Seasonality in intermittent streamflow losses beneath a Semiarid Wadi

Fakir Younes[1], BOUIMOUASS Houssne[1], and Constantz Jim[2]

[1]University Cadi Ayyad
[2]United States Geological Survey

November 16, 2022

Abstract

Streamflow losses beneath non-perennial streams are potentially a major contribution to recharge, though measurements are often challenging due to the transient nature of these non-continuous (both spatially and temporally) streamflow. Significant investigative efforts for ephemeral streams have been described in literature, yet streams with intermittent streamflows lack this level of effort, particularly over an entire hydrological cycle. In this study, streambed water content and temperature were continuously logged over a year for an intermittent stream under semi-arid conditions in a wadi (arroyo) in Central Morocco. The results show that streambed water content and temperature are complementary data for identifying and classifying infiltration events, with respect to determining their duration, depth of water content increase and flow velocity within the sediments. Water content measurements easily allow distinguish between downward surface water percolation as well as upward groundwater wetting front. Over the entire year, the calculated total potential recharge based on temperature modeling was 425 mm. During winter and spring when the alluvium has a higher water moisture, this recharge is predominantly generated by floods. Normal streamflow generally generates low infiltration but contributes to wetting the sediment. During the summer, brief flashfloods over dry sediment result in shallower and slow wetting from infiltration, despite of their higher peak streamflows. Thus, for this wadi, there is clear seasonality (seasonal variation) in relations between amounts of streamflow, streamflow loss and depth of wetting into the streambed, as well as upward advance of wetting through deeper streambed sediments from groundwater receiving lateral mountain-front recharge.

Seasonality in intermittent streamflow losses beneath a Semiarid Wadi

Younes Fakir[1,2], Houssne Bouimouass[1], Jim Constantz[3]

[1]Laboratory GeoSciences Semlalia, Cadi Ayyad University, Marrakech, Morocco.

[2]CRSA (Center for Remote Sensing Application), UM6P, Benguerir, Morocco.

[3] Scientist Emeritus Program, U. S. Geological Survey, Menlo Park, CA USA 94028.

Corresponding author: Younes Fakir (fakir@uca.ac.ma)

Key Points:

- Streambed water content and temperature were continuously monitored during an entire hydrological year to analyze water losses of an intermittent stream in semi-arid climate.
- Streamflow percolation and water table location were determined, indicating a high moisture level in the sediment during several months.
- Winter and spring floods lead to rapid infiltration resulting in high sediment water content, deep percolation and are the main source of groundwater recharge.

Abstract

Streamflow losses beneath non-perennial, intermittent and ephemeral, streams are potentially a major contribution to recharge, though measurements are often challenging due to the transient nature of these non-continuous (both spatially and temporally) streamflow. Significant investigative efforts for ephemeral streams have been described in literature, yet streams with intermittent streamflows lack this level of effort, particularly over an entire hydrological cycle. In this study, streambed water content and temperature were continuously logged over a year for an intermittent stream under semi-arid conditions in a wadi (arroyo) in Central Morocco. The results show that streambed water content and temperature are complementary data for identifying and classifying infiltration events, with respect to determining their duration, depth of water content increase and flow velocity within the sediments. Water content measurements easily allow distinguish between downward surface water percolation as well as upward groundwater wetting front. Over the entire year, the calculated total potential recharge based on temperature modeling was 425 mm. During winter and spring when the alluvium has a higher water moisture, this recharge is predominantly generated by floods. Normal streamflow generally generates low infiltration but contributes to wetting the sediment. During the summer, brief flashfloods over dry sediment result in shallower and slow wetting from infiltration, despite of their higher peak streamflows. Thus, for this wadi, there is clear seasonality (seasonal variation) in relations between amounts of streamflow, streamflow loss and depth of wetting into the streambed, as well as upward advance of wetting through deeper streambed sediments from groundwater receiving lateral mountain-front recharge.

1 Introduction

In arid and semi-arid basins, surface-water resources are more focused than in more humid basins, and with increasing aridity with climate change streamflows and streamflow losses are increasingly produced by ephemeral and intermittent streams. Both ephemeral and intermittent streams channels are dry for extended periods, i.e., both are classified as nonperennial (aka, seasonal) streams, with intermittent streams distinguished from ephemeral streams by intermittent stream channels distinct pools separated of dry channel and/or streamflow reaches separated by sections of dry channel. For ephemeral streams, streamflow losses have been documented to represent a major component of alluvial aquifer recharge (Niswonger et al., 2008); however, for intermittent streams their spatial and temporal dynamics are inadequately documented (Cuthbert et al., 2016) and broad assessment continues to be challenging from both a logistical and analytical perspectives. Ephemeral streams water losses have been largely studied using temperature measurements and related analytical and numerical modeling methods (Constantz et al., 1994; Constantz & Thomas, 1997; Ronan et al., 1998; Stonestrom & Constantz, 2003; Goodrich et al. 2004, Hoffmann et al., 2007; Kulongoski & Izbicki, 2008, Rau et al. 2017). Much lesser studies have used water content as a tracer of ephemeral stream losses (Dahan et al., 2007; Dahan et al., 2008; Schwartz, 2016). These research works were in general stimulated by the role that ephemeral stream losses might play in surface water-groundwater interactions and in groundwater recharge. When analyzing their context, several other reasons might have contributed to the proliferation of research works on ephemeral streams. First, being normally dry for most of the year and flow as floods only during and shortly after precipitation events, ephemeral stream channels are less challenging for deployment of equipment within the streambed before the arrival of a flood; flood events are unpredictable, create scour and damage to equipment. Second, in dry and desert area since floods are rare and have little seasonality, short monitoring and few measurements are generally sufficient to characterize the water losses and the recharge that is subsequently scarce and episodic. Third, since the ephemeral stream losses often occur in dry sediment under unsaturated conditions, their variation are not much influenced by pre-conditions of the sediment moisture; consequently, the infiltration and recharge behavior might present low seasonality. Finally, the early advances in flow modeling under variably saturated flow opened large perspectives of numerically quantifying ephemeral stream losses.

The difficulties in quantifying streamflow loss are greater with intermittent flow compared with spatially continuous ephemeral flows. Intermittent streams are generally more common in semi-arid regions, where the climate is dry in summer and autumn, and wet in winter and spring. During dry seasons, intermittent streams are generally dry or flow after episodic storms; consequently, their recharge pattern might be similar to ephemeral streams, occurring in dry and unsaturated sediment (Reid & Dreiss, 1990). In wet seasons, intermittent streams are fed by rainfall or snowmelt, and may flow continuously or intermittently, thus, their stream losses and recharge pattern might be expected to range between the spatial pattern of perennial stream and ephemeral in addition to intermittent flow patterns. Furthermore, intermittent stream flow during longer periods than ephemeral streams, potentially creating greater streambed infiltration, streambed saturation and groundwater recharge.

For the present research, continuous streambed water content and streambed temperature were jointly monitored beneath a single intermittent stream channel, a wadi, in a semi-arid Mediterranean climate. The goal was to continuously monitor streambed parameter designed investigate infiltrations processes and estimate the stream losses for an intermittent reach over an entire water year as related to groundwater recharge beneath intermittent streams. A pair of primary streambed measurement tools were deployed: continuous vertical streambed sediment temperature profiling and continuous vertical sediment water content profiling. Using heat as a tracer via temperature profiling has been shown to estimate streambed fluxes, while vertical streambed water-content profiling provides crucial information on variations of hydraulic connection between the stream and the groundwater, with clear documentation of streamflow losses converted to groundwater recharge. Water content also allows to easily measure the velocity of the wetting front and infer infiltration fluxes; however, the method can only be used when the streambed is initially unsaturated (Hoffmann et al., 2007; Dahan et al., 2008); once the sediment is fully saturated, it is no longer possible to calculate infiltration fluxes. Using temperature as a tracer of stream losses is more useful in estimating water fluxes in various moisture regimes. Indeed, heat continues to be widely used thanks to technological developments that made temperature acquisition devices rigid, easy to install and inexpensive (Anderson, 2005; Kalbus et al., 2006, Constantz 2008, Shanafield & Cook, 2014), and to the development of various methods and models that use temperature data series (Anderson, 2005; Blasch et al., 2007; Kurylyk et al., 2019).

Discussed in detail in other sections below, after identifying the hydrological events (streamflow occurrence) at the experimental site based on the near surface sediment temperature and flow gauge data, analyzing the stream losses beneath the streambed were determined at a single vertical streambed profile to a depth 5.5 m continuously over an entire 1-year period. The resulting records were used in a 1-dimensionl heat transport model to calculate the potential recharge rates. The specific goals of this study were: 1) describe the seasonal change in the sediment moisture and temperature according to the streamflow losses, 2) analyze the effect of the sediment moisture on the infiltration processes, 3) determine the seasonal variation of the subsequent potential groundwater recharge and 4) possibly investigate any impact of lateral mountain-front recharge on hydraulic connection beneath the channel. All four were able to be addressed to varying degrees during hydrologic events over one year for this single wadi.

2 Study area

The study area belongs the Tensift basin in Central Morocco, which is a typical southern Mediterranean basin (Jarlan et al., 2015). It is located in a piedmont area and is bordered by the High-Atlas Mountains in the south. The climate is characterized by hot and dry periods in summer and autumn, whereas the winter and spring are associated with precipitation, as rainfall and mountain snow, with milder temperatures.

The experimental site is located in the middle of the active channel of the Wadi Rheraya stream. The Wadi Rheraya is one of the main streams coming from the High-Atlas mountain. Its mountain watershed is 227 km^2, culminating at Jbel Toubkal at 4167 m. Precipitation within the watershed is monitored by 6 rain gauges. The average annual precipitation is 400 mm. The streamflow is monitored since 1962 at Tahanaout gauge station. The average annual streamflow is 1.55 m^3/s. There is a large variability in streamflow in space and time. The stream has a nival-pluvial regime and snowmelt contributions are important in spring and early summer (Hajhouji et al., 2018). Below the gauge station, a part of the runoff is used for irrigation, mainly olive and wheat crops. The alluvial aquifer in the area is formed by alluvial fans and fluviatile deposits of Neogene and Quaternary age. It is recharged mainly by high-elevation meteoric water (Boukhari et al., 2015). Within Rheraya streambed (Figure 1), at the surface the alluvium is formed of rollers, sandy gravel, and boulders with different sizes. Clay layers are usually deposited by floods. At the experimental site, the water table at the start of the experiment located at 5.5 m depth.

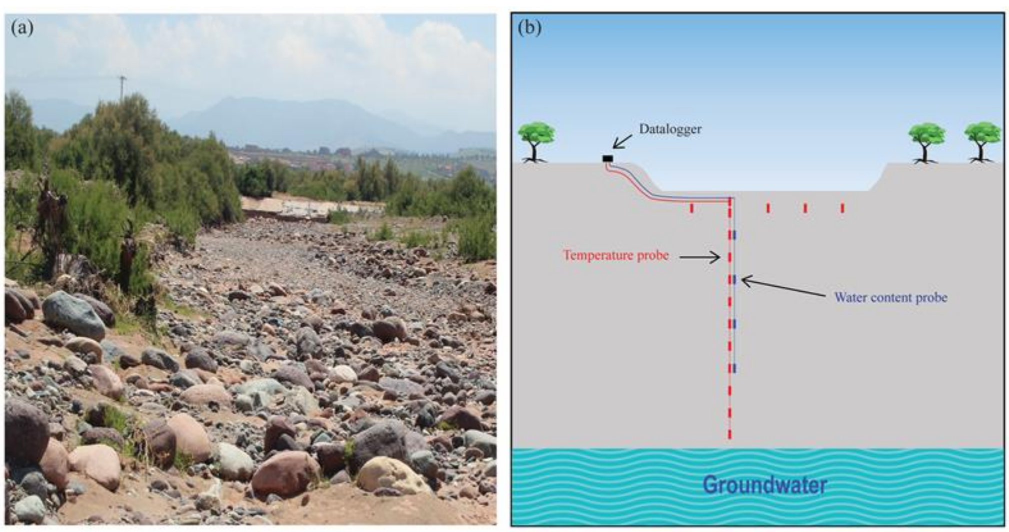

Figure 1: On left, photograph showing the Wadi Rheraya streambed, with in the background the foothills of the High-Atlas Mountains. On right, schematic cross-section of the instrumentation with the temperature probes (4 self-contained temperature probes at the top surface and 12 across

the unsaturated zone) and water content probes (4 Thetaprobes) at different depths. Groundwater was found at 5.5 m below the streambed at the onset of the experiment (November 04, 2013).

3 Materials and Methods

3.1 Streamflow detection

Stream gauges are required to monitor streamflow. However, those stations are expensive to install and maintain, and not always effective because of the flashy and destructive nature of streamflow events especially in ephemeral channels (Constantz & Thomas 1997). The installation of a series of temperature probes at the near surface of streams was successfully used in different studies to detect the presence, extent and duration of streamflow (Blasch et al., 2000; Constantz et al., 2002; Blasch et al., 2004; Mendez, 2005; Moore, 2007; Stewart-Deaker et al., 2007; Stonestrom et al., 2007). As there is only one gauging station located 8 km upstream of the experimental site, and the streamflow recorded at this station does not always reach the study site, we used a temperature-based method to detect the presence of streamflow and its duration at the site. Therefore, four self-contained temperature sensors (Lascar Electronics) were installed at the surface of the sediment across the streambed (Figure 1). Air temperature was also recorded to distinguish between streamflow events and cold fronts. Each sensor recorded temperature every 30 minutes from 11/04/2013 to 11/21/2014. We analyzed the thermographs by visual inspection (as detailed in paragraph 4.2) to detect the perturbation of the temperature at the sediment surface caused by water flowing through the stream and therefore to determine the number of streamflow events and their duration.

3.2 Measurements of changes in sediment water content and temperature

The experiment was designed to vertically monitor the downward movement of intermittent streamflow beneath the semi-arid Wadi Rheraya (Figure 1). The experiment profile was installed in the middle of the active channel that drains water even during periods of low flow. At the start of the experimentation, the water table was located at 5.5 m below the surface of the Wadi Rheraya streambed. Hence, to monitor the volumetric water content of the sediment, four Thetaprobes (Delta-T Devices) were installed at 1, 2, 3 and 4 m. To measure temperature, 12 temperature probes (Cambell Scientific) were installed every 0.5 m to record the sediment temperature. The probes were connected to a data logger (Cambell Scientific) placed on the right stream bank and powered by a solar panel. Data were recorded every 30 minutes. The measurement period was from November 04, 2013 to November 21, 2014. At the end of this period, a strong flood (60 m^3/s) caused serious damages to the set up.

3.3 Calculating vertical infiltration fluxes with 1-Dimensional model of heat transfer

Temperature data were used together with the physical, hydraulic, and thermal properties of the alluvium, to construct a 1-dimentional model to simulate heat transfer beneath the Wadi Rheraya streambed. The computer program VS2DH (Healy & Ronan, 1996), pre- and post-processed by 1DTemPro (Koch et al., 2016), a finite difference-based model designed to solve heat transport problems in variably saturated media, was used to infer vertical water fluxes. A form of the advection-dispersion equation is used within VS2DH to describe heat and groundwater transport (Healy and Ronan, 1996):

$$[\theta C_w + (1-\emptyset)C_s]\frac{\partial T}{\partial t} = \nabla . \mathrm{K_T}(\theta)\nabla \mathrm{T} + \nabla . \theta \mathrm{C_w D_h} \nabla \mathrm{T} - \nabla . \theta \mathrm{C_w q T} + \mathrm{Q C_w T'}$$

The temporal change in sediment temperature at a given depth	Heat conduction (Fourier's law)	Heat dispersion	Heat advection (Darcy's law)	Heat source /sink	(1)

where t is time in s; ϴ is the volumetric moisture content (dimensionless); ϕ is the sediment porosity (dimensionless); Cw is the volumetric heat capacity (density*specific heat) of water (J m^{-3} °C^{-1}); Cs is the volumetric heat capacity of bulk sediment (J m^{-3} °C^{-1}); T is temperature (°C); K_T is bulk thermal conductivity (W m^{-3} °C^{-1}); D_h is the thermomechanical dispersion tensor (m^2 s^{-1}); q is water velocity (m s^{-1}); Q is rate of water added per volume of porous medium from an external or internal source (s^{-1}); T' is temperature of fluid source (°C).

The main physical parameters were assessed at the site. Across the unsaturated zone of the experiment site, four sediment samples, of about 5 kg each, were taken at every m depth to characterize the sediment texture and infer the hydraulic conductivity. Particle-size distribution parameters were determined by sieve analysis (Landon et al, 2001). The hydraulic conductivity was estimated from the formula of Alyamani and Sen (1993) which is based on the slope and intercept of the grain-size distribution curve. This formula (equation 2) was tested by Landon et al (2001) against other techniques and showed a good agreement.

$$K = 1300\,[I_0 + 0.025\,(d_{50} - d_{10})]^2 \qquad (2)$$

The effective porosity of the sediments was estimated based on the water content measured by the Tethaprobes installed at various depths, and is defined here as the difference between the quasi-saturated water content and the field capacity (Heppner et al., 2007), where quasi-saturation is nearly saturated with a small amount of air trapped in the pore space.

The thermal properties (sediment heat capacity, thermal conductivity, and dispersivity) of streambed sediments are almost independent of texture and vary only little between different streambeds (Constantz and Stonestrom, 2003). These parameters generally vary from 1.1 10^6 to 2.9 10^6 (J m^{-3} °C^{-1}) for sediment heat capacity, and from 0.2 to 2.2 (W m^{-1} °C^{-1}) for thermal conductivity and 0.01 to 1 for dispersivity (Pahud, 2002; Niswonger & Prudic, 2003; Kulongoski & Izbicki, 2008).

The model domain is a column that extends vertically from the streambed surface to a depth of 6 m. The model domain was divided in five layers of specific thickness and physical characteristics. Twelve (12) observation points of temperature were centered horizontally in the vertical column. The domain was divided in 100 active cells spanning the distance between the uppermost and the deepest thermistor. The measured temperatures were used to initialize the model but afterwards the temperature of the uppermost thermistor was used as the boundary condition at the top of the domain, and temperature of the deepest thermistor as the boundary condition at the bottom of the domain. The active cells are surrounded by no-flow boundaries. The simulation period was 12 months and each time step was 30 minutes.

The model was calibrated based on a manual-trial and error method, which is considered appropriate for 1-Dimentional modelling (Niswonger & Prudic, 2003, Moore, 2007; Kulongoski & Izbicki, 2008). Model calibration in the context of using heat as a tracer usually requires the adjustment of hydraulic conductivity (K) or head difference (H) until the simulated temperature match the measured one. In our case study, we used the estimated K from grain-size distribution curve and adjusted H taking into account the maximum stream stage values of floods reported from the experiment site. Best fit of simulated temperature-depth profiles to observed ones was determined by minimizing the RMSE (Root Mean Square Error).

4 Results

4.1 Sediments characteristics

The grain size analysis of the sediment samples from various depths shows (Table1) that the sediments are mostly composed of gravel (2000> µm) and coarse sand (250-2000 µm). Among the fine materials, clay (<2 µm) constitutes an important fraction. Sediments from the first and the fifth meters have more coarse material while the second and the third meters have more fine material. The estimated hydraulic conductivity values from grain size analysis vary from 6 10^{-5} to 4 10^{-4} m/s (Tab. 1). They are relatively low but are in good agreement with other reported for the area (Sinan & Razack, 2006). On the streambed surface floods generally deposit clay sediments that forms a thin layer with a thickness ranging from millimeters to several centimeters. This clogging layer is likely to reduce the hydraulic conductivity of the very shallow sediments. In addition, the presence of boulders could further reduce the permeability of the sediment.

Table 1. The Results of Grain Size Analysis of Four Samples Taken from Various Depths in the Experiment Site and Estimated Hydraulic Conductivity.

Depth (m)	Gravel (>2000 µm)	Coarse sand (250-2000 µm)	Fine sand (50-250 µm)	Silt (2-50 µm)	Clay (<2 µm)	Hydraulic conductivity (m/s)
1	58.3	27.4	5.1	0.5	8.7	4 10^{-5}
2	41.9	34.9	9.4	0.7	13.1	6 10^{-5}
3	32.7	41.1	11	1.1	13.3	1 10^{-4}
5	47.2	30.2	9.5	0.8	12.2	4 10^{-4}

The effective porosity of the sediment was deduced from the measured water content data. The results (Table 2) show that the effective porosity at 2m and 3m (0.18 % – 0.20 %) depth is lower than this at 1m and 4m (0.27 % – 0.30%).

Table 2. Calculation of the Effective Porosity in the Study Site Using Water Content.

Tethaprobe number	Depth (m)	Part of sediment represented (m)	Min of water content (%)	Max of water content (%)	Estimated effective porosity (%)
H1	1	0 - 1.5	0.13	0.43	0.30
H2	2	1.5 - 2.5	0.27	0.44	0.18
H3	3	2.5 - 3.5	0.26	0.46	0.20
H4	4	3.5 - 6.5	0.22	0.49	0.27

4.2 Detection of streamflow events

As streamflow was not directly monitored at the experimental site, the surface-streambed temperature is used to determine the effective occurrence of streamflow and flood events (Constantz et al., 2001; Blasch et al., 2004). Streambed temperature is normally influenced by seasonal and diurnal air temperature. The minimum recorded temperature was 8.8 °C in January 2014 and the maximum was 34 °C in August 2014. Abrupt changes in streambed temperature are due to streamflow events or a change in atmospheric conditions (Constantz et al., 2001). Figure 2 presents a detailed inspection of a perturbation : After a decrease in the daily streambed-temperature fluctuation by 5 °C (Figure 2a) due to the decrease in air temperature by 8 °C (Figure 2b), the effect of the streamflow event of September 21st, 2014 is reflected by a perturbation (temperature drop) of sinusoidal shape of the daily streambed-temperature thermographs. The described perturbation is related to a rainfall event and to a flood recorded at the Tahanaout gauging station (Figure 2c). The start of the thermal anomaly is considered as the initiation of the event and the increase of diurnal variation of temperature is considered as the recession of the event (Constantz et al., 2001).

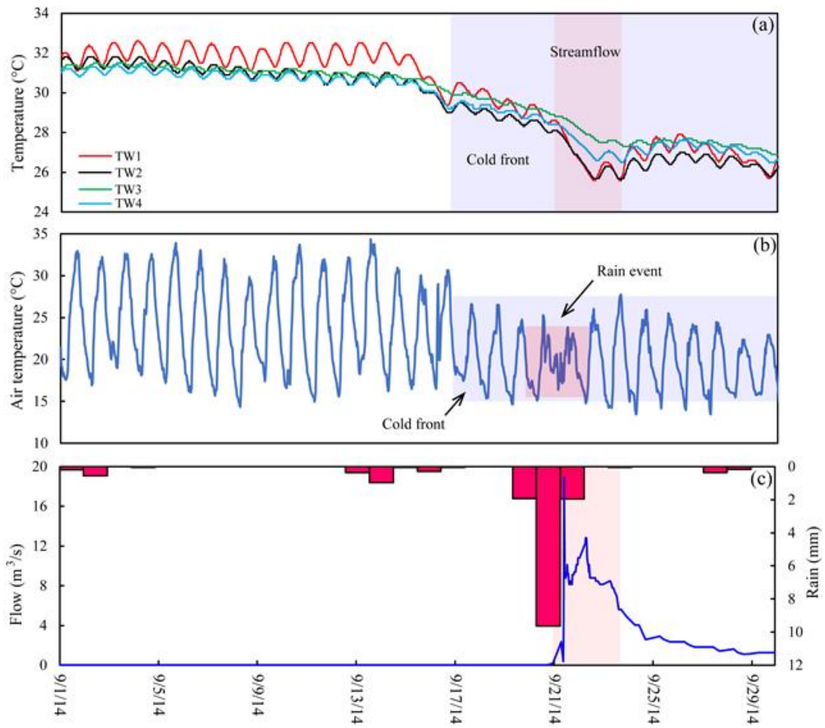

Figure 2: Procedure of detecting thermal anomalies based on near-surface temperature (a) and air temperature records (b). Their superposition to measured data of runoff or precipitation (c) allowed determining the type of the hydrological events that generated the perturbations.

The visual inspection of the surface-streambed thermographs led to the identification of 31 thermal anomalies (Figure 3). According to the gauging station data, 4 events were related to normal streamflow (defined here as flow $\leq$ 1.55 m^3/s that is the average runoff at the gauge station) and 11 were related to floods (defined as flow > 2*1.55 m^3/s). The other events (16 events) are ungauged events (Tab. 3); they could correspond either to rainfall or to flow from small ungauged reaches located below the gauging station.

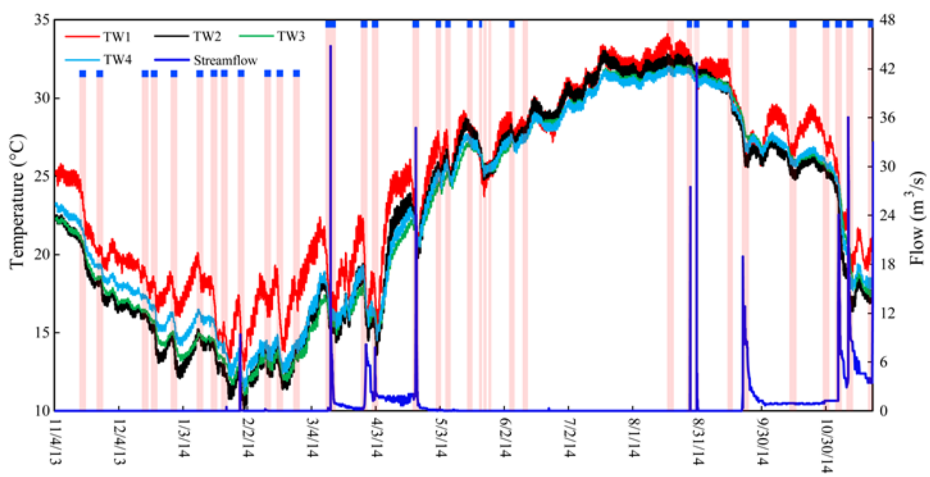

Figure 3: Near-surface thermographs to detect streamflow presence and duration at the experiment site. The bands represent the thermal anomalies that were related to hydrological events.

Table 3 : Type of the Detected Streamflow Losses Events and their Depth. The Rows in Bold Correspond to the Potential Recharge Events

The Detected infiltration events					
Number	Date	Rain (mm)	Measured streamflow m^3/s	Type	Recorded depth of perturbation (m)
1	11/17/2013	0.7		Ungauged	0.5
2	11/25/2013	10.2		Ungauged	0.5
3	12/16/2013	1.0		Ungauged	0.5
4	12/20/2013	3.1		Ungauged	0.5
5	12/28/2013	7.5		Ungauged	0.5
6	1/10/2014	1.4		Ungauged	0.5
7	1/17/2014	10.8		Ungauged	0.5
8	1/22/2014	19.6	0.48	Normal flow	2
9	**1/29/2014**	**34.8**	**9.40**	**Flood**	**5.5**
10	**2/10/2014**	**14.5**	**0.24**	**Normal flow**	**3.5**
11	**2/16/2014**	**8.6**		**Ungauged**	**3.5**
12	2/24/2014	0.1		Ungauged	0.5
13	**3/12/2014**	**45.0**	**44.80**	**Flood**	**5.5**
14	**3/28/2014**	**20.0**	**8.10**	**Flood**	**5.5**
15	**4/2/2014**	**17.6**	**7.76**	**Flood**	**2.5**
16	**4/21/2014**	**31.0**	**34.80**	**Flood**	**5.5**
17	5/2/2014	8.1	0.15	Normal flow	2
18	5/6/2014	1.2		Ungauged	2
19	**5/8/2014**	**15.0**	**0.15**	**Normal flow**	**2.5**
20	5/16/2014	0.8		Ungauged	2
21	5/22/2014	1.8		Ungauged	1
22	6/6/2014	0.6		Ungauged	0.5
23	8/27/2014	17.2	27.50	Flood	1.0
24	8/30/2014	20.0	42.70	Flood	1.0
25	9/17/2014	0.4		Ungauged	1
26	**9/21/2014**	**25.0**	**19.00**	**Flood**	**4**
27	10/12/2014	0.2		Ungauged	0.5
28	10/29/2014	2.6		Ungauged	1
29	**11/4/2014**	**28.6**	**24.00**	**Flood**	**5.5**
30	**11/9/2014**	**23.0**	**36.00**	**Flood**	**5.5**
31	**11/21/2014**	**1.6**	**60.00**	**Flood**	**5.5**

All the measured floods at the gauging station were detected at the site. Most of them occurred in the wet period. The two floods in late August in response to summer storms could be considered as flashfloods since they lasted no more than 6.5 hours. The largest flood (60 m^3/s) in November 21, 2014 caused massive damage to our experiment.

4.3 Water content changes

Water content (WC) changes were monitored over 1 years' time, every 30 minutes, every 1m depth interval, 4 m beneath the streambed surface. The general evolution of WC could be divided in 2 moisture states of the sediment (Fig. 4): (i) wet sediment state during 5 months (February 2014 to June 2014), the WC values increase progressively from the surface to the bottom of the sediment, and (ii) dry sediment state during 3 months (from July to September 2014).

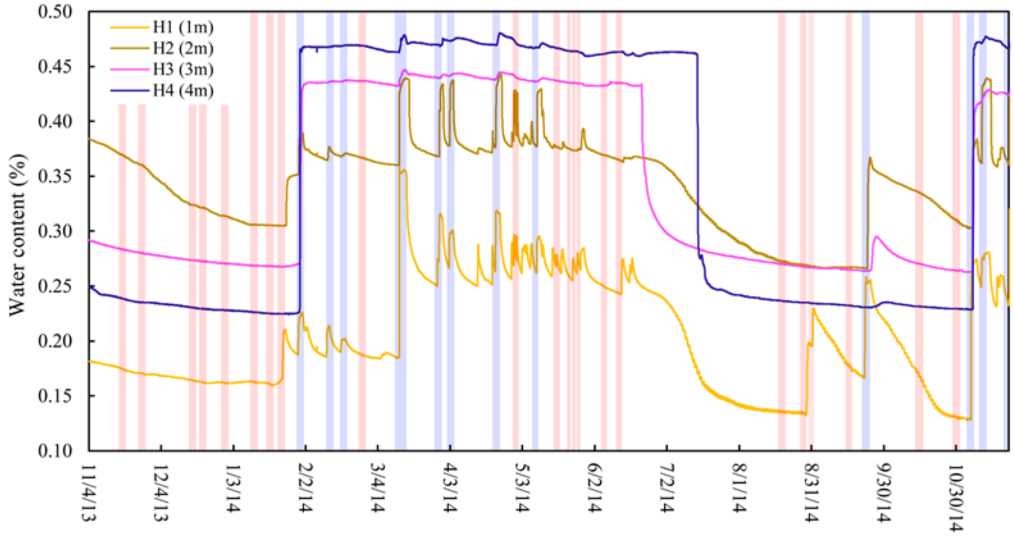

Figure 4: Water content data measured at four depths (1 to 4 m), 1 m apart, beneath the Rheraya streambed. The bands represent the events that led to streamflow losses; the blue ones indicate potential recharge events.

During the wet sediment period, the moisture state of the sediment seems not only due to streamflow losses. Figure 5 presents the WC variation in the vadose zone before, during and after the first flood of January 29, 2014. The probes show different behaviors. WC at the probes 1 and 2 increased by the same magnitude (4%). At probe 3, first the WC increased to 36 % then after a short slowdown it increased to a maximum of 43.6%. Second, the highest rise in WC was observed at the probe 4 installed at 4 m depth, where WC increased to 46.5%. Notably the WC increased at 4 m (probe 4) before increasing at 3 m (probe 3), suggesting that the quasi-saturation at 4 m depth m was caused by the rise of the water table. The latter led to wetting conditions from the bottom that reached with a delay the probe 3 as well. In summary, the increase of WC at 1m and 2m depth as well as the first increase at 3m were due to streamflow losses, while the increase of WC at 4m and the second increase at 3m were due the rise of the water table.

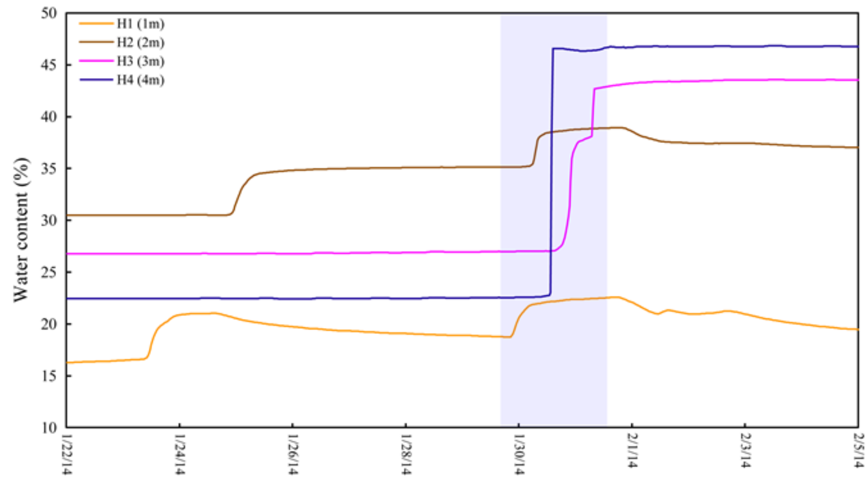

Figure 5: Time series of the water content variation during the event of January 29, 2014. The water content at 4 m increased before the one at 3m, indicating the rise of the water table. At 3m, the first increase in WC could be due to water percolation from the surface and the second to the rise of the water table.

During the wet sediment period, the WC fluctuates significantly in the upper part of the sediment, while remaining stable at a quasi-saturation level at 3 m and 4 m depth. Consequently, the WC at the upper part of the sediment was induced by streamflow losses inducing sharp increases, and at the bottom of the sediment it was maintained by the groundwater. In early summer, a general decrease of water content in the sediment was observed (Fig. 4). The decrease was abrupt at 3 m and 4 m depth marking the drop of the water table. A more progressive decrease at 1 m and 2 m depth indicates a normal drying of the sediment.

4.4 Streambed-sediments temperature analysis

Temperature at very shallow depths (0.25 m and 0.5 m) is influenced by both diurnal and seasonal variations, while the temperatures of the deepest probes show a slight seasonal variation (Figure 6). Overall, the general shape of the thermographs is sinusoidal with the lowest recorded temperatures in the winter and the highest temperatures in summer. From November 2013 to March 2014, temperature increases with depth. From April 2014, the temperature gradient shifted. Streamflow losses induced temperature declines more frequent during winter and spring than summer. The perturbations of temperature induced by the floods are more obvious. The magnitude of the temperature drop was up to 7 °C (floods of March 12, 2014 and November 4, 2014) at the upper temperature probes and up to 2 °C at the deeper probes (flood of November 4, 2014).

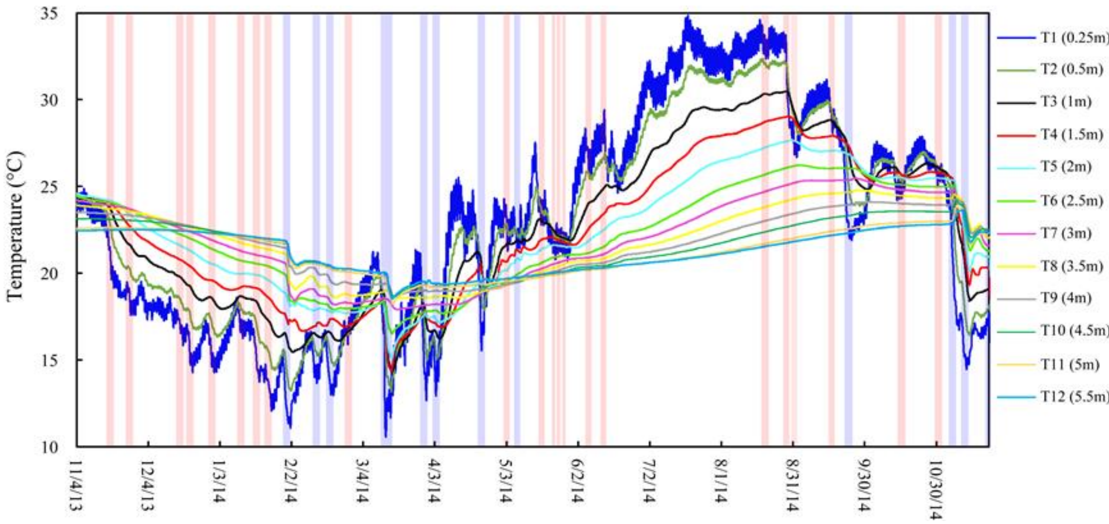

Figure 6: Streambed temperature measured at 12 depths (up to 5.5 m), 0.5 m apart, beneath the Rheraya streambed. The bands represent the streamflow losses events; the blue ones indicate the potential recharge events.

4.5 Delineating potential recharging events

During the one year of monitoring of the sediment temperature and water content, 31streamflow infiltration events were identified (Tab. 3). They correspond to 11 floods, 4 normal streamflow and 16 rainfall/ungauged reach flow. For 9 floods (out of 11), 2 normal streamflow and 1 ungauged event, almost all in the wet period, deep water percolation (beyond 2.5 m depth) was recorded (Table 3, Fig. 4, Fig. 6). Because the water table was maintained around 3 m depth during the wet period, these events are considered to have recharged the groundwater. The two flashfloods in the late August 2014 (N° 23, 24) only led to a temperature and moisture change at 1.0 m depth despite their high flowrate, and are therefore not considered as generating deep percolation. Therefore, the potential recharge events are in general those floods that occurred in wet sediment conditions.

4.6 Numerical modeling of heat for recharging events

Using the elaborated VS2DH model, the recharge events were modeled by matching observed temperature to simulated one, until reaching the best fit between observed and simulated temperature (Fig. 7). The RMSE for each event is listed in table 4. The RMSE values vary between 0.1 and 0.9 °C which seems very acceptable owing to various uncertainties related to this type of modeling. In our case, the main sources of uncertainty could be the scarce data on streamflow stage and by the assumptions related to the one-dimensional vertical model, which does not consider lateral flow derived from infiltration beyond the vertical model's domain (Rau et al, 2014).

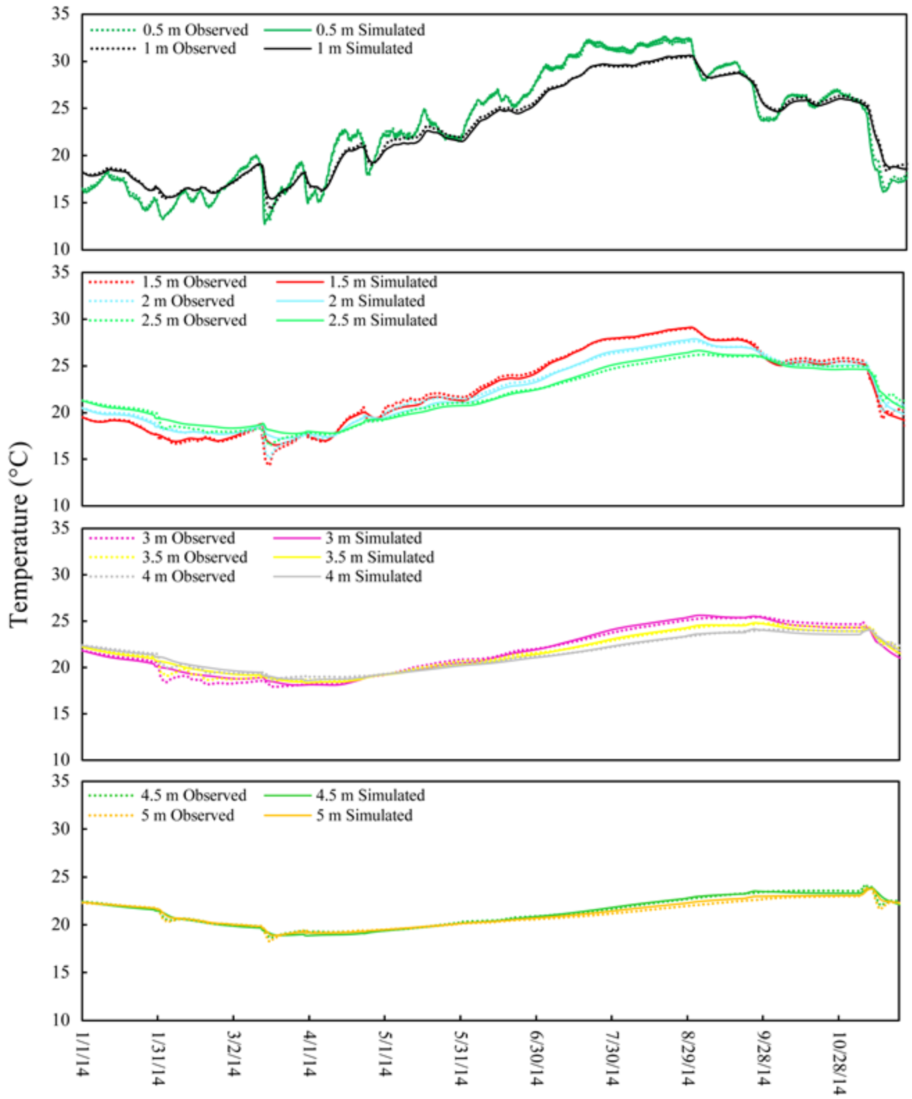

Figure 7: Observed versus simulated temperature at different depths, for the whole study period.

The recharge fluxes that are calculated by VS2DH correspond to the flowrate of water through the streambed per unit of streambed surface area (m^3 m^{-2} s^{-1}). They vary between 0.03 and 4.65 mm/h with a mean of 1.7 mm/h. The highest flux of 4.7 mm/h corresponds to the large flood of November 21, 2014 while the lowest flux of 0.03 mm/h corresponds to the low streamflow event of February 16, 2014 (Tab. 5).

Table 4: Percolation fluxes calculated by VS2DH heat modeling.

Event number	Streamflow m3/s	Type	Start	End	Duration (h)	Fluxes (mm/h)			RMSE (°C)	Total flux (mm)
						Min	Max	Mean		
9	9.4	Flood	1/29/2014 20:30	1/31/2014 16:00	44	0.14	0.86	0.82	0.20	36
10	0.24	Normal flow	2/10/2014 7:00	11/2/2014 16:00	33.5	0.03	0.05	0.04	0.06	1
11	-	Ungauged	2/16/2014 01:00	2/18/2014 13:00	60.5	0.03	0.03	0.03	0.15	2
13	44.8	Flood	3/12/2014 23:00	3/14/2014 00:30	26	0.14	3.69	3.28	0.62	85
14	8.1	Flood	3/28/2014 21:00	3/30/2014 12:30	40	0.10	0.27	0.26	0.15	10
15	7.76	Flood	4/2/2014 13:00	3/4/2014 10:00	21.5	0.20	0.21	0.21	0.04	4
16	34.8	Flood	4/21/2014 19:30	4/22/2014 14:00	19	0.04	2.30	2.13	0.26	40
19	0.15	Normal flow	5/8/2014 22:30	5/10/2014 19:30	45.5	0.33	1.18	1.08	0.12	49
26	19	Flood	9/21/2014 10:00	9/22/2014 16:30	31	0.25	1.00	0.95	0.10	29
29	24	Flood	4/11/2014 23:30	6/11/2014 18:30	43.5	0.56	1.74	1.63	0.12	71
30	36	Flood	9/11/2014 17:30	12/11/2014 9:00	64	0.54	2.58	2.47	0.91	158
31	60	Flood	11/21/2014 08:00	11/21/2014 13:00	5.5	4.63	4.66	4.65	0.36	26

5. Discussion

5.1. Near surface temperature as a proxy to infer streamflow presence and duration

Wadi Rheraya is characterized by intermittent streamflow driven by rainfall storm and snowmelt (Hajhouji et al, 2018). As the Tahanaout gaging station is located several kilometers upstream the experiment site, we examined the effectiveness of using temperature to detect the presence and duration of streamflow in this context. 31 thermal anomalies of the surface-streambed temperature were isolated. 11 events were related to gauged floods, 04 to gauged normal streamflow, and 16 to rainfall or ungauged flow from reaches located below the gauging station. Temperature records at the near surface streambed sediment have detected the occurrence of hydrological events, but were insufficient alone to detect the type of the hydrological events. Using runoff measurements even far from the study site was necessary to help distinguish between different types of events. However, temperature records at the near surface streambed sediment was very useful to measure the duration of each detected event.

5.2. The insights from coupling water content and temperature data to study streamflow losses

In this research, the water content change method was revealed more practical for recording and visualizing the downward surface water infiltration (Fig. 4) and particularly to detect in the deepest probes the upward wetting front in response to groundwater rise (Fig. 5). The drop of the water table was also distinguishable through an abrupt dewatering of the deep sediment while the normal drying of the top sediment generates a more progressive decrease of the water content due to evaporation and low infiltration. Such processes would have been difficult to detect only with temperature variation. However, during near saturation conditions of sediments at 3m and 4 m depth, the water content method was less efficient in analyzing percolation as the induced changes were barely noticeable. This was the reason that the water content variation was used in other studies (Dahan et al., 2007; Dahan et al., 2008; Hoffmann et al., 2007) to assess infiltration only at the onset of infiltration events, during unsaturated conditions.

The occurrence of streamflow losses induces abrupt and obvious temperature perturbations (Fig. 6) regardless of the water content conditions of the sediment, due to advective heat transfer following the downwards movements of water (Constantz & Thomas, 1996, 1997). Sediment temperature responds to streamflow losses by a net decrease due to the cooler water coming from high elevations of the High-Atlas Mountains. In our case representing an intermittent streamflow under semi-arid climate, during one year of monitoring, 31 streamflow infiltration events were identified. This is quite different from the ephemeral streams generally characterized by a much lower number of events that are restricted to episodic intensive rainfall events (Blasch et al., 2004; Stewart-Deaker et al., 2007; Dahan et al., 2008; Schwartz, 2016).

5.3. The water table variation

For Wadi Rheraya, sediment water-content data indicates the first rise of groundwater was not caused by the vertical infiltration at the wadi experimental site, but rather by lateral recharge that raised the ground water elevation upwards through the streambed sediments. The water table beneath the wadi remained elevated during late winter, spring and early summer. During this period, the top streambed sediment was variably saturated, while near saturation conditions were maintained at lower elevations in the sediments. The water table declined to lower elevations beneath the wadi during summer and autumn, as a result of lack of recharge due to generally dry conditions and the lack of recharge from brief summer flow events. This annual water table elevation change is consistent with groundwater variation in intermittent stream alluvial aquifers in mountain front areas under Mediterranean climate (Leduc, et al. 2016; Bioumouass, et al. 2020). In winter and spring, the water table increases due to high recharge from high flows from rainfall and snowmelt, and low discharge. In summer and autumn, the water table decreases due to low or absent groundwater recharge, and high groundwater discharge to satisfy moisture depletion down gradient.

5.4. Deep percolation fluxes

For this specific wadi study for a single water year, the analysis of combined streambed temperature profiles with streambed water-content profiles, lead to the following results. The interpreted result for this wadi is: 9 of 11 large streamflow (flood) events generated groundwater recharge, 1 of 4 baseflow (normal) streamflow events generated ground water recharge and 1 of 9 ungauged rainfall events generated groundwater recharge. For the events interpreted as groundwater recharge, all of these events appeared from analysis of the profiles to generate deep percolation surpassing 2 m depth, and importantly, all of these recharging events occurred in the wet season.

A key finding for Wadi Rheraya is similar streamflow events generated varying streamflow losses, i.e., there was seasonality (seasonal variation) in streamflow losses for similar flows. This seasonality of streamflow versus streamflow-losses relation was shown to be based on pre-existing hydrologic conditions prior to individual flow events. The rainfall/ungauged reach flow and the normal flow seemed to be too low to generate any deep percolation, with the latter was almost generated by floods. As examples of large high-flow rate events failing to generate recharge, examination of a pair of flood events during late August; despite their magnitude both events generated shallow infiltration (1 m deep) resulting in no recharge. This is explained by both pre-existing wadi conditions and their flashy (high flow rate, short duration) characteristics resuling in short-duration infiltration into a dry streambed sediment. To estimate the role of pre-existing sediment water content of on the infiltration process, the maximum velocities of the advance of the wetting front during infiltration were calculated using the time of the first indication of a water content increase at a given probe. They show that the advance of the wetting front is significantly faster in wet sediment (from 19 cm/hour to 330 cm/hour) than in dry sediment (from 3 cm/hour to 9 cm/hour). This demonstrates in a quantitative manner that wet sediments may be orders of magnitude more favorable for deep percolation and recharge for a winter flow event compared with a summer flow event.

For Wadi Rheraya, summarizing the annual variation recharge based on calculated deep percolation fluxes related to the potential recharge events, a vertical 1-dimentional modeling approach was constructed using the heat and water transport model VS2DH. Deep percolation rates varied from 0.03 to 4.7 mm/h with an average of 1.7 mm/h. The cumulative flux per event varied from 1 mm to 158 mm (Tab. 5). Over the one-year experiment, the total percolation amount estimated as 459 mm/year. Almost the entire deep percolation, approximately 90%, occurred during wet period flood events. For baseflow (normal) flow events, percolation was generally low.

5.5. The pattern of streamflow losses

Hence, the depth and magnitude of the stream losses depend on the streamflow type and the moisture conditions of the sediment, factors that assign a seasonality to groundwater recharge. During winter and spring, the recharge is performed mainly by floods. The normal flow generally generates low and shallow infiltration, however contributing to maintain wet conditions at the upper part of the sediment that enhance the percolation conditions. Indeed, high streambed water content greatly enhances potential recharge due to higher hydraulic conductivities and less unsaturated pore volume to absorb event-generated percolation. During the dry period, the scarcity of the streamflow and the dry state of the sediment are much less favorable to recharge. Furthermore, despite the intermittent flow regime fed by the mountain water, due to the semi-arid conditions a significant flow volume is likely diverted to irrigation, reducing the potential of in-stream recharge (Bouimouass et al., 2020).

The sediment moisture data showed that along the study period, no steady saturated hydraulic connection was achieved between the stream and the water table. The sediment above the water table evolved as a variably saturated flow system, and temporal pattern of the groundwater recharge remained transient and dominated by separated recharging events.

6 Conclusions

For wadis and other stream channels with intermittent streams in arid and semiarid basins, streamflow losses may be important sources of groundwater recharge; however, it is more challenging to directly measure recharge than even in ephemeral streams. As a consequence, this study utilized a unique coupling of continuous monitoring of streambed sediment temperature profiles and sediment water-content profiles, for successful, indirect estimates of streambed deep percolation and recharge beneath Wadi Rheraya during an entire hydrological year. However, streamflow monitoring at a gauging station even far from the experiment site, was necessary to determine the type of the hydrological events (flood, normal flow or flow from isolated ungauged reach). Streambed water content allowed monitoring of the moisture conditions of the sediment and to detect downward surface water infiltration and the movements of groundwater table. The streambed temperature records provided insightful information about the depth and the duration of the infiltration from streamflow. Furthermore, the vertical streambed water content profiles lead to parsing at the start of the wet season whether groundwater recharge was created by deep percolation or from lateral inflow beneath the wadi probably derived from mountain-front recharge.

In this study, non-recharging versus potentially recharging events were distinguished according to the stream water infiltration depth. The floods of winter and spring appear to be the main source of groundwater recharge. The normal streamflow or rainfall during the wet period generate low and superficial infiltration but contribute to the wetting of the sediment. During the dry period, the dry sediment and probably the flashy character of the floods, limit the infiltration and therefore subsequent groundwater recharge. In summary, this study demonstrated clear seasonality relations between streamflow magnitude and streamflow loss amounts and percolation depth magnitude, that manifested different streambed moisture response for similar streamflow winter and spring events compared with summer and fall events in the channel of Wadi Rheraya. Furthermore, this study revealed a lateral recharge derived from mountain-front recharge.

Acknowledgments, and Data

The authors are grateful to people and institutions that gave any field or official help : Youssef Hajhouji (UCA), Mohamed Kasbani (TREMA Laboratory), GeoSciences Semlalia Laboratory (UCA), TREMA Laboratory (UCA), ABHT (Agence du basin Hydraulique du Tensift), The Province of the Haouz, Marrakech.

The data used in this study are included as supplements for review purposes.

References

Alyamani MS, Sen Z (1993) Determination of hydraulic conductivity from complete grain-size distribution curves. *Ground Water,* 31(4), 551–555

Anderson, M. P. (2005). Heat as a ground water tracer. *Ground water*, *43(6)*, 951-968.

Blasch, K.W., Constantz, J., Stonestrom, D.A., (2007). Ground-Water Recharge in the Arid and Semiarid Southwestern United States. Appendix 1: thermal methods for investigating ground-water recharge: Stonestrom, et al. (Eds.).

Blasch, K. W., Ferré, T., & Hoffmann, J. P. (2004). A statistical technique for interpreting streamflow timing using streambed sediment thermographs. *Vadose Zone Journal, 3(3)*, 936-946.

Blasch, K. W., Fleming, J. B., Ferre, P. A., & Hoffmann, J. P. (2000). One-and two-dimensional temperature and moisture-content profiling of an ephemeral stream channel in a semiarid watershed [abs]: EOS. Transactions, American Geophyical Union, 81, F50.

Bouimouass, H., Fakir, Y., Tweed, S., & Leblanc, M. (2020). Groundwater recharge sources in semiarid irrigated mountain-fronts. *Hydrological Processes*. https://doi.org/10.1002/hyp.13685

Boukhari, K., Fakir, Y., Stigter, T. Y., Hajhouji, Y., & Boulet, G. (2015). Origin of recharge and salinity and their role on management issues of a large alluvial aquifer system in the semi-arid Haouz plain, Morocco. *Environmental Earth Sciences*, *73(10)*, 6195-6212.

Constantz, J. (2008). Heat as a tracer to determine streambed water exchanges. *Water Resources Research*, *44(4)*.

Constantz, J., Stewart, A. E., Niswonger, R., & Sarma, L. (2002). Analysis of temperature profiles for investigating stream losses beneath ephemeral channels. *Water Resources Research*, *38(12)*.

Constantz J., & Stonestrom D. A. (2003) Heat as a tool for studying the movement of ground water near streams. US Geol Surv Circ 1260.

Constantz, J., Stonestorm, D. A., Stewart, A. E., Niswonger, R., & Smith, T. R. (2001). Analysis of streambed temperatures in ephemeral channels to determine streamflow frequency and duration. *Water Resources Research*, *37(2)*, 317-328.

Constantz, J., & Thomas C.L. (1996). The use of streambed temperatures profiles to estimate depth, duration, and rate of percolation beneath arroyos. *Water Resources Research*, *32*, 3597-3602.

Constantz, J., & Thomas, C. L. (1997). Streambed temperature profiles as indicators of percolation characteristics beneath arroyos in the middle Rio Grande Basin, USA. *Hydrological Processes*, *11(12)*, 1621-1634.

Constantz, J., Thomas, C. L., & Zellweger, G. (1994). Influence of diurnal variations in stream temperature on streamflow loss and groundwater recharge. *Water Resources Research*, *30(12)*, 3253-3264.

Cuthbert, M. O., Acworth, R. I., Andersen, M. S., Larsen, J. R., McCallum, A. M., Rau, G. C., Tellam, J. H. (2016). Understanding and quantifying focused, indirect groundwater recharge from ephemeral streams using water table fluctuations. *Water Resources Research*, *52*, 827–840.

Dahan, O., Shani, Y., Enzel, Y., Yechieli, Y., & Yakirevich, A. (2007). Direct measurements of floodwater infiltration into shallow alluvial aquifers. *Journal of Hydrology*, *344(3-4)*, 157-170.

Dahan, O., Tatarsky, B., Enzel, Y., Kulls, C., Seely, M., & Benito, G. (2008). Dynamics of flood water infiltration and ground water recharge in hyperarid desert. *Groundwater*, *46(3)*, 450-461.

Goodrich, D. C, Williams, D. G., Unkrich, C. L, Hogan, J. F., Scott, R. L, Hultine, K. R., Pool, D., Coes, A. L, Miller, S. N. 2004. Comparison of Methods to Estimate Ephemeral Channel Recharge, Walnut Gulch, San Pedro River Basin, Arizona. In Recharge and Vadose Zone Processes: Alluvial Basins of the Southwestern United States, ed. by F.M. Phillips, J.F. Hogan, and B. Scanlon, Water Science and Application 9, Washington, DC, American Geophysical Union, p. 77-99. 2004.

Hajhouji, Y., Gascoin, S., Fakir, Y., Richard, R., Simonneaux, V., & Chehbouni, A. (2018). Rainfall-Runoff modeling and hydrological regime analysis of a semi-arid snow-influenced catchment Case of the Rheraya river (High Atlas, Morocco) - Modélisation pluie-débit et analyse du régime d’un bassin versant semi-aride sous influence nivale Cas du bassin versant du Rheraya (Haut Atlas, Maroc). La Houille Blanche, 3, 49–62. https://doi.org/10.1051/lhb/2018032

Healy, R. W., & Ronan, A. D. (1996). Documentation of computer program VS2DH for simulation of energy transport in variably saturated porous media: Modification of the US Geological Survey's computer program VS2DT. US Geological Survey.

Heppner, C. S., Nimmo, J. R., Folmar, G. J., Gburek, W. J., & Risser, D. W. (2007). Multiple-methods investigation of recharge at a humid-region fractured rock site, Pennsylvania, USA. *Hydrogeology Journal, 15(5)*, 915-927.

Hoffmann, J. P., Blasch, K. W., Pool, D. R., Bailey, M. A., & Callegary, J. B. (2007). Estimated infiltration, percolation, and recharge rates at the Rillito Creek focused recharge investigation site, Pima County, Arizona. In *Ground-water recharge in the arid and semiarid southwestern United States* (pp. 185-220).

Jarlan, L., Khabba, S., Er-Raki, S., Le Page, M., Hanich, L., Fakir, Y., et al. (2015). Remote sensing of water resources in semi-arid Mediterranean areas: The joint international laboratory TREMA. *International Journal of Remote Sensing, 36(19-20)*, 4879-4917.

Kalbus, E., Reinstorf, F., & Schirmer, M. (2006). Measuring methods for groundwater-surface water interactions: a review. *Hydrology and Earth System Sciences Discussions, 10(6)*, 873-887.

Koch, F. W., Voytek, E. B., Day-Lewis, F. D., Healy, R., Briggs, M. A., Lane Jr, J. W., & Werkema, D. (2016). 1DTempPro V2: New features for inferring groundwater/surface-water exchange. *Groundwater, 54(3)*, 434-439.

Kulongoski, J. T., & Izbicki, J. A. (2008). Simulation of fluid, heat transport to estimate desert stream infiltration. *Ground water, 46(3)*, 462-474.

Kurylyk, B. L., Irvine, D. J., & Bense, V. F. (2019). Theory, tools, and multidisciplinary applications for tracing groundwater fluxes from temperature profiles. WIREs Water, https://doi.org/10.1002/wat2.1329

Landon, M.K. , Rus, D.L. & Harvey, F.E. (2001). Comparison of Instream Methods for Measuring Hydraulic Conductivity in Sandy Streambeds. Papers in Natural Resources, 154. https://digitalcommons.unl.edu/natrespapers/154

Leduc, C., Pulido Bosch, A., Remini, B., & Massuel, S. (2016). Sub-chapter 2.3.5. Changes in Mediterranean groundwater resources. In Moatti, J., & Thiébault, S. (Eds.), The Mediterranean region under climate change: A scientific update. IRD Éditions. doi:10.4000/books.irdeditions.23583

Mendez, G. (2005), Evaluation of two low-flow releases from Big Tujunga Reservoir, Los Angeles County, U.S. *Geological Survey Scientific Investigation Reports, 5003*, 1-53.

Moore, S. J. (2007). Streamflow, infiltration, and recharge in Arroyo Hondo, New Mexico (No. 1703-F). Geological Survey (US).

Niswonger, R. G., & Prudic, D. E. (2003). Modeling heat as a tracer to estimate streambed seepage and hydraulic conductivity: Heat as a tool for studying the movement of ground water near streams (pp. 81-89).

Niswonger, R. G., Prudic, D. E., Fogg, G. E., Stonestrom, D. A., & Buckland, E. M. (2008). Method for estimating spatially variable seepage loss and hydraulic conductivity in intermittent and ephemeral streams. *Water Resources Research, 44*, W05418.

Pahud, D. (2002). Geothermal energy and heat storage. Scuola Universitaria Professionale della Svizzera Italiana.

Rau, G. C., Halloran, L. J.S., Cuthbert, M. O., Andersen, M. S., Acworth, R. I. & Tellam J. H. (2017). Characterising the dynamics of surface watergroundwater interactions in intermittent and ephemeral streams using streambed thermal signatures. *Advances in Water Resources*, doi: 10.1016/j.advwatres.2017.07.005

Reid, M. I., Dreiss, S. J. (1990). Modeling the effects of unsaturated, stratified sediments on groundwater recharge from intermittent streams. *Journal of Hydrology, (114)*, 149-174.

Ronan, A. D., Prudic, D. E., Thodal, C. E., & Constantz, J. (1998). Field study and simulation of diurnal temperature effects on infiltration and variably saturated flow beneath an ephemeral stream. *Water Resources Research, 34(9)*, 2137-2153.

Shanafield, M., & Cook, P. G. (2014). Transmission losses, infiltration and groundwater recharge through ephemeral and intermittent streambeds: A review of applied methods. *Journal of Hydrology*, *511*, 518-529.

Schwartz, U. (2016). Factors affecting channel infiltration of floodwaters in Nahal Zin basin, Negev desert, Israel. *Hydrological Processes*, *30(20)*, 3704-3716.

Sinan M, Razack M (2006) Estimation du champ de transmissivité d’un aquifère alluvial fortement hétérogène à partir de la résistance transversale. Application à la nappe du Haouz de Marrakech, Maroc (Assessing transmissivity of a very heterogeneous alluvial aquifer using transversal resistance. Application to Haouz aquifer, Marrakech, Morocco . *Revue des sciences de l'eau / Journal of Water Science*, 19 (3), 221-232

Stewart-Deaker, A. E., Stonestrom, D. A., & Moore, S. J. (2007). Streamflow, infiltration, and ground-water recharge at Abo Arroyo, New Mexico: Ground-water recharge in the arid and semiarid southwestern United States. Professional Paper, 83-105.

Stonestrom, D. A., Prudic, D. E., Walvoord, M. A., Abraham, J. D., Stewart-Deaker, A. E., Glancy, P. A., et al. (2007). Focused ground-water recharge in the Amargosa Desert basin: Chapter E in Ground-water recharge in the arid and semiarid southwestern United States. Professional Paper, 1703 (No. 1703-E, pp. 107-136). US Geological Survey.

Stonestrom, D. A., & Constantz, J. (Eds.). (2003). Heat as a tool for studying the movement of ground water near streams (No. 1260). US Dept. of the Interior, US Geological Survey.