Dynamics of groundwater recharge near a semi-arid Mediterranean intermittent stream under wet and normal climate conditions

Youssef Hajhouji, Younes Fakir, Simon Gascoin, Vincent Simonneaux, Abdelghani Chehbouni

Dynamics of groundwater recharge near a semiarid Mediterranean stream: wet vs. typical climate conditions

Youssef Hajhouji[1], Younes Fakir[1,2*], Simon Gascoin[3], Vincent Simonneaux[3], Abdelghani Chehbouni[2]

[1] Faculty of Sciences Semlalia, Cadi Ayyad University, Marrakech, Morocco.
[2] CRSA (Center for Remote Sensing Application), UM6P, Benguerir, Morocco. fakir@uca.ac.ma
[3] CESBIO, Université de Toulouse, IRD/UPS/CNRS/CNES, Toulouse, France

Abstract: In semiarid and arid stream-dominated hydrosystems, the temporal variability of groundwater recharge is not widely addressed. It still holds various questions about the sources of recharge, its patterns, and the appropriate measuring technics. Hence, the main objective of the present study was to assess the changes that might affect the pattern of recharge under wetter than normal surface water availability. To this aim, water table fluctuation (WTF) was monitored near an intermittent stream in a piedmont area, over two years (2014-2016) with different conditions: extreme wet and typical weather. The groundwater recharge was assessed using the Episodic Master Recession (EMR) algorithm. During the two years, the recharge pattern was dominated by episodic events and by a high seasonality from wet seasons to dry seasons. In the wet year (2014-2015) the highest recharge was recorded following an extreme flood, which has deeply replenished groundwater. Furthermore, an exceptional steady state of groundwater level took place induced by a steady recharge rate. For several events, the assessed recharges were multisource, mainly from streamflow at local scale, but possibly from precipitation, underflow, deep percolation or irrigation return, from the upstream part of the system. The local recharge by streamflow is likely to be short-lived and the lateral recharge is likely to last longer. Consequently, the EMR algorithm estimated the total recharge that could encompass various sources. More research works and multidisciplinary approaches should be carried out to partition those sources and determine their specific contribution.

In semiarid stream-dominated systems, different recharge patterns induced by extreme hydrological events (e.g. wet events) and various potential sources of recharge are to consider when assessing and predicting groundwater recharge.

Keywords: water table fluctuation; EMR algorithm; episodic recharge; wet year; replenishment; multisource recharge

1 Introduction

In arid and semiarid basins, numerous plain aquifers are experiencing chronical groundwater depletion because of high groundwater abstraction and/or low groundwater recharge (Boukhari et al., 2015; Watto and Mugera, 2016; Van Lanen and Peters, 2000; Ashraf et al., 2021). The low groundwater recharge (GWR) is usually due to low precipitation and high evapotranspiration (Walvoord et al., 2002; Flint et al., 2002). Therefore, in those basins, mountain front GWR linked to streamflow was often considered the primary source of recharge (De Vries and Simmers, 2002; Manning and Solomon, 2003; Simmers, 2003; Wilson and Guan, 2004; Dahan et al., 2008). The infiltration processes of streamflow have been widely analyzed (Ronan et al., 1998; Stonestrom and Constantz, 2003; Niswonger et al., 2005; Keery et al., 2007; Rau et al., 2010; Lautz 2012; Clutter and Ferré, 2018; Kurylyk et al., 2019). However, there are few applied studies on the processes of recharge and its temporal variability (Shanafield and Cook, 2014).

In general, the behaviour of GWR in arid and semi-arid stream-dominated hydrosystems is still not well analyzed (Cuthbert et al., 2016). Indeed, when studying GWR in those systems, particularly those with shallow groundwater, various questions might need to be addressed. Existing studies have shown that the main source of GWR is from the water losses of nonperennial streams, mainly from floods that bring high amounts of water during episodic recharge events (Shentsis and Rosenthal, 2003; Dagès et al., 2008; Cuthbert et al., 2019; Shanafield et al., 2021). However, in case of agricultural practices, substantial GWR could be generated by irrigation returns from diverted streamflow (Bouimouass et al., 2020). Therefore, the recharge could be of multiple sources rather than a single one. Moreover, the typical pattern of GWR is characterized by episodic recharge, which is related to the intermittency of

streamflow and to the episodic character of floods. In this context, research works on the variation of the pattern of recharge under specific climate conditions are still lacking; e.g. extreme wet events could impact the hydrological regime of streams catchment, and hence the subsequent recharge. Finally, the water table fluctuation (WTF) technique is one of the most used techniques due to the advantage over the other methods of being simple to apply and of providing the most direct possible observation and measure of recharge (Cuthbert et al., 2016; Nimmo and Perkins, 2018). However, the WTF method might not be always applicable because of some limitations largely described in Healy and Cook (2002).

In the present study, a well tapping into a shallow alluvial aquifer near a semiarid Mediterranean intermittent stream was monitored over two hydrological years, one of extremely wet climate (2014-2015) and the other of typical climate (2015-2016). GWR was assessed over the two years by the water table fluctuation (WTF) method using the Episodic Master Recession (EMR) algorithm. The main objectives of the study were to analyze 1) the changes that may affect the recharge pattern under wetter than normal surface water availability, 2) the effects of an extreme wet hydrological event on the GWR, and 3) the adequacy of the EMR algorithm to assess GWR in stream-dominated systems. Thus, the study highlighted the complexity of assessing and predicting groundwater recharge in a developed (semi)arid stream catchment.

2 Data and methods

2.1 Study area and data collection

The experimental site is located 35 km south of Marrakech city (Morocco), in the piedmont of the High-Atlas Mountains (Fig. 1), in the stream catchment of the Rheraya Wadi. The climate is typically Mediterranean semi-arid. The average annual precipitation (1970-2016) in the

piedmont is 350 mm. The mountains receive more precipitation (500 mm in average, 2008-2018) both as rainfall and snowfall. The mountain watershed of the Rheraya Wadi at the Tahannaout gauge station is 225 km^2 and encompasses the highest peak in North Africa (Jbel Toubkal, 4167 m.a.s.l, Fig. 1). The streams are generally intermittent or ephemeral. Part of the streamflow is derived for irrigating olive trees and wheat crops. The alluvial unconfined aquifer in the area is comprised of alluvial deposits of Neogene and Quaternary age, which extend downstream to the plain. Measured transmissivity values vary from $5x10^{-5}$ to $9x10^{-2}$ m^2/s with an average of $6.7x10^{-3}$ m^2/s, and hydraulic conductivities values from 5.5×10^{-3} to 4.6×10^{-6} m/s with a mean of 4.4×10^{-4} m/s (Sinan and Razack, 2006). Previous studies have presented piezometric maps of the alluvial aquifer showing evidence of groundwater recharge from streamflow in the piedmont area (Boukhari et al., 2015; Bouimouass et al., 2020). The groundwater is used for drinking water and for irrigation in dry seasons.

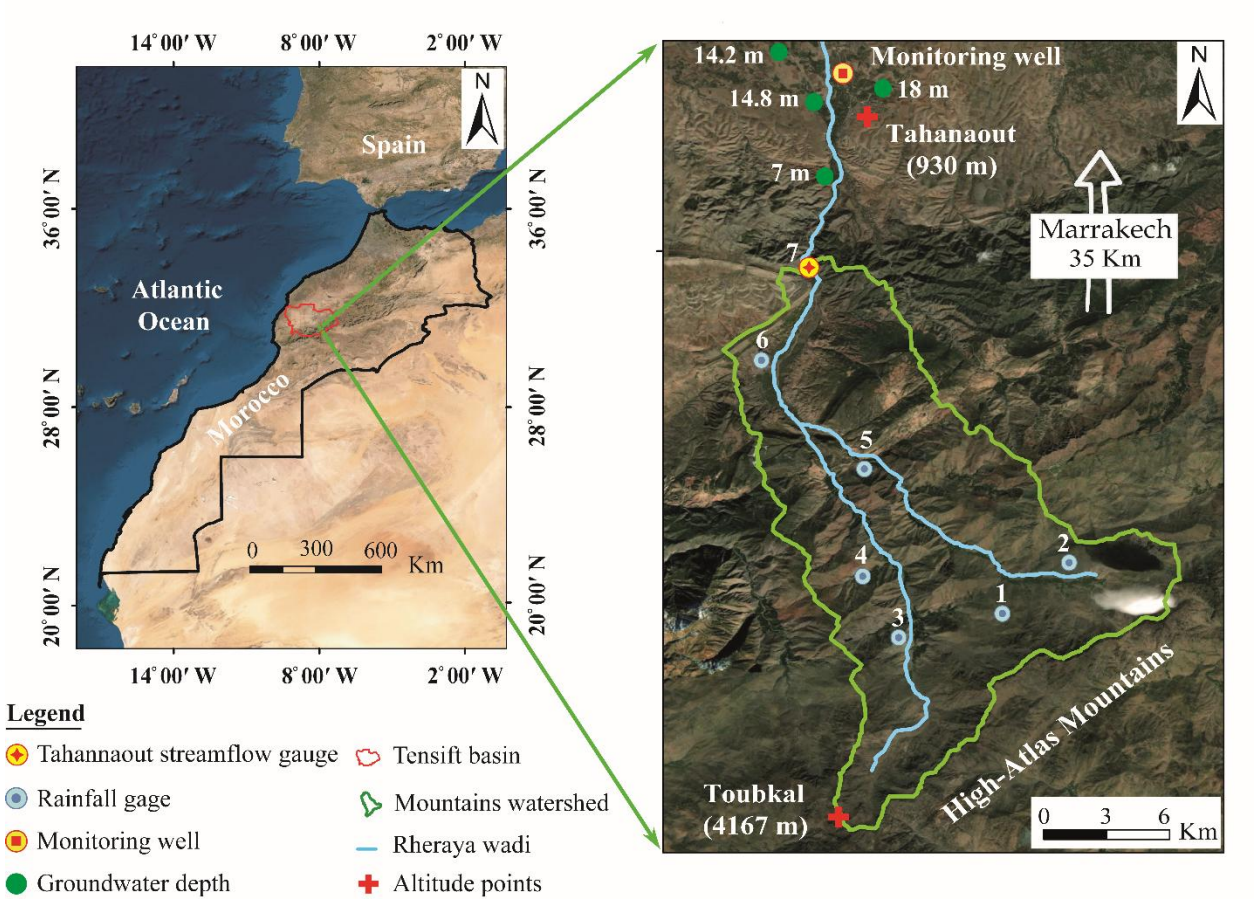

Fig. 1 Location of the experimental site and the Rheraya wadi mountain catchment with its runoff and rainfall gages. Groundwater depths are indicated around the experimental site

The present study extends over two years, from July 2014 to August 2016. The measured data are daily rainfall in the watershed, streamflow at the Tahannaout gauge station, and groundwater levels in a well at a distance of 80 m from the Wadi Rheraya streambed. Daily precipitation data over the mountains area were measured starting 2009 (Fig. 1; Tab. 1) in the frame of the Tensift basin observatory (http://trema.ucam.ac.ma). The longest rainfall time series has been acquired in the piedmont by the Tahannaout station since 1971.

Table 1 Precipitation gages and their measurement period

Precipitation gages	Number	Longitude	Latitude	Altitude (m)	Measurement period	
					Start time	End time
Tamatert	1	7° 52' 48" W	31° 8' 31.19" N	1924	18 June 2013	31 December 2016
Tachedert	2	7° 50' 56.4" W	31° 9' 25.2" N	2343	01 September 2009	31 December 2016

Aremd	3	7° 55' 22.8" W	31° 7' 33.6" N	1940	01 December 2009	31 December 2016
Matate	4	7° 56' 27.6" W	31° 9' 21.6" N	1751	19 June 2013	31 December 2016
Imskerbour	5	7° 56' 24" W	31° 12' 25.2" N	1404	01 September 2009	31 December 2016
Asni	6	7° 58' 51.6" W	31° 15' 0" N	1170	01 September 2009	31 December 2016
Tahanaout	7	7° 57' 46.8" W	31° 17' 31.2" N	1064	01 September 1970	31 December 2016

Daily streamflow has been monitored since 1962 at the Tahannaout gauging station, located in the hillslope region, 8 km upstream from the experimental site (Fig. 1). The main floods were specifically measured between 1962-2006, afterwards only daily flows were measured.

The groundwater levels were measured in a well equipped with two automatic measuring probes. A TD-Diver probe, based on a pressure sensor, measured the pressure exerted by both the water column and the atmospheric pressure. Besides, a Baro-Diver probe measured the atmospheric pressure to account for the changes of the groundwater level induced by the atmospheric pressure alone and correct the TD-Diver measurements. The equivalent hydrostatic pressure of the water was used to calculate the groundwater depth. The well was selected to be far from any direct pumping influence. First, the well was located in an area surrounded by bare soil and natural vegetation (Fig. 1). Second, the groundwater level does not show any abrupt drawdowns or perturbations that might be induced by pumping. The groundwater depth at the well was 9 m at the start of the monitoring, and it varied between a minimum value of 7.69 m and a maximum value of 10.72 m.

The value of the specific yield (Sy) was estimated to 0.23 near the experiment site (Fakir et al., 2021) as the difference between the quasi-saturated water content and the field capacity (Heppner et al., 2007). The latter values were inferred from water content measurements of the alluvial sediment during one hydrological year, using soil moisture sensors (Thetaprobes, Delta-T devices) at different depths. This value is consistent with values indicated by a previous study

of the alluvial aquifer (Sinan, 2000) and is comparable to the average value of 0.21 assigned by Healy (2010) to alluvial aquifers.

2.2 Recharge assessment using WTF method

In the present study, the WTF approach (Healy and Cook, 2002) was used to estimate recharge by applying the Episodic Master Recession method (EMR) developed by Nimmo and Perkins (2018). The WTF method stipulates that rises in groundwater levels in unconfined aquifers are due to episodic recharge reaching the water table. The recharge *R* (m) is calculated as the product of two key terms (Eq. 1), the change in groundwater level (ΔH, m) attributable to recharge and the specific yield (Sy, unitless):

$$dH/dt \; R = \Delta H \times S_y \qquad (1)$$

ΔH is the difference between the peak of the rise of groundwater and the low value of groundwater level estimated for the extrapolated precedent recession phase, i.e. the level if no recharge had occurred. The method is adequate to measure individual and short-term (hours or a few days) recharge events of shallow aquifers with rapid water-level fluctuations and for which groundwater drainage can be approximated by graphic extrapolation. It can also be applied to assess long-term recharge rates (seasonal or annual); in that case, as the groundwater drainage might be significant, what is measured is an estimate of change in subsurface storage (ΔSgw, m^3), referred to as net recharge (Healy and Cook, 2002). The WTF approach considers the recharge during a given period as the sum of the episodic recharges calculated from individual water-level rises.

The main uncertainties of the method could be the frequency of groundwater level measurements, and the difficulty in determining a accurate specific yield (Sy) (Crosbie et al.,

2005). Furthermore, the method excludes the situations of high drainage and steady rate of recharge (Healy and Cook, 2002). In this study, the water table variation was measured at an hourly time step, which is ideal for the WTF method. The specific yield (Sy) was estimated near the experiment site (Fakir et al., 2021) as explained in the previous section.

The EMR algorithm automatically allows identifying the main discrete recharge episodes and estimates the recharge generated during each of those episodes based on WTF rates. To apply the EMR method, three site-specific parameters are required (Nimmo et al., 2015; Nimmo and Perkins, 2018) and are inferred from the water table data:

- Lag-time (T_p): the time interval between the occurrence of a water-input event and its resulting water table response.
- Fluctuation tolerance (σ_T): the maximum value of water level variation as a function of time which can be considered as system noise rather than a response to incoming recharge flux.
- Master recession curve: MRC is a mathematical representation of expected water table decline (recession) in the absence of episodic recharge as a function of hydraulic head (Heppner and Nimmo, 2005; Crosbie et al., 2005; Nimmo and Perkins, 2018). It is considered as the relation between the water-table elevation (H) and the water-table decline rate (dH/dt).

Based on a first analysis of the observed water table fluctuation, T_p is taken equal to 1 day and the fluctuation tolerance (σ_T) is taken equal to 0.01 m. A T_p of 1 day is justified by the rapid reaction of the water table to the hydrological events and by the multiday duration of recharge episodes. A low value was assigned to σ_T (1 cm), that is small enough to detect all episodes of

significant recharge. Both parameters were determined once for a given site, consequently they do not affect episode-to-episode comparisons (Nimmo et al., 2015; Delottier et al., 2018). The MRC parameters, estimated based on the curve fit of dH/dt as a function of H, were established over the study period as a linear regression function with a coefficient R^2 of 0.64. Since the monitored well is near the Wadi and far from pumping influence, and as the used water table measurements are free of barometric-pressure oscillations, it is considered that the recorded groundwater level rises are due to general recharge (not related to a single source) and the drops to natural discharge.

3 Results

3.1 Precipitation analysis

The seasonal analyses were performed according to the four seasons of autumn (September–November), winter (December– February), spring (March–May) and summer (June–August). The annual scale is the conventional hydrological year from September to August of the following year. Over the catchment, the average annual precipitation for 2009-2016 varied from 305 mm in Asni to 595 mm in Tachedert (Tab. 2). The 2014-2015 year is by far the wettest (650 mm) with a high precipitation gradient across the watershed, while during 2015-2016 the precipitation was low (262 mm) and homogeneous (Fig. 2).

Table 2 Annual and average precipitation over the catchment

Precipitation gages	Altitude (m)	Annual precipitation (mm)		
		2014-15	2015-16	2009-2016
Tachedert	2343	1093	284	595
Aremd	1940	860	296	473
Tamaterte	1924	684	261	-
Matate	1751	383	198	-
Imskerbour	1404	600	247	393
Asni	1170	281	268	305
Tahanaout	1064	647	275	426
Average		650	261	-

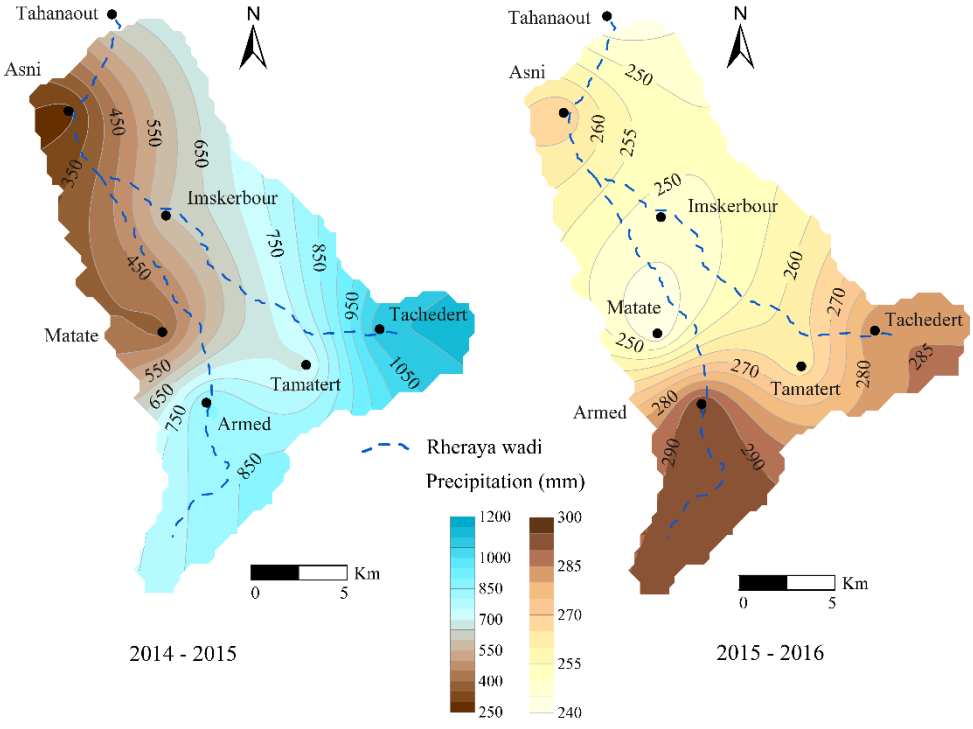

Fig. 2 Precipitation isohyetal maps of the Rheraya catchment for the hydrological years 2014-2015 (a) and 2015-2016 (b)

The Standardized precipitation index (SPI) (McKee et al., 1993) and recommended by the World Meteorological Organization for meteorological drought monitoring (WMO, 2012) was applied since 1971 using the Tahanaout rainfall gage data. The SPI is calculated as:

$$SPI = \frac{X_i - \bar{X}}{\sigma} \qquad (2)$$

Where:

- X_i = Precipitation for the station
- $\bar{X}$ = Mean precipitation
- σ : Standardized deviation

The SPI drought severity classes are presented on the table 3.

Table 3 The Standardized precipitation index (SPI) values and climate classes (McKee et al., 1993)

SPI	Class
2.0 or more	Extremely wet
1.5 – 1.99	Very wet
1.0 – 1.49	Moderately wet
0.99 to -0.99	Near normal
-1.0 to -1.49	Moderate drought
-1.5 to -1.99	Severe drought
-2.0 or less	Extreme drought

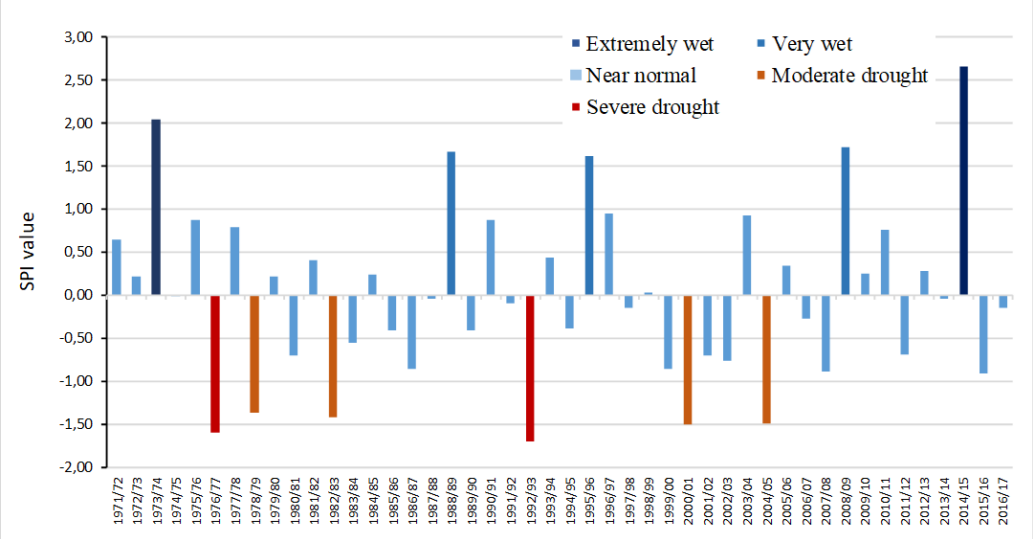

Fig. 3 Calculated Standardized precipitation index (SPI) over 1970-2016 using the Tahanaout rainfall gage data, and the corresponding annual climate types

Over 46 years of precipitation data over the mountain catchment (Fig. 3), the series is dominated by normal precipitation years constituting 76%, dry years constitute 13% and wet years constitute 11%. The 2014-2015 year is classified as an extremely wet year and the 2015-2016 as a normal year.

3.2 Streamflow analysis

Over the period of 1962-2016, the average annual streamflow of the Rheraya Wadi was 1.55 m^3/s. The hydrological regime (Fig. 4) shows an important snowmelt contribution in spring and early summer (Hajhouji et al., 2018).

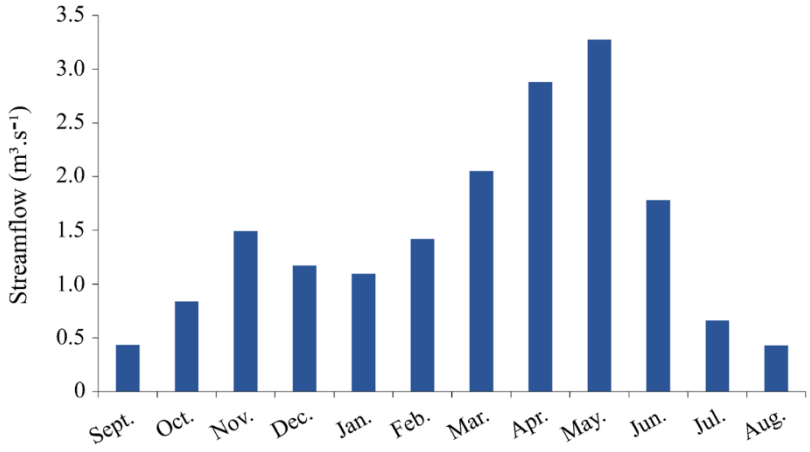

Fig. 4 Average monthly streamflow rate showing the snow regime of the Rheraya wadi over the period of 1962-2016

The analysis of the main flood events between 1962 and 2006 showed that those floods are generally flashy (Fig. 5); 77% had a base time lesser than 30 hours.

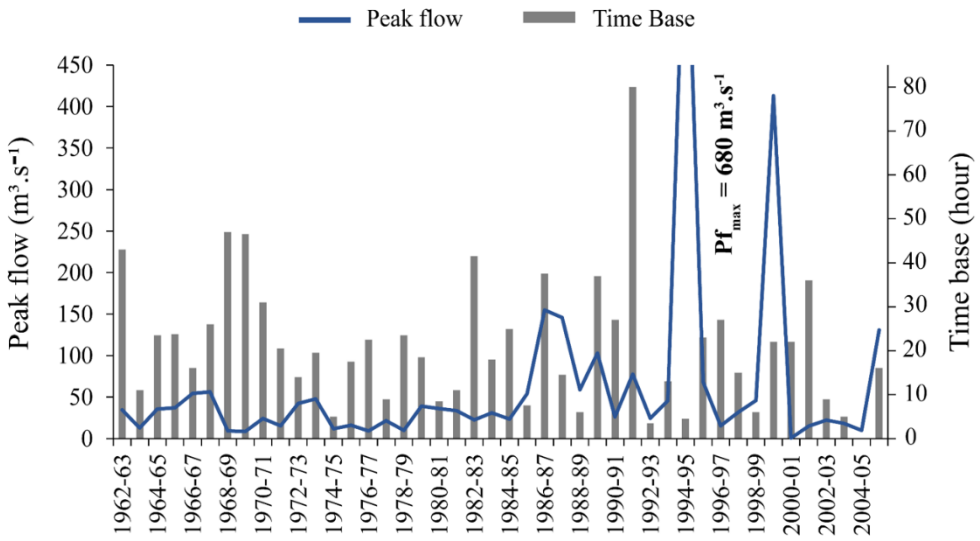

Fig. 5 Variation of the peak flow and the time base of the main floods from 1962 to 2006

The most frequent flowrate was between 20 and 40 m^3/s (Fig 6), but some exceptional ones can be very high and destructive (e.g. 680 m^3/s in August, 1995). Normally, floods can occur throughout the year, but more frequently in autumn and spring (Fig. 6).

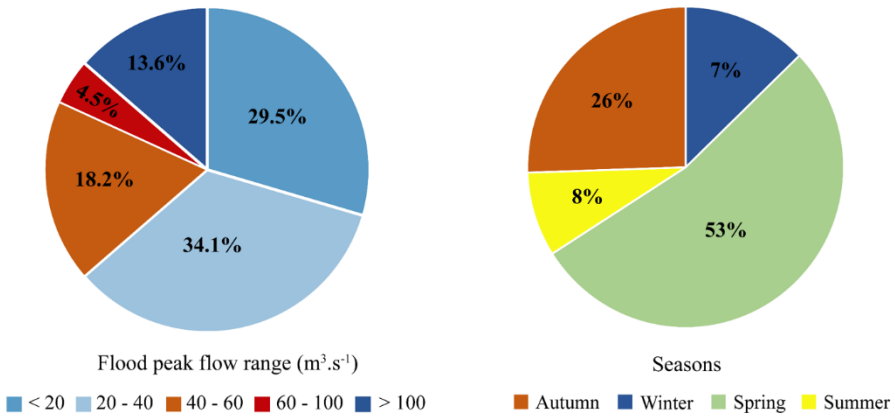

Fig. 6 Frequency of peak-flows (left) and seasonal distribution (right) of the main floods from 1962 to 2006

In the wet year 2014-2015, the average streamflow was 2.97 m^3/s. High flow events were frequent during winter and the largest flood was recorded in November 21st, 2014 with a daily streamflow of 48 m^3/s. The baseflow remained high during 2014-2015 (Fig. 7). In the normal year 2015-2016, the average streamflow dropped to 1.17 m^3/s. High flow events are less frequent and the highest event was 12.93 m^3/s in February 16, 2016. The baseflow decreased dramatically in summer.

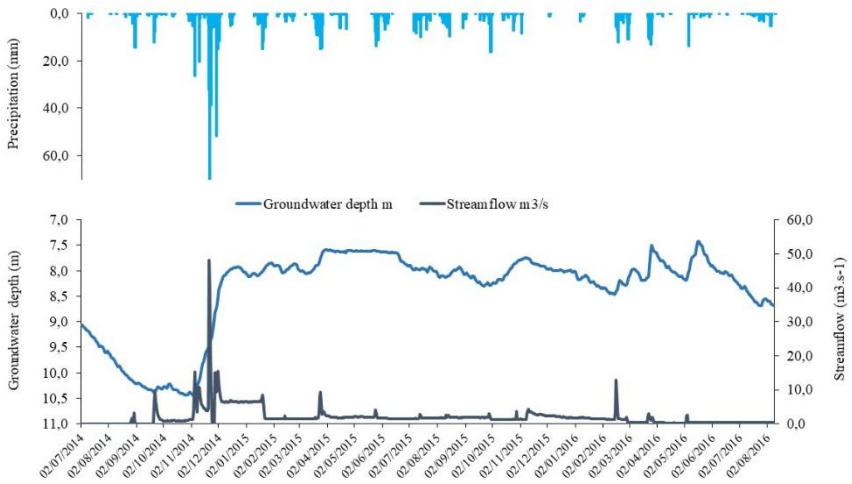

Fig. 7 Variation of streamflow rate, precipitation and water table depth over 2014-2016

3.3 Groundwater dynamics

The groundwater dynamics were strongly characterized by fluctuations reflecting the alternation of recharge episodes, which coincided with periods of precipitation and floods in the Wadi, and discharge episodes (Fig. 7). The magnitude and duration of those fluctuations were very different between the wet year and the normal year.

At the start of the wet year in November 2014, a notable rise in the water table of 2.53 m was concomitant to the precipitation and to the biggest flood of November 21th, 2014. The water table remained high during several months. During spring, the water table rose again following the flood of end of March 2015 and stayed at a stable level during almost 1.5 month, until the end of May 2015. From June to September 2015, the groundwater experienced a long and smooth recession. During the normal year of 2015-2016, the groundwater fluctuations occurred more rapidly than the previous year. After the rise of the water level during spring events, the level of the water table dropped significantly in summer when the runoff in the wadi became very low.

3.4 Groundwater recharge variation

From July 2014 to August 2016, 13 GWR episodes (E1 to E13, Tab. 4) were identified by the EMR algorithm (Fig. 8), eight in the wet year and five in the normal year.

During the wet year of 2014-2015, the highest recharge (0.66 m) occurred in November 2014 (E2) following an exceptional hydrological event characterized by the highest recorded flood (48 m^3/s) and precipitation (334 mm). The 6^{th} recharge episode (E6) that lasted 44 days corresponds to the period when the water table was stable, which can be explained by a steady rate of recharge. In this case, the WTF fluctuation developed for episodic events cannot accurately calculate the recharge rate. However, using the same MRC as the other events, the recharge of this episode was estimated to 0.06 m (Tab. 4).

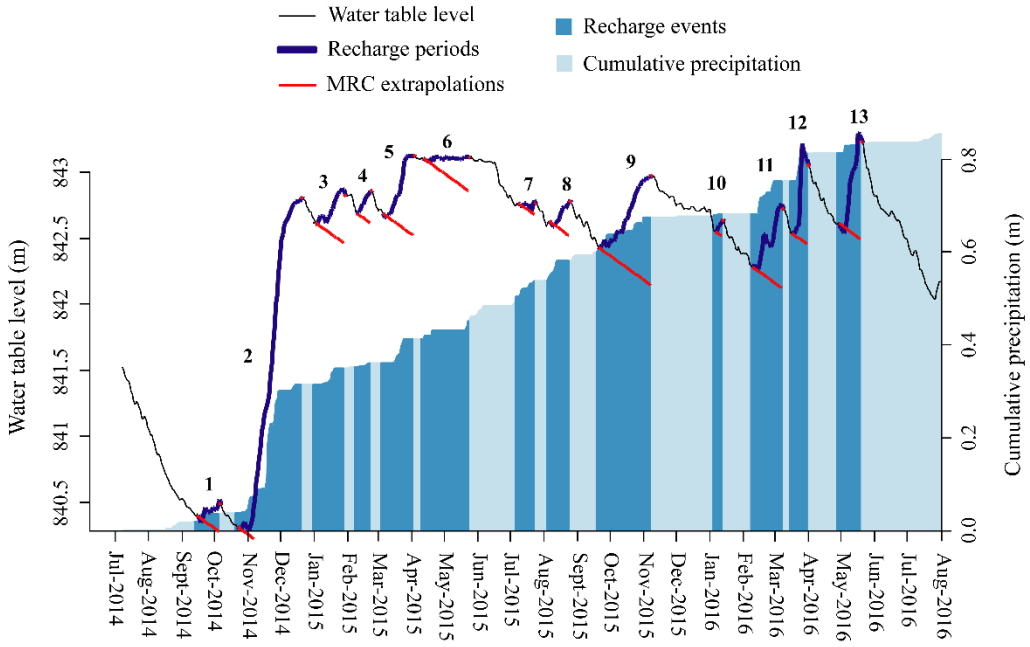

Fig. 8 Results of the EMR analysis showing the groundwater recharge episodes

Table 4 Characteristics of the groundwater recharge episodes inferred from the EMR

Year	Episode of Recharge	Start time	End time	Duration (d)	Recharge (m)	Cumulative recharge (m)	Total precipitation (mm)	Number of rainy days (d)	Peak streamflow m^3/s
2014-2015	E1	17 September 2014	10 October 2014	24	0.05	0.05	23.14	3	9.87
	E2	24 October 2014	24 December 2014	62	0.66	0.71	334.19	19	48.02
	E3	04 January 2015	01 February 2015	29	0.08	0.79	52.19	8	8.46
	E4	11 February 2015	26 February 2015	16	0.06	0.85	13.90	6	2.30
	E5	08 March 2015	06 April 2015	30	0.14	0.99	89.62	10	9.41
	E6	14 April 2015	27 May 2015	44	0.06	1.05	50.73	7	4.17
	E7	09 July 2015	26 July 2015	18	0.02	1.07	30.98	7	2.85
	E8	06 August 2015	27 August 2015	22	0.06	1.13	36.72	8	2.58
2015-2016	E9	20 September 2015	09 November 2015	51	0.19	1.32	55.43	10	3.73
	E10	07 January 2016	14 January 2016	8	0.03	1.35	1.68	1	1.88
	E11	09 February 2016	09 March 2016	30	0.14	1.49	55.21	10	12.93
	E12	16 March 2016	01 April 2016	17	0.14	1.63	46.36	6	3.05
	E13	27 April 2016	21 May 2016	25	0.17	1.80	19.07	4	2.48

The cumulative estimated episodic recharge of the wet year was 1.19 m (63% of the total recharge for both years). The winter recorded 70% of the annual recharge. It is mainly generated by the event 2 of 22 November 2014 (up to 83.5%). Recharge occurred over 245 days, or 67.5% of the year.

During the normal year of 2015-2016, the cumulative episodic recharge was 0.67 m (37% of the recharge for both years). Up to 72% of recharge occurred during the wet period with the majority in spring (46%). The events in summer did not generate recharge leading to a drop of the water table. Recharge processes only lasted 131 days, or 38% of the year.

For the whole study period, the cumulative recharge was 1.80 m. The total duration of recharge was estimated to 375 days, which is 48% of the observation period. The duration of recharge events was longer than the duration of the corresponding precipitation events (Tab. 4). This may indicate that recharge is more due to streamflow. In addition, there is a low correlation

between the recharge and the peak flow ($r = 0.19$, $R^2 = 0.03$) or average streamflow ($r = 0.30$, $R^2 = 0.03$) of each event; those coefficients were calculated without considering the exceptional 2nd event because of its large difference with the others.

4 Discussion

The experimental site is located near an intermittent stream that is generally characterized by high snowmelt contribution from the High-Atlas mountains, responsible of high flow and floods in spring and early summer. In our basin, the snow regime is a main characteristic as shown by several previous studies. The annual contribution of snow to streamflow was assessed from 15% to 50% depending on meteorological conditions of the year (Boudhar et al., 2009; Marchane et al., 2013). According to SPI, the climate in the piedmont is characterised by 13% of years considered as dry and 11% as wet years, the 76% remaining years being considered as normal.

The present study focuses on the changes that may affect the recharge mechanisms during wet years. In both the wet year (2014-15) and the typical year (2015-16), the majority of the GWR occurred during the wet seasons. During the wet year, the very rainy winter, with its associated streamflow and floods, was the highest GWR period (almost 70%), while in the normal year, as winter had lower precipitation, the spring season with its floods issued from snowmelt was the highest GWR period (46%). Therefore, the time of greatest recharge was during high waters (precipitation, high-flows or floods) when the amount of water allows saturating the underlying sediment and generates high amounts of recharge (McCallum et al., 2014). During summer, there was little (wet year) or no recharge (normal year). The seasonality is a main characteristic of the temporal distribution of the recharge under semiarid climate. The

seasonality was explained (Fakir et al., 2021) by high moisture of the sediment in the wet season, which generates higher hydraulic conductivities and less unsaturated pores than during the dry period characterized by dry sediment due to water scarcity.

During the wet year, two additional features were observed. First, the effects of the largest flood of 22 November 2014 that was classified as an extreme event with a return period estimated to approximately 20 years (Zkhiri et al., 2017). The amount of surface water generated by this event led to above normal groundwater level rise and subsequently to a very high recharge amount. The latter represents 60% of the recharge recorded during the wet year. The alluvial aquifer was significantly replenished. Second, in spring 2015, an exceptional steady state of groundwater took place during almost 1.5 months, due to a steady rate of GWR. In this case the rate of recharge was constant and equal to the rate of groundwater drainage. This GWR regime seems unusual in semi-arid stream catchments where the typical pattern is mainly characterized by episodic recharge. For that regime, the recharge was not episodic and its estimation falls beyond the scope of the WTF method (Healy and Cook, 2002). However, it was possible to use the EMR algorithm to have an estimation of this recharge. Other techniques could be used in such conditions, but they require further investigations and aquifer characteristics (Eaton, 2019). In semi-arid catchments, such sustained recharge can only be linked to an exceptionally high and constant streamflow.

The recorded duration of the recharge events, often of several weeks, was longer than the one of the corresponding precipitation. It is also longer than the duration of floods that are generally flashy (77% are lesser than 30 hours). Furthermore, low correlation exists between the recorded recharge, precipitation and streamflow. Therefore, the groundwater recharge near the streambed seems to be due not only to local recharge from streamflow, but could also

encompasses upstream lateral recharge from several potential sources including underflow, deep percolation from upper reach of the catchment, or irrigation return from upstream. The local recharge by streamflow is likely to be short-lived and lateral recharge at slower rate is likely to last longer. Therefore, the EMR algorithm estimated the amounts of total recharge that probably integrated various components. Hence, the time lag used in the EMR algorithm should not be considered as a representative characteristic of a unique source of recharge.

This fact emphasizes the importance of combining other methods (e.g. hydrochemistry, isotopes) to assess each component of the total recharge. Consequently, in semiarid stream dominated systems the variation of groundwater recharge is rather erratic, because controlled by numerous parameters. Among them are the above mentioned multiple sources of recharge and their time scale, the sediment moisture conditions (Batlle-Aguilar and Cook, 2012; Schwartz, 2016; Fakir et al., 2021), the soil depth above the water table (Cao et al., 2016), the sediment permeability (Shanafield, 2012; Villeneuve et al., 2015), the climate variability (Moeck et al., 2020) and land use changes (Lasagna et al., 2020). Therefore, assessing and predicting recharge variability in such developed semiarid catchments is complex and needs to consider the various parameters controlling the processes of recharge. In addition, a long-term and large scale monitoring would better characterize the temporal variability and the catchment-scale heterogeneity of recharge.

5 Conclusion

Water table fluctuation was monitored near an intermittent stream, in a semiarid piedmont, over two years with contrasted climate conditions: a very wet and a typical year. In general, the recharge was episodic and presented a high seasonality from wet seasons to dry

seasons. Extremely wet periods brought a large amount of water that introduced an unusual groundwater dynamic and hence recharge rates. An extreme hydrological event induced a very large rise in the groundwater level. Also, an unusual steady state regime of groundwater was observed, induced by a steady recharge rate. Those conditions have strongly replenished the alluvial aquifer.

The groundwater recharge near the stream is due to local recharge mainly from streamflow and probably from heavy precipitation of the wet year. However, the duration of some recharge events was longer than the recorded floods or precipitation events, showing the importance of lateral recharge from various potential sources, probably combining underflows or irrigation returns from a large part of the stream system. Therefore, the EMR algorithm allows to estimate a total recharge that could encompass various sources. More research works should be carried out at large temporal and spatial scales to segregate those sources and determine their respective contribution. This is vital to assess and predict recharge in a such developed semiarid stream catchment, especially considering the threat of climate change.

In arid and semiarid climates, the wet conditions are rare and their return period is generally of several years or decades. Consequently, despite their importance for recharge and aquifers replenishment, they could not counterbalance the effects of droughts and mismanagement that have severely affected the groundwater resources.

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