	-25.20
River	Count	10	10	16	16	16	16
	Max	-4.51	-20.98	-2.91	-5.09	-4.3	-20.12
	Mean	-4.65	-21.89	-3.95	-15.72	-4.73	-24.39
	Min	-4.77	-23.06	-4.85	-24.00	-4.91	-27.14
	Std	0.07	0.68	0.71	6.63	0.17	2.02
Rain	Count	6	6	6	6	6	6
	Max	-0.90	-2.20	-0.13	15.25	-3.07	-12.50
	Mean	-1.95	-7.74	-1.50	7.34	-3.73	-17.55
	Min	-2.83	-13.72	-2.06	3.92	-4.21	-21.36
	Std	0.76	4.33	0.71	4.14	0.43	3.36

Std: Standard deviation.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

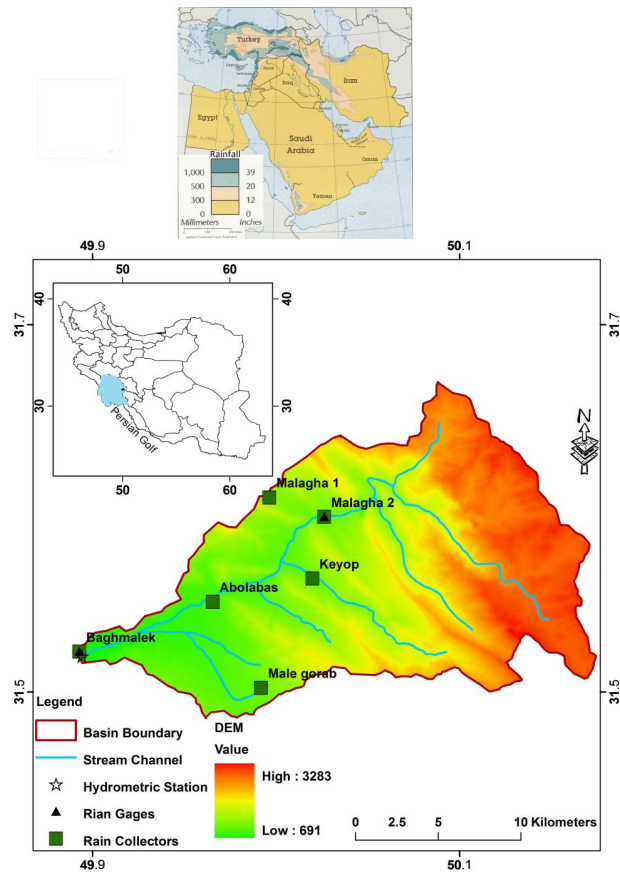


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11, 3787–3810, 2014

## Runoff generation processes during the wet-up phase in asemi-arid basin

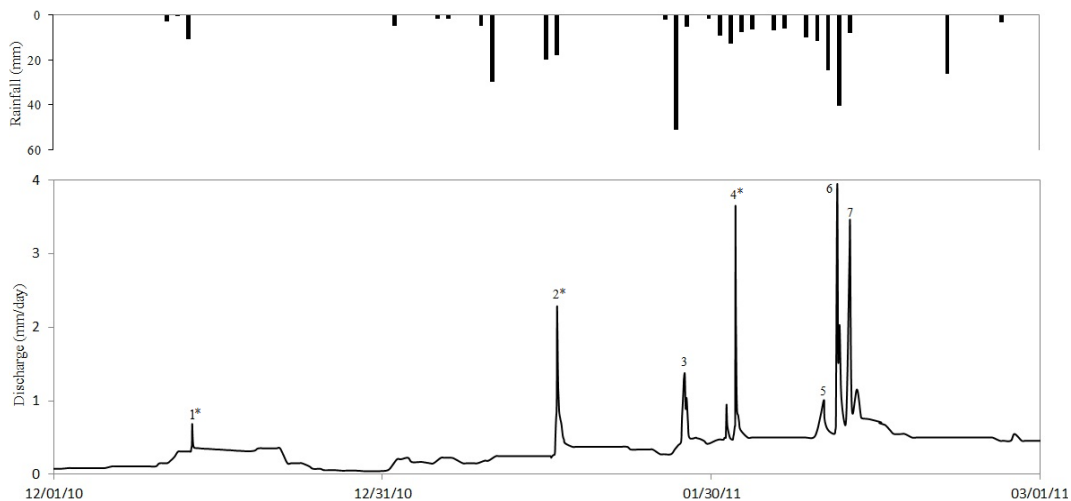
H. Zarei et al.



**Fig. 1.** Study area and distribution of rain sampling locations and Pole Manjeniq hydrometric station.

**Runoff generation processes during the wet-up phase in asemi-arid basin**

H. Zarei et al.

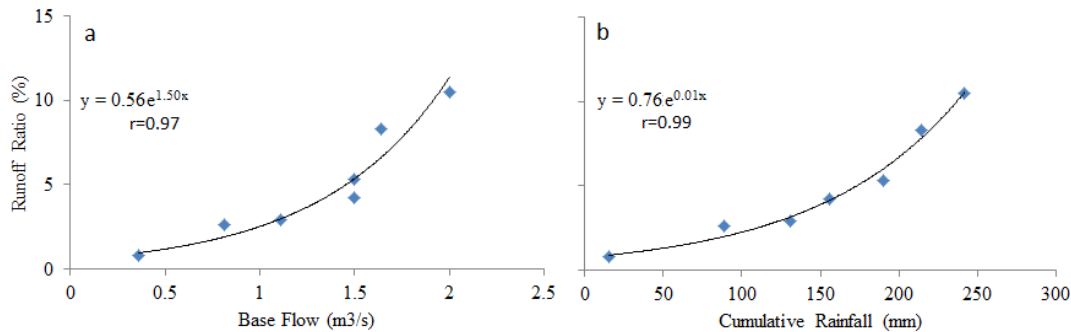


**Fig. 2.** Time series of rainfall and runoff for during wet season of hydrologic year 2010–2011 (October to April) at Pole Manjeniq station. The numbering of the event (1–7) are the labels for the events used throughout. The events marked with asterisks (\*) are the events analyzed for  $\delta^{18}\text{O}$  and deuterium ( $\delta^2\text{H}$ ).

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Runoff generation processes during the wet-up phase in asemi-arid basin**

H. Zarei et al.

**Fig. 3.** The correlation between runoff ratio **(a)** base flow and **(b)** cumulative rainfall.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

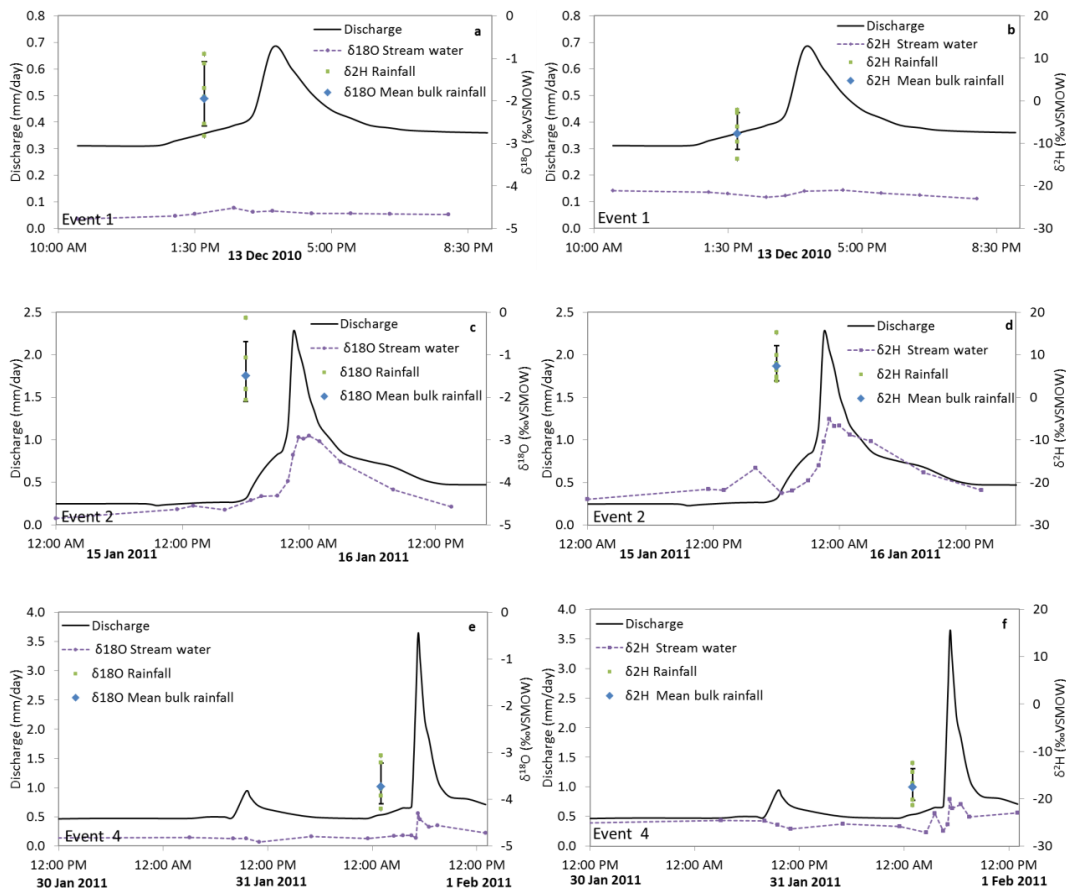
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.



**Fig. 4.** Variations of  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  during three investigated events. The error bars in the rainfall denotes the standard deviation of the precipitation.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

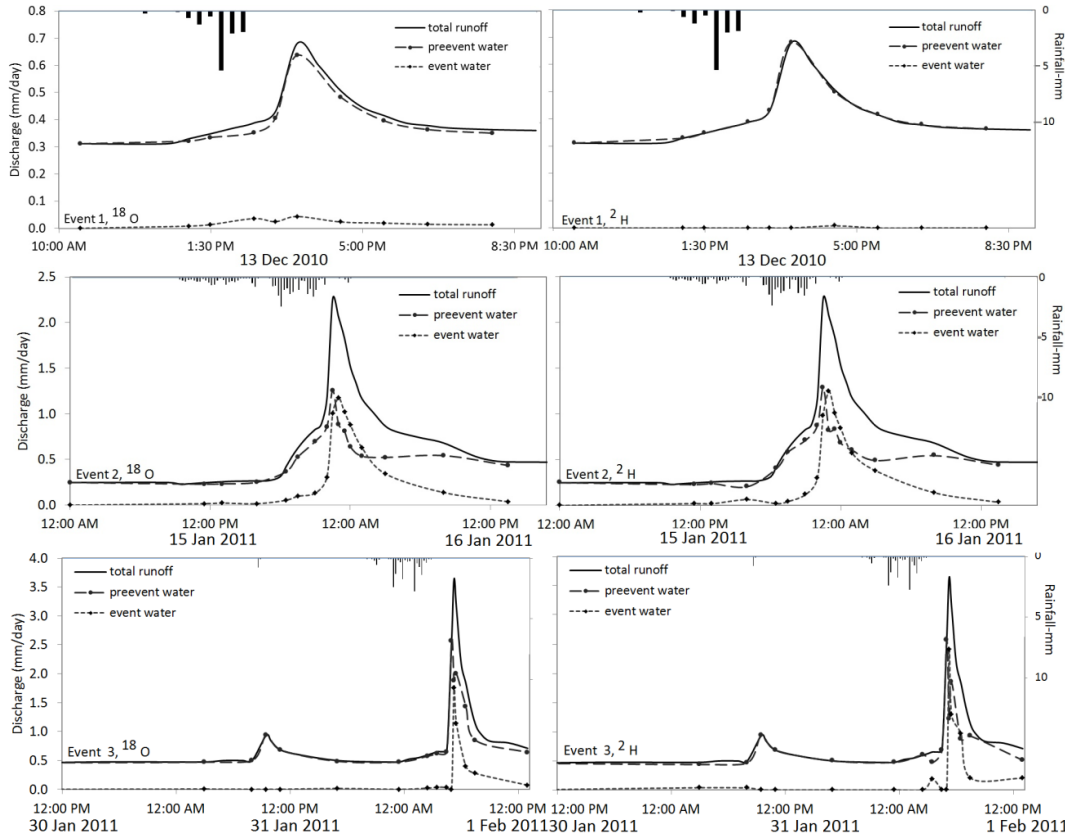
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

## Runoff generation processes during the wet-up phase in asemi-arid basin

H. Zarei et al.



**Fig. 5.** Two-component hydrograph separations for three events using  $^{18}\text{O}$  (a) and  $^2\text{H}$  (b) at Pole Manjeniq station.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

