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ORIGINAL ARTICLE

Isotopic signatures for the assessment of snow water resources in the Moroccan high Atlas mountains: contribution to surface and groundwater recharge

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Abstract To characterize snow isotopic signatures, monitoring of snowmelt was carried out at two sites (Oukaimden and Ifni) in the Moroccan High Atlas Mountains. For the Oukaimden site, samples of snow were taken by two methods to compare sampling techniques: (1) coring with a polyvinyl chloride (PVC) tube and (2) passive capillary sampling (PCS) installed at the snow/soil interface. The analyses show variable isotope contents, ranging from −14.7 to −2.5 ‰ for oxygen-18 and from −116 to −28.2 ‰ for deuterium. The most depleted values are observed in March 2013 at high elevation (3229 m asl). The majority of snow core samples display fractionation by sublimation, whereas those collected by the PCS sampling method are close to the Global Meteoric Water Line. The isotopic signature is comparable for snow, surface water and groundwater samples, indicating that snowmelt plays an important role in recharging aquifers, lakes, and rivers on the southern and northern sides of the Atlas Mountains. Recharge by snowmelt allows the dilution of salinity in adjacent aquifers. Characterization of the stable isotopic composition of snow obtained from snow cores is limited in comparison with the PCS method, which provides realistic compositions of the melt water contribution to water resources in this semi-arid area.

Keywords Stable isotopes · Snowmelt process · Water resources · High Atlas mountains · Semi-arid · Morocco

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Introduction

In many parts of the world, mountains represent important water storage because of the orographic effect (increasing precipitation with elevation), which has earned them the nickname "water towers" (Messerli and Ives 1997; De Jong et al. 2005). Mountains are the most important sources of freshwater for surrounding watersheds (Gil'ad and Bonne 1990). The importance of mountains for the hydrological cycle is even more marked for arid and semi-arid regions, as in the case of the Mediterranean basin (Viviroli et al. 2003; Shaban et al. 2004), providing essential water resources for agricultural irrigation. The contribution of mountains to total discharge is much higher in semi-arid and arid areas (50–90 %) than in humid temperate regions (20–50 %) (Messerli et al. 2004). A common global practice in such arid zones is upstream water storage in dammed reservoirs that capture mountainous snowmelt and stream flow for irrigation.

In the southern watersheds of Morocco, the High Atlas Mountains, with elevations ranging from 700 to 4200 m above sea level (asl), represent the most important water supply. Precipitation in the mountains falls as both rain and snow, but the snow cover is non-permanent and varies during winter. The High Atlas is the main recharge area for

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aquifers beneath the adjacent plains (Bouchaou et al. 2008; Bouragba et al. 2011; Cappy 2006; Lgourna et al. 2015; Ait Brahim et al. 2015). The fractions of snowmelt contributing to stream flow are variable from 1 year to another and from one sub-catchment to another. Modeling studies show that snowmelt from the northern slopes of the High Atlas contributes approximately 25 % to stream flow in its catchments (Boudhar et al. 2009), but the snowmelt proportion in the Ourika basin was estimated to be 38 %. Future climate scenarios predict a decrease in winter precipitation by 15 % with an increase in dry periods throughout Morocco by the year 2050. This announced climate change may exacerbate the water problems of the region, which is already under high water stress (Giorgi 2006; Driouech et al. 2010).

To better understand the hydrological relation between the High Atlas Mountains and the adjacent plains, several studies have been carried out in recent years using multiple isotope investigations in collaboration with the International Atomic Energy Agency (IAEA) and the Hydraulic Basin Agencies of Souss Massa Drâa and Tensift. The results show that the contribution of precipitation on the plains is negligible and the major recharge of the aquifers beneath the plains is provided by High Atlas stream flows (Bouchaou et al. 2008; Bouragba et al. 2011; Warner et al. 2013; Rochdane et al. 2015), but the contribution rate of snow cover has not been quantified. Improved knowledge about the snow-water storage is of crucial importance to understand the contribution of the different components of the hydrological cycle to water resources. This is, however, a challenging task since there is no systematic monitoring of snow dynamics, especially at high elevation.

In the context of monitoring equipment shortages, stable isotopes are a standard tool for hydrologists to understand and evaluate water resources in watersheds to distinguish surface and groundwater sources, as well as water mixing processes (Dansgaard 1964; Gat and Gonfiantini 1981; Simpson and Herczeg 1991; Vrbka et al. 1993). The use of stable isotopes is based on the fact that $\delta^{18}O$ and $\delta^{2}H$ compositions of natural waters vary measurably because of meteorological and hydrogeological effects. Generally, depending on local specificities, multiple effects, such as temperature, latitude and altitude, modify the original isotopic composition of meteoric water (Clark and Fritz 1997; Kendall and McDonnell 1998; McGuire and McDonnell 2007; Jeelani et al. 2010).

Some studies have been conducted on the isotopic characteristics of snowpack (Moser and Stichler 1975; Martinec et al. 1977), isotopic fractionation of water vapor during formation of snow (Lehmann and Siegenthaler 1991), the processes and isotopic exchange affecting the water during snowmelt (Arnason 1969; Lee et al. 2009), and the isotopic interactions between snowmelt and snow grains (Taylor et al. 2001; Zhou et al. 2008). These studies have shown that water from melting snow usually exhibits a different isotopic signal compared to that of precipitation. Water is more depleted in oxygen-18 at the beginning of melting and gradually becomes enriched as the snow continues to melt. Taylor et al. (2001) and Earman et al. (2006) showed significant difference between isotopic composition of fresh snow and the bulk melt water. They concluded that using the isotope composition of high elevation springs as a proxy for precipitation may not be sound if snow is a recharge source, and the collector design influences the stable isotope composition of collected snow. Penna et al. (2014) have developed an improved approach for obtaining snowmelt isotopic analysis using passive capillary sampling (PCS).

By comparing the isotopic signal of rain and snow with the isotopic signals of surface water and groundwater in the area, their respective contributions can be distinguished. The global objective of this study is to investigate the contribution of the runoff generated by snow cover using isotopic tracers near the headwaters of two basins in the High Atlas Mountains. The specific objective is to test the new PCS sampling method.

Study area and methods

Study area

The investigated area is located in the central High Atlas Mountains between longitude 7°30′, 9°00′ west and latitudes 30°40′, 31°30′ north at elevations ranging from 700 to 3244 m asl. The region is influenced by meteorologically contrasting areas (Atlantic Ocean to the west, desert area to the south and Mediterranean Sea to the north). The climate in the study area is semi-arid to arid, with the rainy season extending from November to April and the dry season from April to October. Locally, the annual rainfall varies in time and space, ranging from 200 mm/year on the plains (mean altitude: 460 m asl) to 600 mm/year in the mountains (altitude >700 m asl).

This investigation was conducted in two sub-catchments: Ifni in the upstream Souss basin and Oukaimden in the upstream Tensift basin (Fig. 1). The two sites are dominated by Jbel Toubkal, which is the highest summit in Morocco (4200 m asl). The Ifni catchment is characterized mainly by crystalline Paleozoic rocks, while the Oukaimden site is dominated by Triassic sedimentary sandstones occupying more than half of the study area (Biron 1982; Ben Mlih et al. 2004). The monitoring within the two sites aims to characterize the snow isotopic signatures

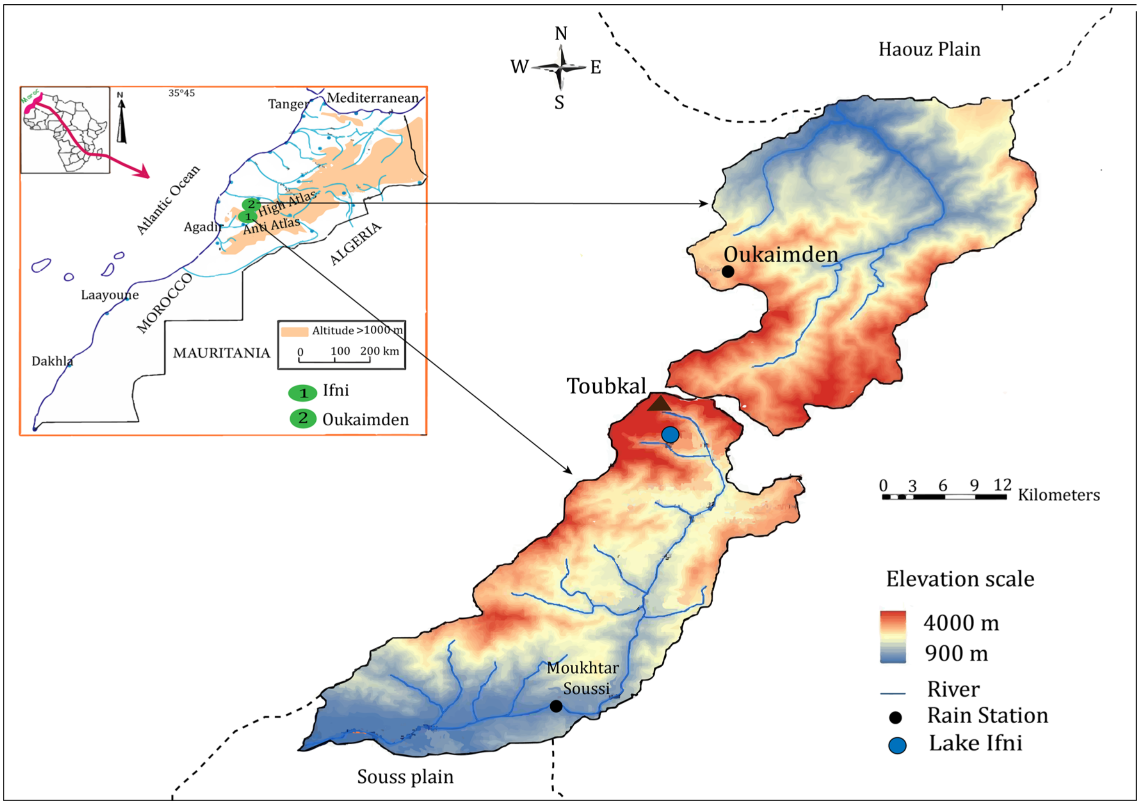

Fig. 1 Location map of study area

contributing to the recharge of the main Tensift and Souss aquifers on the northern and southern sides of the High Atlas Mountains, respectively.

Sampling and analysis methods

In the Souss upstream catchment, the sampling was carried out in 18 places (springs, rivers, dams and snow pack) along the river, from a high altitude of 2248 m asl around Ifni Lake to the Souss plain at ~700 m asl (Fig. 2). Sampling campaigns were conducted in the watershed of Ifni Lake during May 2011 and February 2012. Additional data are available from multiple campaigns previously performed on the same site from 2004 to 2005, and again in January 2008.

The monitoring in the Oukaimden area was focused on six sites from 2011 to 2014 (three places for snow pack, one lake and two springs) (Fig. 3a). Additionally, meteorological data are available for the winter and spring. Snow sampling was performed with two methods:

(1) Coring with polyvinyl chloride (PVC) tubes at different depths. The sampling depth depends on the height of the snow cover, varying from 10 to 50 cm. The altitude of these experimental sites ranges between 1194 and 3244 m asl

(2) The new PCS method, which has been established within a coordinated research project in collaboration with the International Atomic Energy Agency (IAEA) and other partners from many countries (Penna et al. 2014). The instruments were installed in the study area during 2013 and 2014. The PCS system installed is a slightly modified version of the system of Frisbee et al. (2008, 2010). During 2013 and 2014, four bottles of 2 L each were installed in two boxes in the same station (at 3229 m asl) beginning in October (start of the snow season) and collected by May–June (end of total snowmelt). The coil, whose water from melting snow enters the wick, was placed on top of a plastic barrier material and fixed on the floor with a U-shaped pin (Fig. 3b, c).

Stable isotope analyses (δ^{18}O and δ^{2}H) were performed by cavity ring down spectrometry using a laser spectrometer (Picarro L2120) at Duke University (USA) prior to use in the Applied Geology and Geo-Environment Laboratory, Ibn Zohr University, Agadir, Morocco. All the samples were conditioned and shipped to the laboratory in double-capped polyethylene bottles directly from the source, as recommended by the IAEA (Gat et al. 2001). The Picarro machine was calibrated at the Duke Environmental Isotope Laboratory (DEVIL) and the results were compared to

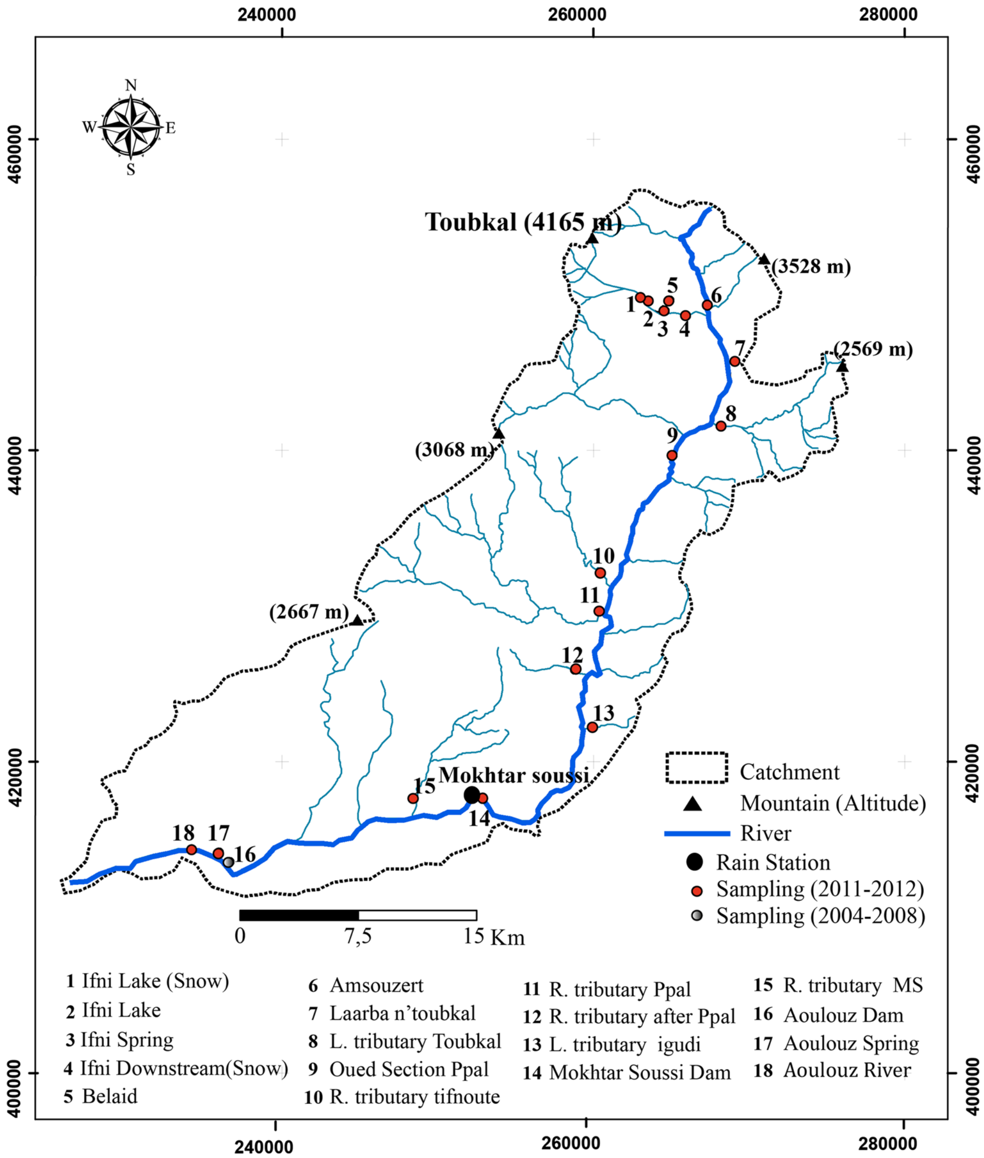

Fig. 2 Sampling points in Ifni area (Souss upstream sub-catchment)

those determined by continuous flow isotope ratio mass spectrometry (TCEA-CFIRMS), using a Thermo Finnigan TCEA and Delta + XL mass spectrometer (with analytical precisions of 0.08 ‰ for δ^{18}O and 0.9 ‰ δ^{2}H). Replicated and supplementary measurements of δ^{18}O and δ^{2}H were determined using cavity ring down spectrometry at IDES laboratory in Paris-sud University before 2011 and during 2012. In all laboratories, the isotopic analyses were performed according to IAEA standards (IAEA-ILS) and show similar values. Analytical precisions by laser machine for δ^{18}O and δ^{2}H were estimated as ±0.1 and ±1.5 ‰, respectively. The values of the isotopic results are presented in the standard notation delta per mille (‰) and referenced to Vienna Standard Mean Ocean Water (VSMOW).

Results and discussion

Climatic characterization

Rainfall decreases from the mountains to the bordering plains, where monthly rainfall rarely exceeds 100 mm (Fig. 4a). The monthly values indicate a decrease during the last four decades after a relatively wet period during the 1960's, as well as seasonal variability.

The snow cover area of the Atlas Mountains was monitored from 2000 to 2014 using remote sensing (Marchane et al. 2015). The annual snow cover area shows strong intra-seasonal and inter-annual variability, both in terms of maximum snow surface and total amount, and in terms of distribution of events and duration of the season. This

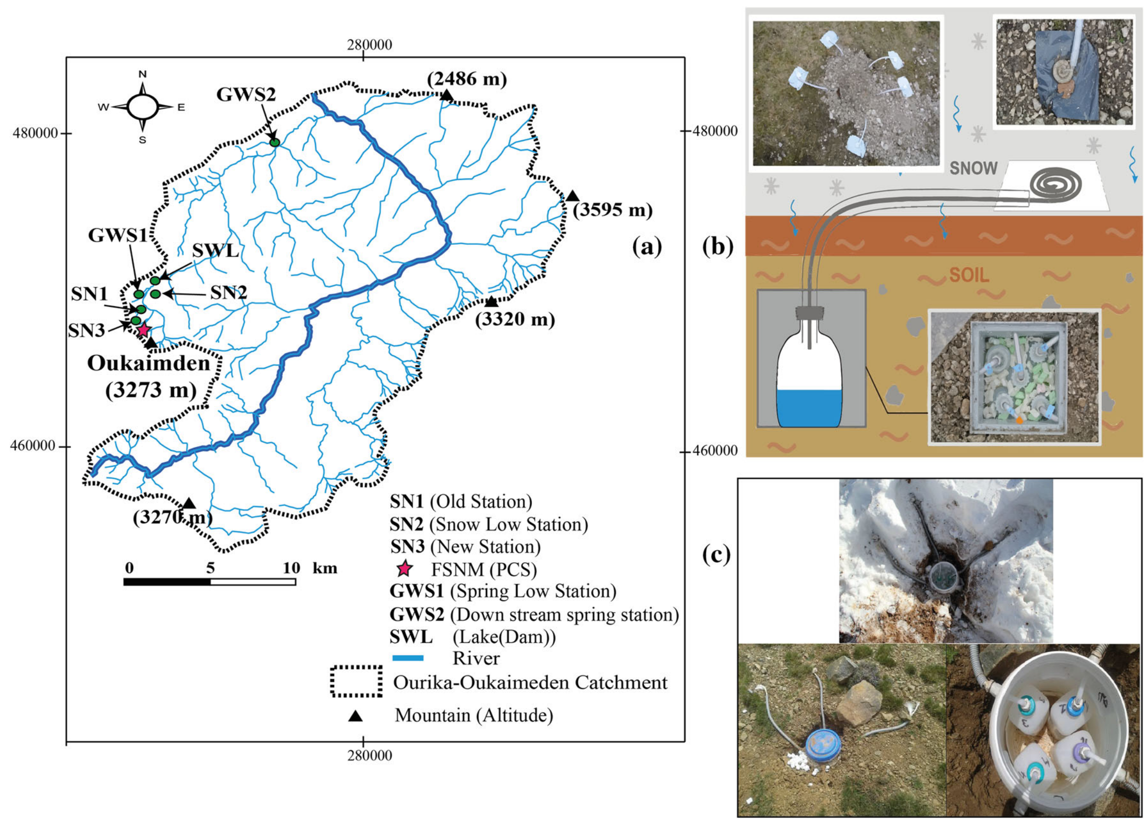

Fig. 3 **a** Sampling points in Oukaimden area (Tensift upstream sub-catchment); **b** *Drawings and photos* of the passive capillary sampler showing details of the construction and deployments (Penna et al. 2014); **c** Design of passive capillary sampling (PCS) installed in Oukaimden during 2013 and 2014

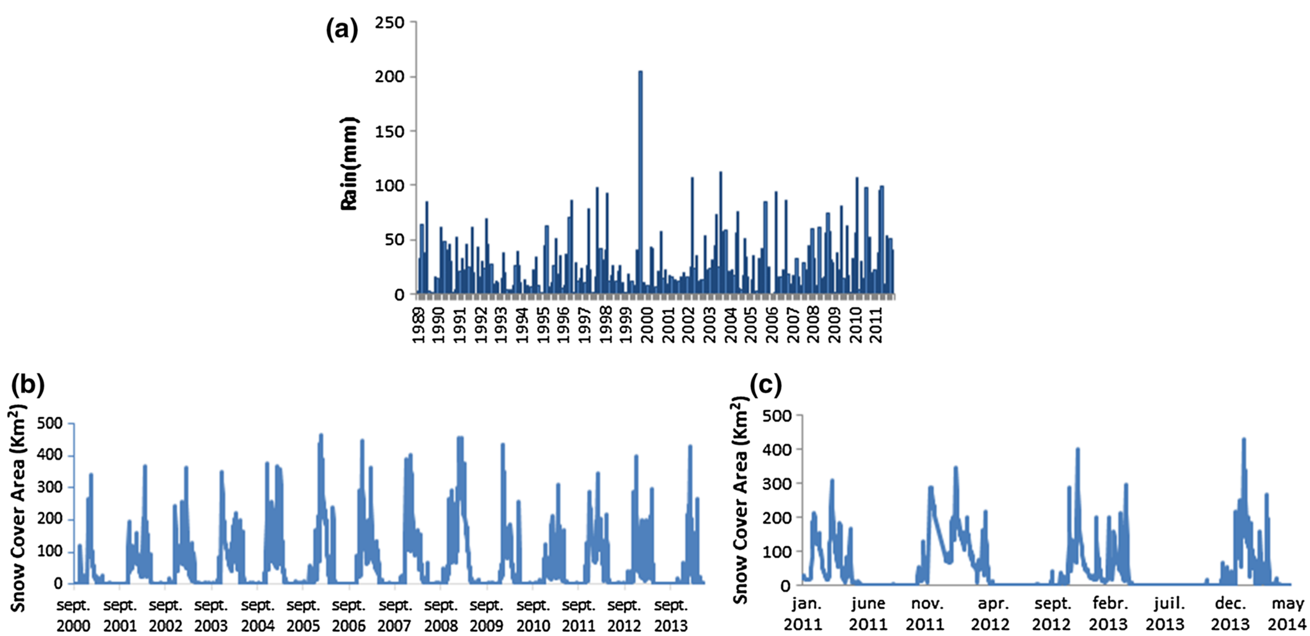

Fig. 4 **a** Seasonal variation in precipitation (1989–2012) at Oukaimden area; **b** Annual snow cover area (SCA; average of 15 days) in the High Atlas Mountains during 2000–2014 and **c** inset of **b** (January 2011–May 2014)

variability is related to the high spatial and temporal variability of solid precipitation (Fig. 4b, c). Snow accumulates and forms a cover between 1500 and 4000 m asl, usually from November to May. The monthly average snow cover varied between 5 km^2 (for May 2005) and 14,894 km^2 (for January 2006). The melting process is generally characterized by the snap release of the water in short time periods with the concomitant increase of air temperatures. However, the process of sublimation occurs regularly throughout the season, and its effects can cause a water loss corresponding to as much as 44 % of snow ablation (Schulz and De Jong 2004).

Isotopic results

Ifni area

Isotopic results obtained for the Ifni site vary strongly in space and in time. In particular, δ^{18}O ranges from −6.0 to −8.6 ‰ for snow; from −5.4 to −8.8 ‰ for rivers; from −5.4 to −8.6 ‰ for lakes and reservoirs; from −6.3 to −8.4 ‰ for groundwater and from −4.4 to −11.3 ‰ for rain samples; δ^{2}H values range from −39.3 to −56.2 ‰ for snow; from −37.7 to −56.8 ‰ for rivers; from −36.1 to −56.5 ‰ for lakes and reservoirs; from −40.9 to −54.7 ‰ for groundwater and from −7.7 to −77.4 ‰ for rain samples (Tables 1, 2; Fig. 5). The results indicate a large variation from upstream to downstream. The most negative values are observed in surface water upstream and in the snowmelt. The enriched values are shown in surface water downstream, especially the lake and reservoir (dam) waters, which are the most enriched ones.

The 2012 samples are notably more depleted than the 2011 samples. This difference in isotopic composition may be due to the temperature difference between sampling periods (May 2011 and February 2012). The isotopic composition of precipitation is related to the condensation temperature, and temperature is also largely responsible for seasonal isotopic variations in surface water and groundwater (Yurtsever 1975; Moser and Stichler 1975; Siegenthaler and Oeschger 1980). When the temperature is low, as in February, evaporation is low and δ^{18}O is depleted. The median isotopic compositions of the rain samples, which were collected at 884 m asl, are similar to the median values from adjoining and downstream stations (#14-18) in the lower basin. The exceptionally depleted rainfall δ^{18}O value of -11 ‰, recorded on 1 December 2007, may reflect an amount effect associated with extreme rain events (Cappy 2006).

The relationship between δ^{18}O and δ^{2}H (Fig. 6) indicates that most of the samples are close to the Global Meteoric Water Line (GMWL: $\delta^{2}H = 8\delta^{18}O + 10$ ‰, after Craig 1961) and the Local Meteoric Water Line for the High Atlas Mountains ($\delta^{2}H = 8\delta^{18}O + 13.5$) established by Raibi et al. (2006). Comparing the different water samples with the LMWL is useful for describing the water origin and isotopic fractionation (Clark and Fritz 1997, Williams 1997). The samples of surface water fall along the GMWL and LMWL, except for the lake and reservoir samples, which are generally more enriched than rivers and precipitation (Roldão et al. 1989). Isotopic compositions of stream water can be impacted by groundwater in the form of base flow. Groundwater samples fall close to the GMWL, which indicates that groundwater is of meteoric origin (Dansgaard 1964; Praamsmaa et al. 2009; Jeelani et al. 2010). Only the groundwater sample from the Ifni spring in 2011 indicates a deviation, with a δ^{18}O value of −6.6 ‰. The isotopic range for surface water and groundwater (−5.4 to −8.6 ‰) is similar to that found by Bouchaou et al. (2008) (−6.0 to −7.8 ‰) for the upper Souss plain.

Oukaimden area

The isotopic results from Oukaimden are compiled in Tables 3 and 4. Table 3 presents the results of the monitored snow pack points (SN1, SN2, and SN3), surface water (SWL), and groundwater (GWS1, GWS2). Overall isotopic values from the Oukaimden area range from −14.7 to −2.5 ‰ for δ^{18}O and from −116.0 to −28.2 ‰ for δ^{2}H. Snow cores have δ^{18}O values ranging from −2.5 to −14.7 ‰ in SN1, −3.1 to −8.7 ‰ in SN2, and −4.2 to −13.4 ‰ in SN3 (Fig. 7; Table 4). The majority of these core samples fall below both the GMWL and the LMWL (Fig. 8). The differential enrichment in δ^{18}O can be explained by sublimation, which produces an isotopic fractionation by the direct conversion of snow into water vapor. In general, melting and sublimation alter the content of the fresh snow in the snow cover, but the isotopic contents in the deeper layers remain intact, since the processes described take place near the surface (Moser and Stichler 1975; Martinec et al. 1977). The phenomenon of sublimation is frequent in alpine zones with decreasing pressure and increasing wind speed at altitude. Schulz and De Jong (2004) have described this phenomenon in the High Atlas region. Some snow samples sampled in March 2013 (SN1, SN3) and January 2014 (SN3) show particularly depleted values in isotopes, perhaps due to the fact that the isotopic composition of snow is also controlled by individual precipitation events, which may be extreme. These depleted values are more negative than the minimum values for Ifni snow samples, which is consistent with the higher elevation at Oukaimden. As observed in other mountain regions, there is a spatial variation of the isotopic signature with altitude (Stewart and Taylor 1981; Jeelani et al. 2010).

Table 1 Stable isotope results of Ifni area sampling

Sampling points	Type	Alt (m)	2004		2005		2006		2011		2012	
			$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
1	Snow	2458	–	–	–	–	–	–	−6.1	−39.3	−8.6	−56.2
2	Lake	2458	–	–	−7.4	−51.2	–	–	−6.4	−40.9	−8.6	−56.5
3	Spring	2174	–	–	−8.4	−54.7	−8.2	−54.7	−6.7	−51.8	−7.7	−51.8
4	Snow	2171	–	–	–	–	–	–	−6.8	−50.0	–	–
5	River	1966	–	–	–	–	–	–	−6.9	−49.5	−8.0	−53.4
6	River	1771	–	–	−8.8	−56.8	–	–	−6.6	−44.8	−8.8	−56.7
7	River	1665	–	–	−8.1	−54.7	–	–	−6.2	−41.9	−8.	−53.9
8	River	1509	–	–	−7.1	−50.5	–	–	−7.7	−51.7	−7.4	−50.9
9	River	1466	–	–	−7.9	−52.7	–	–	−8.0	−53.3	–	–
10	River	1414	–	–	–	–	–	–	−8.0	−53.0	–	–
11	River	1285	–	–	–	–	–	–	−6.9	−50.6	−6.7	−47.6
12	River	1216	–	–	−7.2	−47.0	−7.1	−45.9	−6.6	−37.7	−6.6	−44.8
13	River	1202	–	–	–	–	–	–	−5.4	−41.4	–	–
14	Dam	884	−5.4	−36.1	−6.0	−40.7	–	–	–	–	−6.2	−41.9
15	River	852	–	–	–	–	–	–	−6.8	−56.8	–	–
16	Dam	712	−5.9	−40.4	−6.0	−41.3	−6.8	−44.3	–	–	–	–
17	Spring	720	–	–	−6.5	−42.6	−6.3	−42.2	–	–	−6.4	−40.9
18	River	720	–	–	−6.3	−40.4	−8.8	−49.6	–	–	−6.0	−39.4

Table 2 Monthly stable isotope values in rain sampled in Mokhtar Soussi station (altitude 884 masl)

Description	Date	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	Date	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
Rain water	01/12/2004	−4.4	−30.9	01/09/2007	−6.8	−44.0
Rain water	11/12/2005	−5.4	−25.7	01/10/2007	−6.4	−41.2
Rain water	15/11/2005	−6.0	−26.6	01/11/2007	−6.5	−44.0
Rain water	16/06/2006	−4.9	−7.7	01/12/2007	−11.3	−77.4
Rain water	01/07/2006	−5.9	−40.9	05/02/2008	−5.1	−34.0

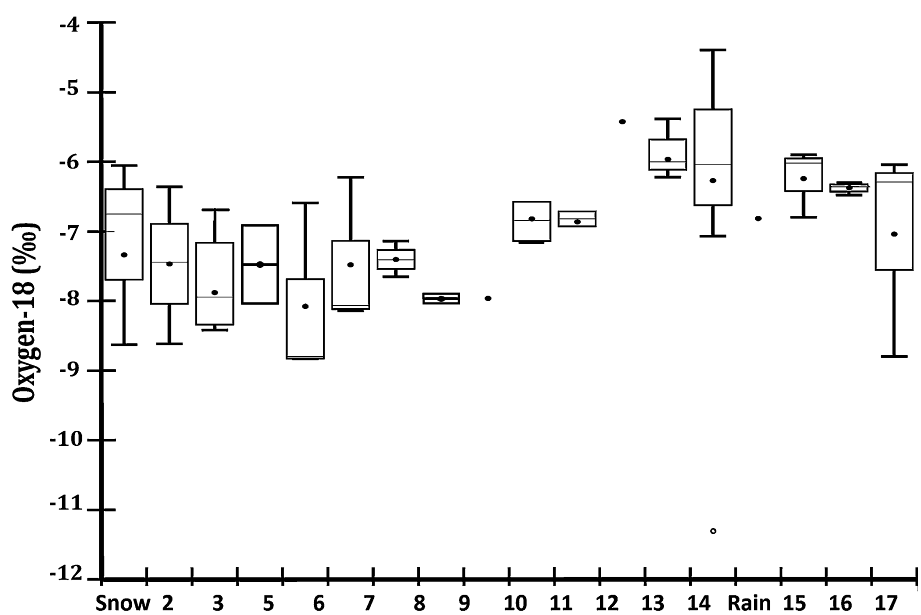

Fig. 5 *Box-plot* showing $\delta^{18}O$ variation for different sampling points in the Ifni area: groundwater (GWS), surface water (SWS), rain. Samples are *plotted* according to their number on Fig. 2

Snowmelt samples collected by PCS have δ^{18}O values ranging between −7.3 and −11.4 ‰ (mean −8.9 ‰) and δ^{2}H values ranging between −81.1 and −49.4 ‰ (mean −63.3 ‰) (Fig. 7; Table 4). Comparing the mean PCS isotopic signatures with snow samples from other sites in the High Atlas Mountains (δ^{18}O = −8.0 ‰, δ^{2}H = −51.0 ‰; Cappy 2006) indicates a small depletion in the samples from Oukaimden. However, the relationship between δ^{18}O and δ^{2}H (Fig. 8) indicates that the snowmelt samples (final snowmelt: FSNM) collected by PCS are close to the GMWL. Comparable results have been obtained by PCS in various places around the world

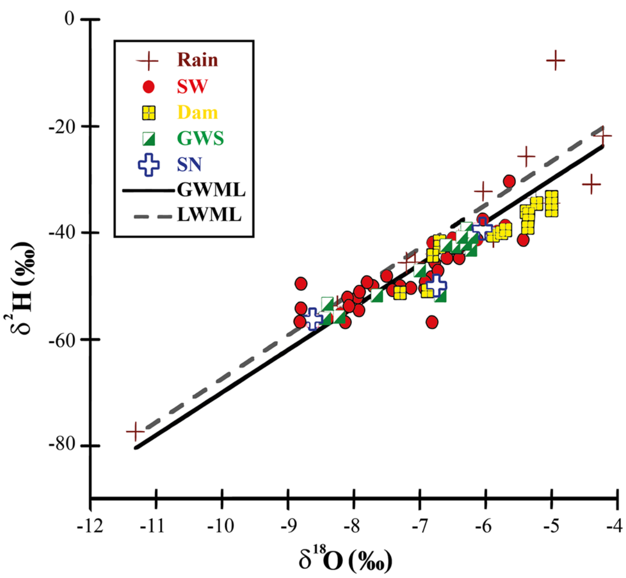

Fig. 6 Relationship between δ^{18}O and δ^{2}H of rain, snow (SN), surface water (SW and dam) and groundwater (GWS) in the Ifni area. Samples are sorted according to their geographical distribution and type

(Frisbee et al. 2008). Thus, this sampling method preserves the isotopic composition of water from melting snow that seeps directly into the ground as opposed to that collected by coring from the surface.

The δ^{18}O values of the surface water sample (SW) range from −6.3 to −9.3 ‰ with a mean value of −6.6 ‰, and groundwater samples (GWS1 and GWS2) vary between −4.7 ‰ and −8.2 ‰ with a mean value of −5.6 ‰ (Fig. 7; Table 3). Surface samples have a seasonal variation and the groundwater samples vary in space and time. As surface temperatures are involved in seasonal variations in the isotopic signature of precipitation (Dansgaard 1964; Gat 1996; Rozanski et al. 1993), they are also generally responsible for seasonal and annual variations in the isotopic signals of surface water and groundwater, particularly in semi-arid areas. The samples of surface water are usually positioned on or close to the GMWL or LMWL, but evaporation can affect the relative abundances of oxygen-18 and deuterium (Mook 1982; McKenna et al. 1992; Vrbka et al. 1993), as observed for lake samples in the Ifni sub-catchment. Changes in the isotopic composition may also be due to altitude and the amount of precipitation (noted above), as well as distance from the coast and latitude (Friedman et al. 1964; Ingraham and Taylor 1991).

Estimates of recharge elevation and snowmelt contributions

Snow, surface water, and groundwater from both catchments sampled during the various campaigns are characterized by a significant variation of δ^{18}O values. However, the isotopic signature obtained from PCS samples overlaps the isotopic ranges of surface water and groundwater in both the study sites. This implies that the melting of the

Table 3 Isotopic analysis results of Oukaimden site

Year	Month	Snow pack sampling						GWS1 (Spring1		SW (Lake)		GWS2 (Spring 2)	
		SN1 (Snow)		SN2 (Snow)		SN3 (Snow)							
		δ^{18}O (‰)	δ^{2}H (‰)	δ^{18}O (‰)	δ^{2}H (‰)	δ^{18}O (‰)	δ^{2}H (‰)	δ^{18}O (‰)	δ^{2}H (‰)	δ^{18}O (‰)	δ^{2}H (‰)	δ^{18}O (‰)	δ^{2}H (‰)
2012	11.	−4.1	−38.4	−6.5	−45.56	−7.1	−48.6	−7.1	−56.0	−8.0	−60.7	−5.6	−37.9
	12.	−2.5	−33.5	−3.2	−32.01	−4.3	−33.9	−4.9	−49.7	−6.3	−52.1	−4.7	−36.8
2013	2.	−2.9	−28.2	−7.5	−53.90	−4.2	−34.0	−7.5	−53.9	−7.5	−52.1	−5.5	−35.0
	3.	−14.7	−116.1	−5.8	−32.73	−13.4	−111.3	−7.9	−55.0	−7.0	−51.8	−5.9	−39.1
	4.	–	–	–	–	–	–	–	–	−8.2	−56.6	−6.0	−38.9
2014	1.	−8.7	−70.6	−8.7	−70.59	−13.36	−107.9	−8.0	−60.2	−9.3	−75.1	−5.8	−40.4
	2.	−7.6	−62.8	−7.6	−62.67	−8.79	−63.6	−8.2	−58.8	−7.4	−53.5	−6.1	−41.7
	3.	–	–	−7.5	−54.08	−8.39	−57.3	−8.2	−59.0	−7.7	−55.5	−5.8	−38.3
	4.	–	–	–	–	–	–	−7.6	−78.0	−8.0	−76.1	−5.2	−63.9

The snow samples (SN1 at 3244 masl; SN2 at 2658 masl and SN3 at 3229 masl) were taken with a PVC tube

Table 4 Isotopic analysis results of the snow samples from the Oukaimden site sampled with passive capillary sampler design (PCS)

Sampling points	2013		2014	
	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
PCS 1	−11.4	−81.1	−8.80	−68.73
PCS 2	−8.6	−55.4	–	–
PCS 3	−8.4	−55.9	−8.30	−62.93
PCS 4	−7.3	−49.4	–	–
PCS 5	−8.7	−55.5	−8.83	−64.63
PCS 6	−9.4	−62.5	−8.79	−65.71
PCS 7	−9.3	−64.1	−8.51	−66.02
PCS 8	−8.9	−61.8	−9.23	−72.17

The PCS was installed at 3229 masl as shown in Fig. 3c. The eight bottles were installed in two boxes since October and collected by end of May

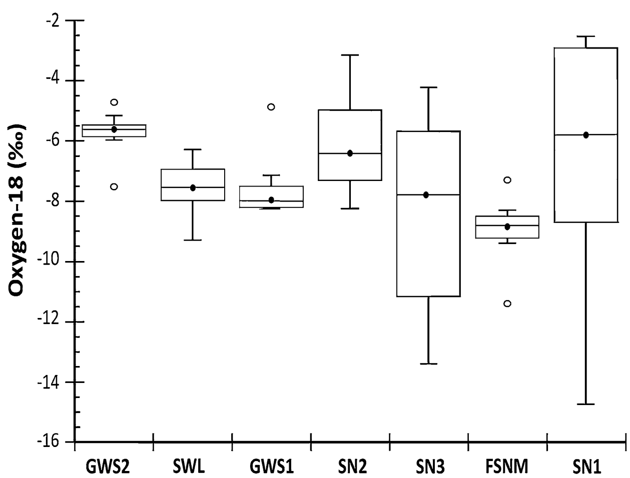

Fig. 7 *Box plot* showing $\delta^{18}O$ variation for different sampling points at the Oukaimden site: groundwater (GWS), surface water (SWS), snow (SN), lake water. Samples are sorted according to their position on Fig. 3a

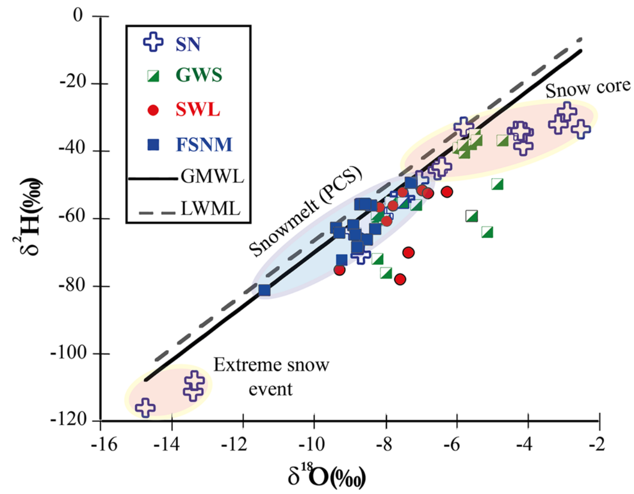

Fig. 8 Relationship between $\delta^{18}O$ and $\delta^{2}H$ of snow sampled with PVC (SN) and PCS (FSNM), surface water (SWL) and groundwater (GWS) at the Oukaimden site (2012–2014). Samples are sorted according to their geographical distribution and type

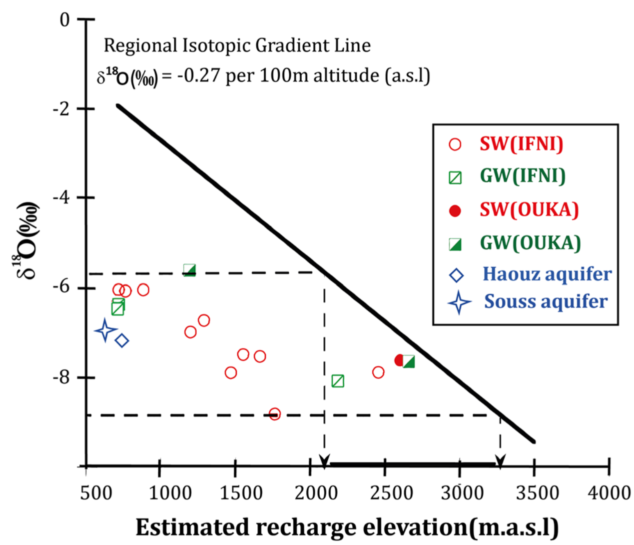

Fig. 9 Estimation of the mean recharge altitude of sampled points from the Ifni and Oukaimden sites using the regional isotopic gradient line for the High Atlas (Bouchaou et al. 1995). The samples for the Haouz and Souss aquifers represent average isotopic contents in the upstream parts of both aquifers. Samples are sorted according to their geographical distribution and type

snow cover of the High Atlas plays an important role in recharge in this region. To confirm the probable origin of surface water and groundwater in the studied areas, the results were compared with the isotopic gradient of $\delta^{18}O = -0.27$ ‰ per 100 m asl defined for the High Atlas (Bouchaou et al. 1995) (Fig. 9). Results indicate that water originates from altitudes between 2000 m and 3300 m asl, corresponding to the relief of the High Atlas in the two watersheds.

Based on isotopic values obtained in the upstream Souss basin (Bouragba et al. 2011) and Haouz aquifer (Boukhari et al. 2015), rough estimations of the contribution of snowmelt to groundwater in the two study sites and adjacent plain aquifers (Haouz and Souss) were performed using the following isotope-balance equation:

$$\delta^{18}O_{GW} = (1 - X)\delta^{18}O_{SN} + X\delta^{18}O_{R} \quad (1)$$

where $\delta^{18}O_{GW}$, $\delta^{18}O_{SN}$, and $\delta^{18}O_{R}$ represent the $\delta^{18}O$ content of groundwater (GW), runoff derived from snowmelt (SN) and rain (*R*), respectively. *X* is the estimated contribution of snowmelt to groundwater.

The contribution of runoff derived from snowmelt (SN) ranges between 42 and 71 % in the headwaters of the studied catchments, while the component of rainfall is 29–58 % (Table 5). Prior hydrological and sublimation

Table 5 Estimation of snowmelt contribution to groundwater in the High Atlas Mountains and the adjacent Souss and Haouz plain aquifers

Sites	Average $\delta^{18}O$ snowmelt value	Average $\delta^{18}O$ rain value	Average $\delta^{18}O$ GW value	Estimated snowmelt contribution (%)	Estimated rain contribution (%)
Oukaimden	−7.98	−6	−7.42	71	29
Haouz plain aquifer	−7.98	−6	−7.12	57	43
Ifni spring	−7.98	−6.27	−7.75	52	48
Souss plain aquifer	−7.98	−6.27	−7	42	58

modeling in the High Atlas indicated a snowmelt contribution of 15–51 % (Boudhar et al. 2009; Schulz and De Jong 2004). For the main five tributary sub-catchments of the Tensift watershed (Nfis, Rheraya, Ourika, Zat and Rdat) the snowmelt contribution varies within similar range depending on the sub-catchment and snow cover area during the year (Chehbouni et al. 2008; Boudhar et al. 2009). The contribution of snowmelt to springs in the High Atlas Mountains is 80 % (Cappy 2006).

Conclusions

Isotopic data from the High Atlas Mountains indicate qualitatively and quantitatively that snowmelt contributes to the recharge of stream flow and groundwater, which reduces the salinity of water resources downstream (Bouchaou et al. 2008; Bouragba et al. 2011; Warner et al. 2013). Using an isotope-balance model, the quantitative contribution of snowmelt varies between 42 and 71 %. Stable isotope signatures from the Ifni sub-catchment indicate contributions from rain water too, and the extent of stream water evaporation varies with location in the sub-catchment. Inferred recharge elevations are consistent with an empirical oxygen-18 vs. elevation relationship previously established for the High Atlas. The passive capillary sampling (PCS) design preserves the isotopic composition of infiltrating melt water, reducing the effect of isotopic fractionation by snow sublimation, which was observed in the samples collected with a PVC tube. The isotopic results will be used to help refine hydrological conceptual models at a variety of scales.

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