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Origin of recharge and salinity and their role on management issues of a large alluvial aquifer system in the semi-arid Haouz plain, Morocco

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Abstract The present study has analyzed the origin of recharge and groundwater salinity in the Haouz alluvial plain, located in Central Morocco. Stable isotopic data (^{18}O, ^2H) indicate that the recharge of the alluvial aquifer is dominated by high-altitude meteoric water originating from the High-Atlas Mountains that border the plain to the south. Tritium globally indicates the presence of recent groundwater, as well as mixing between old and recent groundwater. Alluvial groundwater salinity varies from east to west. This variability is mainly induced by enrichment in chloride and sulfate salt contents. Strontium content reveals that sulfate could be related, respectively, to the influence of the Senonian carbonate deposits containing gypsum. Dissolution of halite is revealed by the plot of ^{18}O vs Cl, where the most saline samples do not show any changes in ^{18}O. Br/Cl ratio varies in a wide range, probably due to an orographic effect. The nitrate distribution was analyzed using indicator-geostatistical techniques resulting in probability maps. Nitrate contamination is shown to occur particularly in the eastern part of the Haouz plain. In this paper, some aspects of groundwater resources management are addressed. Different management actions are identified with regard to the current water resources status and to the land and water uses. In this framework controlling groundwater abstraction, optimizing irrigation and enhancing mountain-front recharge constitute the major key management actions that should be carried out.

Keywords Groundwater · Salinization · Nitrates · Isotopes · Alluvial plain · High-Atlas Mountains

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Introduction

In arid and semi-arid regions large alluvial plains offering access to shallow groundwater and crossed by rivers which enhance water availability, are privileged areas for human activities. However, in these areas groundwater resources generally undergo intensive exploitation due to agriculture, domestic and industrial needs, and face inadequate management (Foster et al. 2004; Ma et al. 2005; Hoque et al. 2007; Aureli et al. 2008, Dimkic et al. 2008; Masciale et al. 2011; Sanz et al. 2011). In this context for setting up new or improving existing water resources planning and management actions, a better understanding of aquifer systems hydrology, recharge and salinization processes is always required. Concerning the hydrological behavior, the recharge origin is one of the main parameters to identify due to its role in replenishing aquifers and in assessing the groundwater balance. The recharge could have various origins such as local rainfall, rivers or surface water irrigation return flows (e.g., Stigter et al. 2006; Andrade and Stigter 2011). Mountain fronts when present could bring a large amount of groundwater recharge to aquifers located in plains (Wilson and Guan 2004; Matter et al. 2006; Vanderzalm et al. 2011; Liu and Yamanaka 2012). Salinity is a main concern due to its determinant impact on groundwater utilization, both for public supply and irrigation purposes (e.g., Ayers and Westcot 1994). The

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distribution and extent of groundwater salinity can be controlled by several factors such as physical parameters (e.g., geology, flows pattern) and anthropogenic effects. Investigating salinity processes is necessary to build integrated water management strategies based both on quality and quantity aspects.

In this paper, the large alluvial plain (6,800 km^2) of the Haouz in Central Morocco is investigated. The plain has a semi-arid climate, characterized by low rainfall ($\sim$250 mm/year) and high evaporative demand ($\sim$1,400 mm/year). The plain is limited by the High-Atlas Mountains in the south (culminating at 4,165 m) and by the wadis (seasonal rivers) of Tensift, Lakhdar and Chichaoua, respectively, in the north, east and west (Fig. 1).

Several wadis originate from the High-Atlas Mountains and cross the plain from south to north, forming the left bank tributaries of the Tensift River (Fig. 1). They play an important role in the water supply system. Groundwater is commonly drawn from the alluvial aquifer and used mainly for irrigation and drinking water. Irrigated agriculture is the main activity in the plain, dominated by olive groves, citrus orchards and winter wheat. The growth of water demands and the succession of droughts during the last decades have led to increasing groundwater abstractions. A modeling study operating on a monthly time scale was carried out for the water resources in the plain (Fakir et al. 2010; Le Page

et al. 2012). During the simulation period (2001–2008) the gross agricultural demand was estimated by remote sensing to 650–700 10^6 m^3 year^{-1} accounting for about 90 % of the total water demand. The net groundwater abstraction was assessed around 400 10^6 m^3 year^{-1}. The cumulative budget deficit for this period was assessed to about 1.1 billion m^3, highlighting the importance of groundwater depletion in the area.

Following this quantitative assessment, the aim of this study is to analyze the origin of recharge and groundwater salinization processes in the alluvial aquifer and to give key recommendations on groundwater management in the Haouz plain. For this purpose, geochemical and isotopic analyses are used, as they constitute robust investigation tools for sedimentary aquifers in arid and semi-arid contexts (e.g., Sami 1992; Herczeg et al. 2001; Mahlknecht et al. 2002; Cartwright et al. 2004, 2006; Cartwright and Weaver 2005; Matter et al. 2006; Wen et al. 2005; Bouchaou et al. 2008, 2009; Eastoe et al. 2008; Han et al. 2009; Ben Moussa et al. 2010; Bouragba et al. 2011; Currell and Cartwright 2011; Ako et al. 2012; Hamed et al. 2012; Dogramaci et al. 2012; Trabelsi et al. 2012; Wang et al. 2012; Hchaichi et al. 2013). The geochemical characterization is based on major anions and cations, nitrates and the trace elements bromide (Br) and strontium (Sr). Stable isotopes (^{18}O and ^{2}H) and tritium (^{3}H) are used to identify
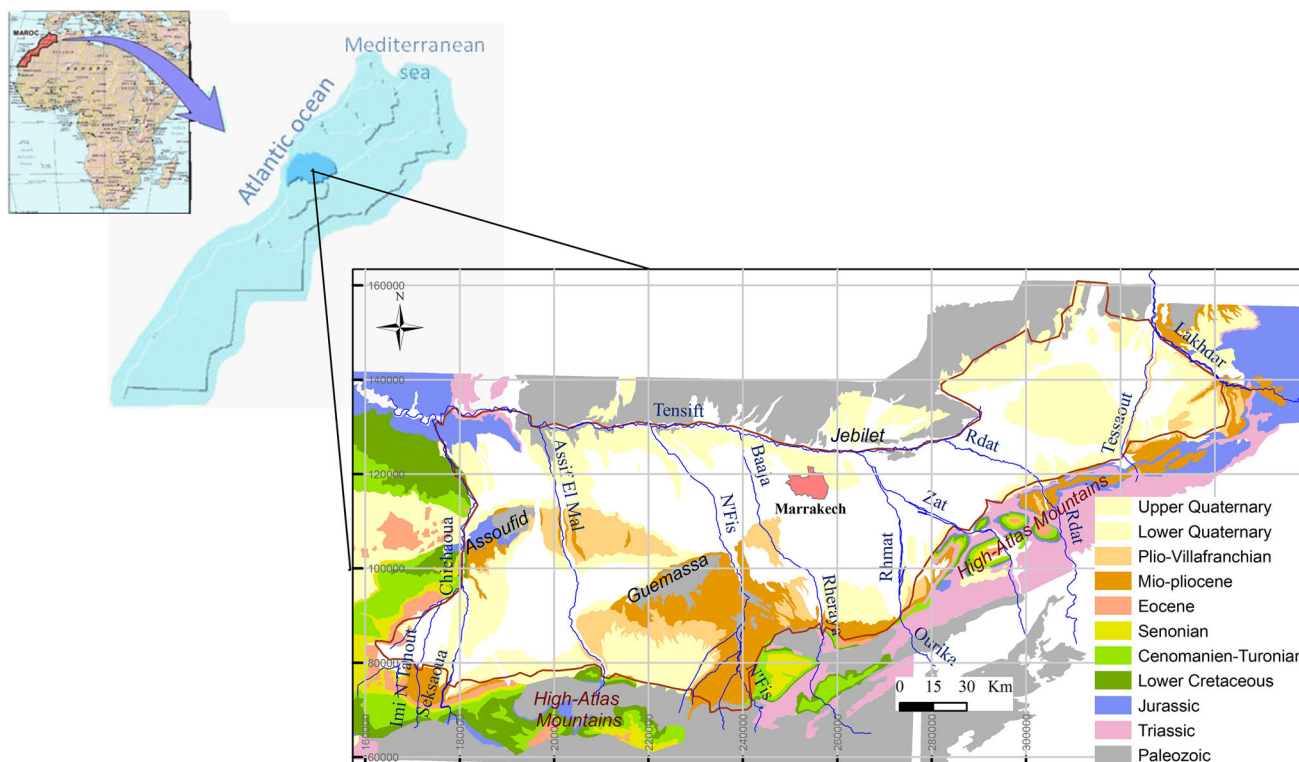
Fig. 1 Location map of the Haouz plain in Morocco. The figure shows also the geology within and around the plain as well as the network of wadis which come from the High-Atlas Mountains and cross the plain from south to north

the origin of groundwater recharge and to have indications on groundwater residence time.

Furthermore the spatial distribution of nitrate is discussed using indicator-geostatistical techniques, resulting in maps that indicate the probability of nitrate concentrations in groundwater exceeding predetermined threshold values. In this non-parametric approach, using a binary transformation at various cutoff levels and applying the kriging algorithm to these so-called indicator variables, the uncertainty around the unsampled value is modeled in a conditional distribution function (Deutsch and Journel 1998). For groundwater management purposes, the existence of a robust tool that specifically incorporates uncertainty into contamination assessment can be extremely useful (Andrade and Stigter 2009). The cutoff level may correspond to drinking water guideline values, and the resulting maps illustrate the probability of exceeding such values, therefore, easily interpretable for water managers and decision makers. Hu et al. (2005) used a similar methodology to assess the risk of nitrate contamination in shallow groundwater in Quzhou County in the North China Plain.

Finally and due to the problem of groundwater overexploitation, some aspects of groundwater resources management are addressed in this study. For this purpose several data about irrigation and water supply are used in a spatially distributed form, supplemented by the obtained results on hydrology, salinity and nitrates. The aim is to give key recommendations of groundwater management integrating qualitative aspects.

Geological and hydrogeological settings

The alluvial aquifer in the Haouz plain consists of alluvial fans and fluviatile deposits of Neogene and Quaternary age, which cover almost the entire study area (Fig. 1). The alluvial aquifer is unconfined. It constitutes the principal groundwater resource of the plain. It is characterized by an important heterogeneity. Measured transmissivity values vary from $5\ 10^{-5}$ to $9\ 10^{-2}\ m^2 s^{-1}$ with an average of $6.7\ 10^{-3}$ $m^2 s^{-1}$ (Sinan and Razack 2006). The basement of the alluvial aquifer generally consists of Miocene marls with intercalated lacustrine limestone and conglomerates (Sinan 2000).

Cenozoic and Mesozoic sedimentary deposits and Paleozoic bedrocks are exposed widely in the High-Atlas Mountains (Fig. 1). Eocene and Cretaceous terrains (Senonian, Cenomanian and Turonian) are located in low mountain areas and also form a vast carbonate plateau beyond the western limit of the plain. In the western Haouz, Eocene and Cretaceous form a large syncline covered by alluvial deposits (Fig. 2, Cross section C). The Eocene is composed of limestone and marls. The Cretaceous layers consist of gypsiferous marls of the Senonian intercalating

between the Eocene and the limestone and dolomite of the Turonian–Cenomanian. The Eocene and the Turonian–Cenomanian constitute deeper aquifers and are tapped by deep wells or boreholes in the western Haouz whenever the overlying alluvial aquifer productivity is insufficient. Little knowledge is available on the hydrogeological characteristics of these aquifers.

The Jurassic and Permo-Triassic terrains outcrop locally in the NW of the plain but they are largely present in the eastern part of the study area. The Jurassic is composed mainly of limestones. The Permo-Triassic is composed of clay alternating with sandstone beds and salt deposits which could constitute a source of water salinization. The Jurassic limestones form an aquifer drained by several springs in the High-Atlas valleys. Groundwater of these formations can also flow into the alluvial aquifer in the South-East of the plain (Fig. 2, cross section A). The Permo-Triassic underlies the Jurassic but towards the north it lies beneath the Miocene or the Plio-Quaternary alluvial deposits due to the absence of the Eocene and Cretaceous formation (Fig. 2, cross section A).

Methods and sampling

The study relies on piezometric, geochemical and isotopic data. Field measurements (piezometry, temperature, electrical conductivity (EC), pH) and geochemical sampling were carried out during the wet period of January–February 2011. The piezometric and EC maps of the surface alluvial aquifer were elaborated based on 240 measurement points selected in a spatially distributed way. The majority are private wells used for irrigation. The piezometric map is used to analyze the current state of groundwater flow and to locate potential recharge and discharge areas. The EC map is used to address the spatial variability of the groundwater salinity.

Water samples were collected after appropriate well purging and stored according to standard procedures. About 60 water samples were taken for geochemical analyses (Fig. 3). Among them 34 were also analyzed for stables isotopes and 13 were analyzed for tritium (Table 1). Figure 3 shows the location of the geochemical sampling points, distributed according to their geographical distribution and aquifer type in the Haouz plain. Within the alluvial deposits three zones are distinguished: Eastern Haouz, Middle Haouz and Western Haouz. Nine wells tapping the Miocene rocks in the south are also sampled. Two reference samples were taken from wells installed in the Eocene–Cretaceous carbonate aquifers beyond the western limit of the study area. Three springs located on the western limit of the study area along the Chichaoua wadi were sampled. Among them, the Abainou spring is the most important of the entire basin, with an average (interannual)

Fig. 2 Geological sections across the Haouz plain (in Abourida 2007). The alluvial aquifer basement is generally constituted by Miocene terrains. However, the Permo-Triassic (containing salt) could lie beneath the alluvial deposits at East (*cross section A*). Eocene and Cretaceous form a large syncline in the plain (*cross section C*) while their extent is limited under the plain in the Middle and Eastern Haouz due to the uplift of the Paleozoic basement
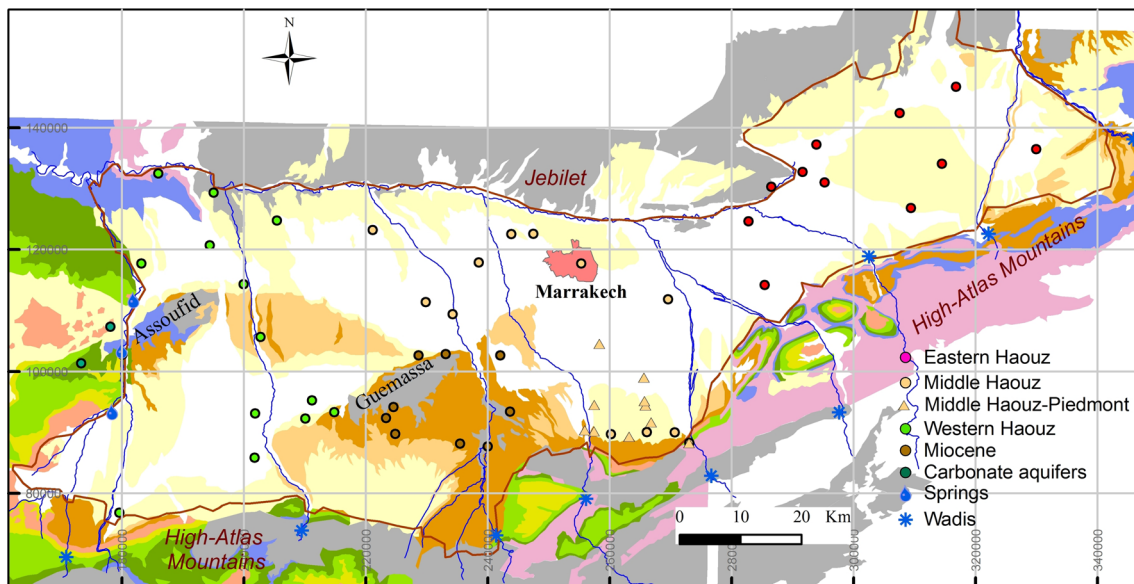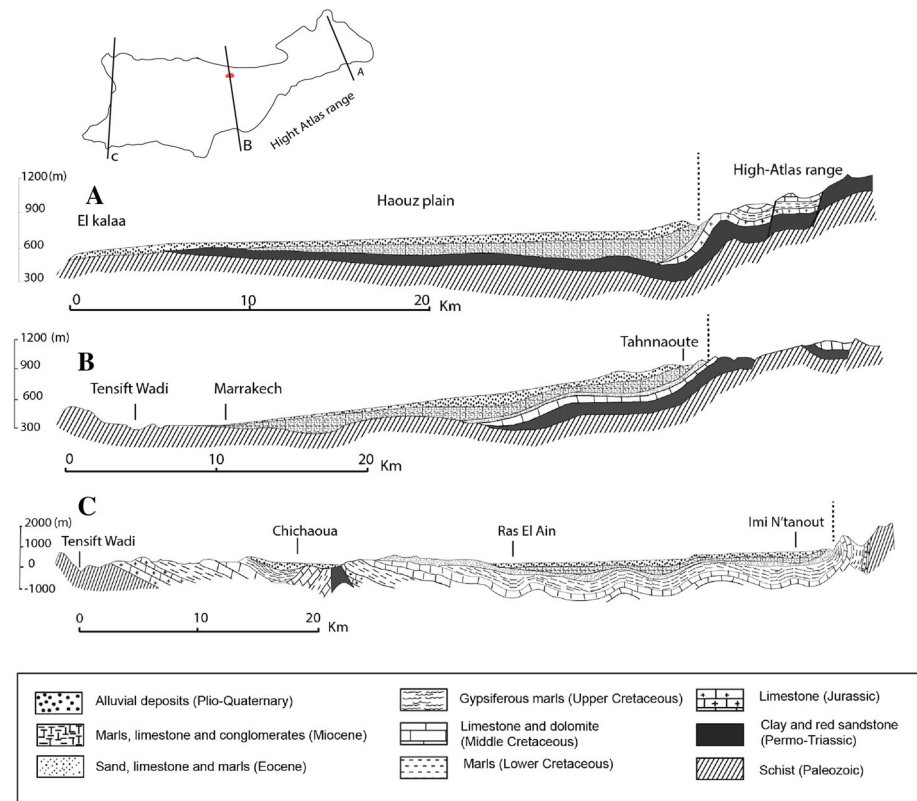
Fig. 3 Sampling points of surface water, springs and of groundwater sorted by their geographical distribution. Three zones are distinguished in the alluvial Haouz plain: West, Middle and East. Groundwater is also sampled from wells located in the Miocene terrains (crossed by Nfis wadi) at south and in the Eocene–Cretaceous carbonate terrains at west outside of the study area

flow rate of 520 l s^{-1}. The two other springs are Ras El Ain (45 l s^{-1}) and Rmech (55 l s^{-1}). The aim is to determine their origin within the aquifer systems. The wadis were also sampled (nine samples) at their entrance to the plain and their chemistry was compared to that of groundwater. Ten

wells located in the piedmont of the Middle Haouz were also sampled but only for ^{18}O and ^{2}H analyses (Fig. 3). Although these points do not have chemical analyses, they were integrated in the study because of their particular isotopic signature, as discussed below.

Table 1 Chemical and isotope analysis

	Water depth (m)	E.C. (µs/cm)	PH	HCO$_3$ (mg/l)	Cl (mg/l)	NO$_3$ (mg/l)	SO$_4$ (mg/l)	Ca (mg/l)	Mg (mg/l)	K (mg/l)	Na (mg/l)	Br (mg/l)	Sr (mg/l)	δ^{18}O (‰)	δ^{2}H (‰)	^{3}H (TU)
Eastern Haouz																
E1	12.8	1,593	7.63	365.5	165.4	20.8	49.3	86.0	36.0	1.6	90.4	0.11	0.36			
E2	70.0	3,500	7.85	305.0	872.5	26.6	78.2	249.1	120.4	11.7	224.7	n.a.	1.17			
E3	42.0	1,196	7.84	303.0	167.0	14.8	33.8	70.7	50.2	1.7	77.2	0.15	0.43			
E4	31.0	4,100	7.84	352.8	826.0	37.5	209.8	146.8	181.0	10.2	414.4	1.14	1.63	−7.16	−50.83	
E5	33.0	1,653	7.92	293.0	278.8	34.2	37.9	108.3	74.2	2.4	93.6	0.43	0.66			
E6	65.8	745	7.14	414.0	264.4	16.0	39.9	98.1	55.6	3.0	86.6	0.09	0.50			
E7	81.0	1,481	7.11	292.8	1,845.7	18.3	422.7	321.2	186.1	9.5	898.9	n.a.	2.84	−5.57	−32.93	
E8	55.0	879	7.13	425.5	280.1	26.3	82.7	106.5	101.7	1.0	112.0	0.32	0.56	−6.62	−46.19	
E9	19.0	973	7.19	415.0	365.6	16.3	122.3	117.1	75.6	2.1	170.6	0.12	0.58	−6.95	−48.97	
E10	24.0	3,780	7.77	426.0	865.8	57.1	118.6	235.9	171.1	10.0	231.2	1.38	1.58	−6.56	−46.84	1.90
E11	28.0	4,751	7.51	380.6	1,097.3	34.9	263.5	170.3	68.6	11.5	675.1	n.a.	1.66			
Middle Haouz																
M12	17.0	842	6.71	378.8	21.5	5.0	25.5	55.5	34.2	1.3	20.3	0.05	0.23			
M13	17.0	1,534	7.35	468.9	53.7	16.8	54.9	41.1	36.7	0.9	160.4	0.14	0.33			
M14	60.0	800	7.09	312.7	115.4	15.0	123.4	112.6	53.0	1.0	64.6	0.47	0.53			
M15	49.8	1,204	7.33	276.0	62.8	5.9	41.4	68.9	21.5	1.4	48.0	0.08	0.25	−7.67	−48.35	
M16	16.0	1,304	7.88	217.0	59.1	8.6	46.8	73.0	25.2	3.1	35.6	0.07	0.27			
M17	48.3	882	7.42	298.0	119.1	6.6	55.0	46.6	31.3	2.3	104.0	0.19	0.59	−8.79	−58.79	1.20
M18	55.0	965	7.24	492.7	29.6	28.3	61.1	109.3	2.8	10.8	94.3	n.a.	0.45			
M19	31.0	1,524	7.53	287.9	238.1	19.2	124.0	147.4	44.6	2.2	117.9	0.26	0.53			
M20	36.0	1,963	7.14	281.0	111.6	5.0	60.0	44.0	43.9	2.1	66.2	0.04	0.16	−5.09	−36.94	3.50
M21	10.0	2,262	7.22	430.9	212.4		190.8	154.8	68.7	10.6	150.7	0.13	0.83	−6.58	−45.25	
M22	35.7	1,040	7.18	297.8	80.9	14.0	33.8	86.8	29.0	0.9	47.3	0.09	0.42	−7.48	−44.22	
M23	22.0	977	7.49	406.8	59.453	20.581	113.27	74.588	49.716	1.3,032	68.573	0.1,913	1.503			3.40
Western Haouz																
Southern part																
W23	56.6	292	6.82	298.0	139.4	18.0	86.7	101.2	52.5	2.3	61.5	0.55	0.56			
W24	6.0	1564	7.88	309.0	63.3	7.8	234.4	109.0	72.0	4.1	48.5	0.25	0.92			
W25	27.0	1045	7.54	369.5	77.4	4.6	195.6	104.0	46.4	0.9	41.1	0.24	0.52			
W26	87.5	430	7.65	320.7	21.3	9.2	75.9	76.5	24.5	1.2	22.3	0.09	0.35	−7.84	−54.02	4.50
W27	98.0	598	7.58	468.0	22.4	9.8	152.1	96.1	45.4	1.7	29.1	0.09	0.45	−6.61	−54.69	3.50
W28	50.0	518	7.71	342.4	44.4	7.7	95.4	82.4	33.3	2.3	19.6	0.15	0.42	−7.15	−42.52	
W29	40.6	649	7.61	475.8	83.6	10.0	117.6	84.5	55.3	2.2	80.6	0.26	0.70	−6.51	−49.52	
W30	53.0	622	7.49	261.3	13.2	9.1	79.7	79.2	21.9	1.2	20.1	0.06	1.04			

Table 1 continued

	Water depth (m)	E.C. (µs/cm)	PH	HCO$_3$ (mg/l)	Cl (mg/l)	NO$_3$ (mg/l)	SO$_4$ (mg/l)	Ca (mg/l)	Mg (mg/l)	K (mg/l)	Na (mg/l)	Br (mg/l)	Sr (mg/l)	δ^{18}O (‰)	δ^{2}H (‰)	^{3}H (TU)
Northern part																
W31	20.0	3,440	7.14	388.0	385.0	32.4	1,018.1	276.2	188.5	4.8	188.7	1.19	3.43			
W32	31.8	2,036	7.33	422.0	327.0	5.4	637.7	241.9	81.5	1.1	180.6	1.12	0.87	−6.47	−45.06	
W33	30.0	3,980	7.11	320.0	234.1	7.6	486.3	188.8	90.5	2.7	112.2	0.78	1.21			2.70
W34	14.0	8,770	7.8	471.0	2,176.1	–	878.1	221.3	229.6	155.1	1,188.5	3.65	3.40	−3.97	−28.06	2.80
W35	9.0	995	7.44	420.3	222.9	51.0	187.2	114.6	54.5	1.1	131.9	0.88	2.26			
W36	16.0	3,020	7.4	429.9	1,661.7	23.1	538.5	302.9	275.6	7.9	720.6	5.20	13.69	−6.58	−40.76	
Miocene terrains																
Mc37	15.0	1,203	7.64	453.8	137.7	1.9	70.0	75.2	57.9	1.8	99.9	0.46	0.48			
Mc38	7.1	703	7.62	393.0	39.6	20.7	38.2	70.4	48.8	5.0	23.4	0.14	0.36			
Mc39	35.0	2,500	7.55	309.8	604.9	20.1	356.1	222.1	112.0	2.1	259.0	1.88	1.99	−7.17	−44.51	
Mc40	23.0	1,325	7.14	295.2	301.7	21.7	96.3	112.4	45.8	0.7	177.1	0.51	0.47	−5.40	−40.45	
Mc41	16.0	1,234	7.36	283.0	204.9	9.3	118.2	47.0	34.4	4.6	218.2	0.52	0.68			
Mc42	77.5	1,247	7.36	269.6	140.1	28.9	184.8	89.5	52.0	1.9	125.5	0.40	1.51			
Mc43	84.0	805	7.85	271.0	243.3	16.3	267.9	85.3	101.0	2.4	163.3	0.73	1.50	−6.69	−45.44	
Mc44	47.0	913	7.38	419.4	102.7	9.2	77.2	86.5	51.0	1.6	43.1	0.41	1.51			
Mc45	29.0	2,341	7.56	497.9	219.0	2.0	655.2	237.6	122.3	7.1	98.8	0.77	2.93	−6.84	−44.05	
Mc46																
Wells from carbonate aquifers																
Cr43	35.3	1,265	7.5	412.0	88.4	9.2	603.6	174.1	91.3	7.3	59.8	0.32	1.92	−6.69	−43.60	2.00
Cr47	59.0	1,869	7.69	427.0	171.9	5.9	458.8	104.2	55.2	21.0	206.6	0.49	5.58			
Chichaoua springs																
Abainou		1,171	7.61	234.0	55.3	17.6	196.4	99.5	49.4	2.1	38.3	0.23	2.71	−6.72	−48.77	0.60
RasElAin		1,125	7.19	285.5	90.7	10.8	306.9	132.2	76.5	5.3	62.6	0.33	3.79	−6.85	−46.89	1.20
Rmech		1,548	7.6	238.0	260.0	21.0	832.9	236.7	139.8	5.1	145.5	0.85	8.75	−7.35	−39.08	1.50
Wadis																
Tassaout		1,414	7.84	210.0	149.2	4.3	75.5	55.2	24.9	2.7	98.4	0.0	1.1	−7.776	−52.68	
Lakhdar		1,025	7.07	169.0	14.9	5.0	117.2	66.7	32.5	2.7	12.6	0.0	2.3	−8.29	−52.352	
R'Dat		6,720	7.5	229.4	1,332.4	20.0	272.9	174.6	36.9	16.4	828.9	n.a.	4.8	−5.147	−39.802	
Zat		362	7.64	148.9	14.4	4.4	12.3	30.8	5.6	2.5	14.3	n.a.	0.3	−6.945	−44.502	
Ourika		363	7.77	131.3	8.2	4.0	12.4	30.5	5.3	1.1	9.1	0.0	0.3	−8.749	−56.627	5.20
Rheraya		717	6.56	208.5	211.0	6.5	42.0	70.6	24.5	2.4	134.1	0.0	0.8	−8.232	−50.547	
N'Fis		303	7.18	182.4	13.2	5.9	15.6	37.8	10.1	2.4	13.2	0.0	0.4	−8.172	−51.009	
Assif El Mal		100	7.87	130.0	244.0	3.5	36.7	112.7	28.7	3.9	15.0	0.0	0.8	−7.797	−52.42	
Chichaoua		475	7.75	223.5	22.7	14.9	76.6	56.2	22.7	1.8	17.3	0.1	1.4	−6.572	−46.598	

Total alkalinity was determined by titration. Major ions and trace elements (Br, Sr) were measured in the Center of Analyses and Characterisation (CAC) of Cadi Ayyad University by high-performance liquid chromatography (HPLC). The stable isotopes (^{18}O and ^{2}H) were analyzed in the Ecolab laboratory (http://shiva.univ-tlse3.fr/). Samples of water were collected in 10-mL tight-capped glass vials for δ^{18}O and δ^2H measurements and were kept at a stable temperature of 20 °C until analysis. In the laboratory, 0.2 mL aliquots of the water were taken in capped 3.7-mL-Exetainer vials (Labco Ltd, High Wycombe, UK). To measure the δ^{18}O values of the water samples, the samples and the internal standards were flushed offline with a gas mixture of 5 % CO_2 in He. The Exetainer vials were then left to equilibrate at 40 °C for about 8 h. The analytical precision of the measurements by this system, Multiflow, was 0.25 per mil. To measure the δ^2H values of the samples, Hokko beads were added to the Exetainer vials containing the water samples and the internal standards before the vials were flushed offline with a gas mixture of 5 % H_2 in He. The Exetainer vials were left to equilibrate at 40 °C for about 8 h. The analytical precision of the measurements was 2.5 per mil. The spectrometer Elementar Isoprime-100 was calibrated using four working standards that are traceable to the primary reference standards V-SMOW2 (Vienna-Standard Mean Ocean Water) and V-SLAP2 (Vienna-Standard Light Antarctic Precipitation). Tritium analyses were performed in the laboratory of Hydrogeology of Avignon using a liquid scintillation counter after electrolytic enrichment.

Based on the approach of coupling physical knowledge and land use data, which is increasingly used in natural resource management and land use planning (Sanchirico and Wilen 2005; Tang et al. 2005; Walsh et al. 2007; Woltjer and Al 2007; Chowdary et al. 2009; Wiley et al. 2010; Ray et al. 2012a, b), data related to irrigation and groundwater exploitation over the Haouz plain are integrated. Several layers were elaborated by means of GIS (Geographical Information System), comprising irrigation areas, irrigation network, water transport canals, dams, pumping wells and the Marrakech city well fields. The resulting map is elaborated in Lambert coordinates. Through the coupling of the hydrological and the salinity data together with the information provided by this map, the major issues of groundwater management are identified and discussed.

Elaboration of probability maps

Variables for which a statistical distribution that is far from Gaussian, where no mathematical function is fully adequate to transform the original variable into a normal variable, indicator kriging (IK) is an alternative, because its application does not require any hypotheses about the statistical distribution of the variable (Deutsch and Journel 1998). In the specific case of indicator variables, the data are binary coded with regard to a cutoff value (concentration), attributing 0 to all values below or equal to the cutoff value and 1 to the remaining values. These binary-coded data are submitted to variographic analysis, variogram model adjustment and kriging interpolation. The resulting interpolation results in a map with values between 0 and 1, representing probabilities between 0 and 100 % that the actual value/ concentration exceeds the cutoff value.

The method was applied in the current study to create probability maps for the nitrate concentration. After studying the data, two cutoff values for indicator kriging were defined (resulting in two probability maps): i) the WHO drinking water guideline of 50 mg l^{-1} NO_3^- and ii) half this value, 25 mg l^{-1} NO_3^-, providing an indication of the occurrence of increasing trends and need for trend reversal. The data were first binary codified (separately for each of the two cutoff levels): 0 where the concentration was below or equal to the cutoff level and 1 where the concentration was above the cutoff value. Subsequently, the experimental (semi)-variograms were constructed for each so-called "indicator variable", to analyze the spatial configuration of the codified data. These revealed the distance (range of influence) and associated value (sill) at which the nitrate data become independent from each other, as well as the fraction of the total data variance corresponding to small-scale variability and measurement errors (nugget effect) visible at the origin. Different spatial orientations were analyzed to detect the presence of anisotropy. This was followed by the fitting of theoretical models, defined as the expected squared differences in value (concentration) between pairs of data a distance h apart. The type of model used was the spherical or Matheron model. Fitting resulted in the calculation of the model parameter values, namely the range, sill, nugget effect and anisotropy, which were then introduced into an ordinary kriging algorithm to create the spatial interpolation maps. Ordinary kriging assumes a constant but unknown mean. The software SURFER from Golden Software was used for the spatial interpolation.

A large advantage of kriging is that every estimate is accompanied by a corresponding standard deviation of the estimation error, also known as the standard error or kriging standard deviation. A larger SE denotes a lower reliability of estimation. At short distances from sampled locations the SE is largely determined by the nugget effect, and as the distance increases, the error depends on the distribution of the sample network, as this determines the length of the search radius with respect to the range of influence in the experimental variogram. According to Clark (1979), a standard error larger than the original sample standard deviation denotes an unreliable estimate.

Results and discussion

Groundwater flow

The regional piezometric contour map of the alluvial aquifer shows that globally groundwater flows from south to north, towards the Tensift wadi that constitutes a natural discharge line of groundwater (Fig. 4). The configuration of the piezometric contours reveals interactions between groundwater and other wadis as well. The wadis N'Fis, Baaja, Seksawa and Chichaoua seem to drain groundwater in some places, whereas upstream of the Middle Haouz, groundwater mounds are linked to the wadis of Rheraya and Ourika, most likely indicating recharge from wadis during floods and generally through river bed infiltration. The south-eastern sector located between Lakhdar and Tassaouate wadis and the south-western sector also seem to be recharge areas. An extended groundwater mound is observed in the Eastern Haouz, which could be related to the effect of recharge from irrigation. Stigter et al. (2006) and Andrade and Stigter (2011) found that surface water irrigation contributed significantly to the recharge of shallow alluvial aquifers, with several effects such as the rise of the water table and groundwater freshening.

Isotopes analyses and groundwater recharge

Previous observations in the study area (Raibi et al. 2006) have shown heterogeneous values (−24.4 ‰ to −110.7 ‰ for δ^2H and −5.5 ‰ to −15.6 ‰ for $\delta^{18}O$) representing isotopic variation of rainfall from the plain to the High-Atlas Mountains. A local meteoric water line (LMWL) with a deuterium excess of 13.5 ‰ was drawn using these values (Raibi et al. 2006). Due to the scarcity of rain isotopic measurements used for the LMWL, the $\delta^{18}O$ and δ^2H values from the water samples of the present study are plotted and compared both to the LMWL and the global meteoric water line GMWL (Rozanski et al. 1993; Craig 1961) with a deuterium excess of 10 ‰ (Fig. 5). The samples of the wadis are close to the meteoric water lines (MWLs) except for the Rdat wadi which is the most enriched in isotopes and plots below the MWLs. The isotope values of the wadis of Assif El Mal, N'fis, Rheraya, Ourika and Tassaout vary from −7.8 ‰ to −8.75 ‰ for $\delta^{18}O$ and from −50.5 ‰ to −52.68 ‰ for δ^2H and are significantly lower than those of the Zat and Chichaoua wadis. This could traduce the altitude effect implying that water from an air mass that condensed at higher altitudes contains a greater amount of the lighter isotopes of oxygen and hydrogen and, therefore, has lighter $\delta^{18}O$ and δ^2H values.

Groundwater isotopic content varies within a larger range, from −8.8 ‰ to −4 ‰ for $\delta^{18}O$ and from −62.5 ‰ to −31.3 ‰ for δ^2H. Groundwater samples from the different parts of the plain are scattered around the MWLs, indicating generally a meteoric origin of groundwater. Some wells enriched in isotopes and located below the meteoric water lines could reflect an evaporation effect; this process will be addressed below.

Some other samples, including the Rmech spring and wells located in the piedmont of the Middle Haouz, plot slightly to the left of the MWLs. This could be linked to isotope content variation in the rainfall recharging the aquifers (as the meteoric water line is a linear relationship of average values). In arid regions the humidity-related kinetic isotope effect could result in meteoric waters being enriched in deuterium and thus plotting to the left of the GMWL (Maliva and Missimer 2012). On another hand, silicate hydrolysis can lead to ^2H enrichment in groundwater from crystalline rock (Coplen 1993); crystalline rocks are widely present in the High-Atlas Mountains and water coming from these terrains could contribute to the groundwater recharge in the plain. This may be more likely, as recharge from direct rainfall in the plain is most likely limited. To be able to provide a more detailed explanation more isotope analyses would be needed of rainfall, surface water and groundwater from different reservoirs and in different periods of the year.

To have information about whether the groundwater is old or recent, tritium measurements are interpreted qualitatively. For this purpose, it is assumed that (i) groundwater with values of tritium lower than 1 TU has been recharged before the last 50 years and has not incorporated any significant amount of recent recharge, (ii) groundwater with values of tritium comprised between 1UT and 2UT represent a mixing between old and recent groundwater and (iii) groundwater with values of tritium higher than 2 UT is recent (Clark and Fritz 1997). Three measurements are made on surface water indicating the following values: 4.1 TU for rainfall from Marrakech city (450 m), 4.2 TU for snow (2,650 m) in High-Atlas, and 5.2 TU for Ourika wadi (1,600 m). Six springs located in mountain have tritium values from 1.3 to 5.2 TU. Samples from the alluvial aquifer show values from 1.2 to 4.5 TU with an average of 3 TU (Table 1). Therefore, they generally indicate recent groundwater with possible existence of mixing process between old and recent groundwater. The reference well located in carbonate deposits has a tritium content of 2 TU. The Chichaoua springs exhibit the following values: Abainou 0.6 TU (520 l s^{-1}), Ras El Ain 1.2 TU (45 l s^{-1}) and Rmech 1.5 TU (55 l s^{-1}). These values suggest a longer residence time of groundwater from the carbonate aquifer and from the Chichaoua springs, which could originate from Eocene or Mesozoic aquifers.

An altitudinal line (Fig. 6) was elaborated by Raibi et al. (2006) from ^{18}O analyses concerning meteoric water (snow and rainfall) sampled at different altitudes from the plain
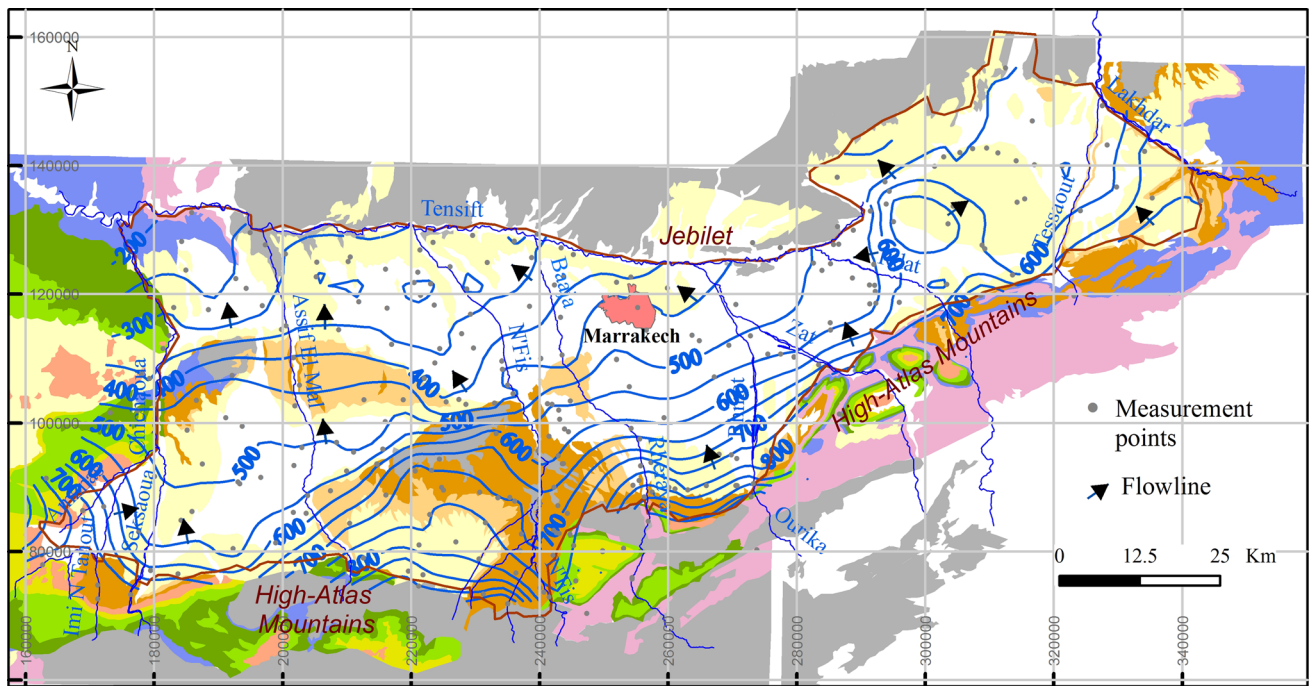
Fig. 4 Piezometric map of the alluvial aquifer (2011). *Flowlines* indicate the direction of groundwater flow generally toward the Tensift wadi. A recharge mound exists in the Eastern Haouz due probably to irrigation effect
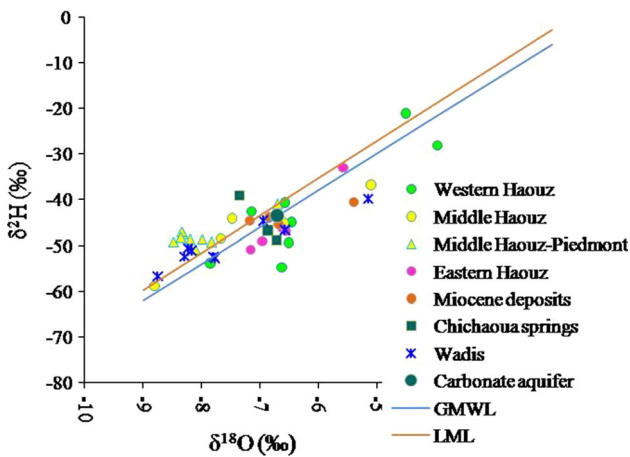
Fig. 5 δ^2H vs $\delta^{18}O$ values of sampled waters as compared to the global and local meteoric water lines

(altitude = 450 m) to the High-Atlas Mountains (altitude = 4,165 m). This altitude line has an ^{18}O depletion of 0.32 ‰ per 100 m rise in altitude. The line is used to estimate the recharge altitude of sampled waters in the present study. Only the wadis and the wells close to the meteoric water line were plotted. The projection of the wadi samples with regard to the altitude line is likely to indicate the dominant altitude range, namely in the high mountains, whose meteoric waters feed the wadis upstream from the sampling points. The isotope-depleted wadis (Ourika, Rheraya, N'Fis, Tassaout, Lakhdar) seem to be

recharged in majority by water coming from altitudes over 2,500 m; here we can underline the role of snowmelt as a source of surface water in the wadis (Boudhar et al. 2007, 2010). The Zat and Chichaoua wadis, more enriched in isotopes, reveal a lower altitude of recharge probably because of the lower altitudes of their watershed. The wells show that the groundwater recharge in the plain would consist mainly of water coming from various altitudes of the High-Atlas Mountains generally higher than 2,000 m. Consequently, direct rainfall infiltration in the plain seems to have a low contribution to aquifer recharge. This could be explained by low rainfall and high evaporative demand in the Haouz plain. Therefore, the recharge of the alluvial aquifer seems to be mainly insured by the wadi floods or dam releases coming from the High-Atlas Mountains which receive important precipitation either as rainfall or snowfall (Boudhar et al. 2007, 2010).

Salinity distribution and origin

The groundwater-EC map (Fig. 7) shows that over a large part of the plain EC values are lower than 1,500 µS cm^{-1}. Fresher groundwater (EC <1,000 µS cm^{-1}) is observed in several sectors including the recharge areas previously indicated according to the piezometric map. Brackish groundwater (EC >2,000 µS cm^{-1}) occupies a large area in the east of the plain and is also observed at the north-west (northern part of the Western Haouz).

According to the Piper diagram (Fig. 8), the fresh groundwater is mainly predominated by Ca–Na–Mg–HCO$_3$ ions. According to the siliciclastic nature of the alluvial deposits and the large presence of carbonate rocks, this indicates that in freshwater the main processes of mineralization are silicate mineral weathering and carbonate dissolution. Concerning the two wells tapping directly the
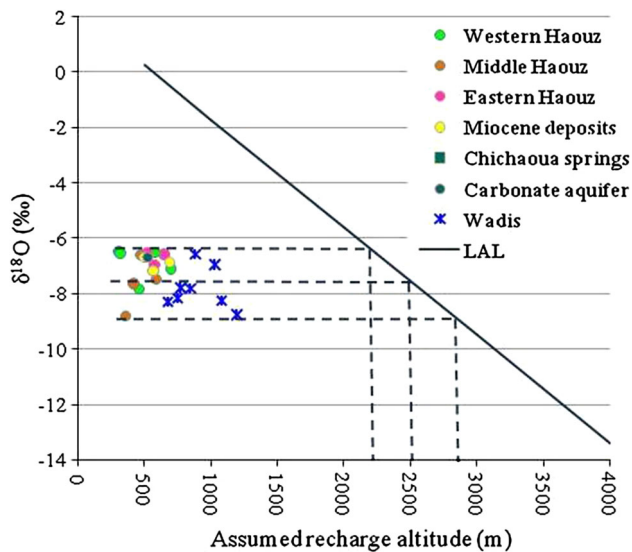

Fig. 6 Assumed recharge altitude with regard to the local altitudinal line (LAL). Solely the samples close to the *meteoric water lines* are plotted on the diagram

carbonate aquifers (Eocene–Cretaceous) the groundwater type is dominated by Ca, Mg, SO$_4$ and HCO$_3$. The springs of Chichaoua (Abainou, Ras el Ain and Rmech) also have a similar facies. This similarity suggests that the springs could originate from the carbonate aquifers.

In the Piper diagram (Fig. 8), gradual enrichment in Na, Cl and SO4 is also observed. In the scatter plot of Cl vs SO$_4$ (Fig. 9), chloride and sulfate enrichments are most relevant in groundwater sampled in the areas affected by salinity. Indeed, high chloride contamination affects the Rdat wadi and samples from the Eastern Haouz (E2, E4, E7, E10, E11). High sulfate contamination affects samples from the carbonate aquifers (Cr 43, Cr 47), the Rmech spring, and wells from the alluvial aquifer, located in the northern part of the Western Haouz (W31, W32, W33). The samples W34 and W36 located in the same area are also enriched in sulfate and particularly in chloride. In the context of the study area, chloride contamination could be related to the influence of (i) Triassic terrains containing sodium-chloride salts which are widely present in the east (both in the mountains and under the plain) and in the extreme north-west (Figs. 1, 2) or (ii) of evaporation effect, the existence of which is indicated by stable isotopes. Sulfate contamination could be related to gypsum dissolution contained in the Senonian gypsiferous deposits.

Bromide (Br) and chloride (Cl) are analyzed in groundwater to identify the origin of the high chloride concentrations. Due to the lack of Br and Cl
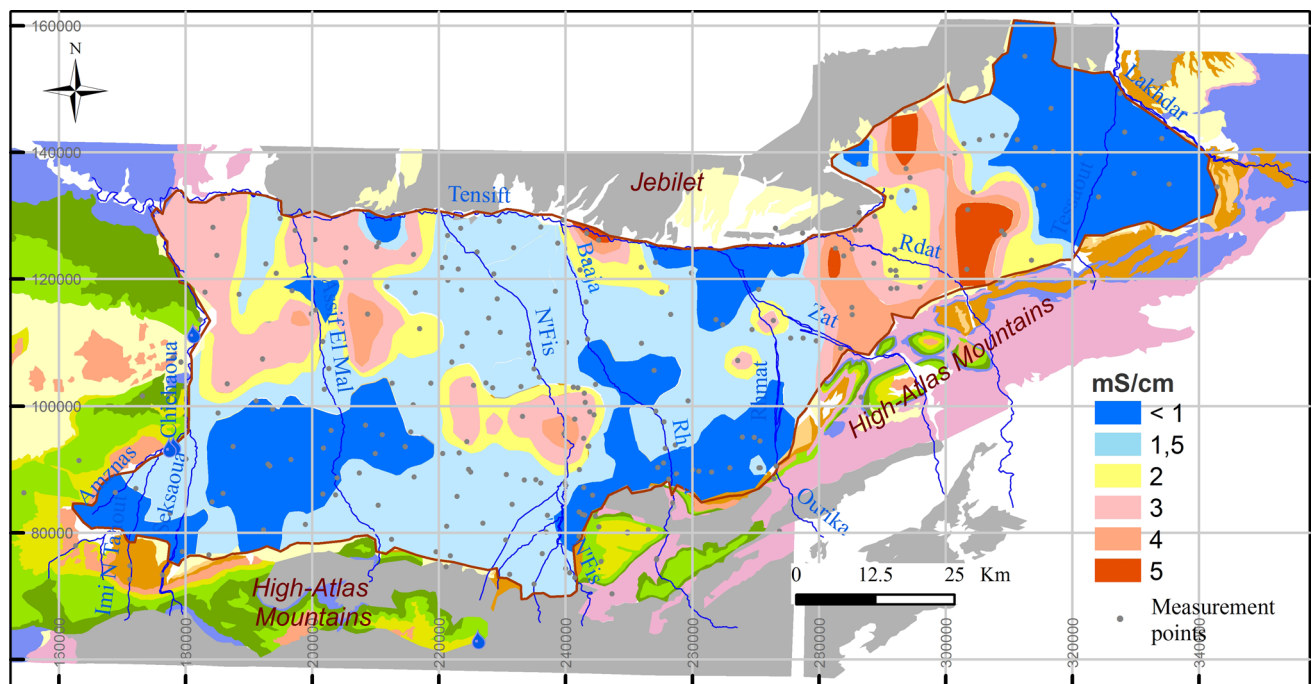
Fig. 7 Electrical conductivity map (2011) in mS.cm^{-1}. Large part of the alluvial aquifer has fresh groundwater. High salinity areas are observed in the Eastern Haouz and in the north part of the Western Haouz
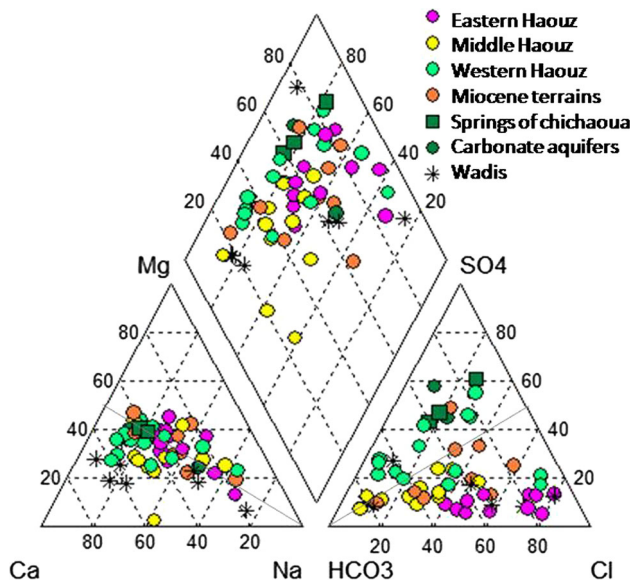
Fig. 8 Piper diagram of the chemical composition of sampled groundwater

measurements in rainfall in the study area, data from other works are used. Previous woks showed that inland rainfall, especially in arid or semi-arid climates, may have higher Br/Cl ratios than coastal rainfall (Davis et al. 1998, 2001; Edmunds 2001) which commonly has Br/Cl ratio of ~1.5 ‰ (Richter and Kreitler 1993; Andreasen and Fleck 1997). This is due to the tendency of Cl to be removed by deposition of marine aerosols in coastal areas. Br/Cl ratios of halite are commonly in the order of 1–0.1 ‰ (Kloppmann et al. 2001; Cartwright et al. 2004). Thus, halite dissolution will produce a rapid decrease in Br/Cl ratios with increasing Cl concentrations (Cartwright et al. 2006).

In the Br/Cl vs Cl diagram (Fig. 10) it is observed that at low chloride concentrations, the Br/Cl ratio allows clearly to segregate two groups of samples. The first group has higher values of Br/Cl ratio, similar to rainfall values. This group corresponds to groundwater sampled in the Western Haouz, Miocene deposits and Chichaoua springs. The second group is depleted in bromide inducing lower values of Br/Cl ratio which are closer to the values measured for the wadis. This group corresponds to groundwater from the Middle and Eastern Haouz, and the similarity of Br and Cl contents between groundwater and wadis could be explained by an important contribution of the latter to the alluvial aquifer recharge.

The depletion of bromide in the wadis water could be linked to its origin at higher altitudes. Orographic effects on Cl and Br ions concentrations have been observed in previous studies (Davis et al. 2004; Alcala and Custodio 2008). For the study area measurements of Cl and Br in

surface water, rainfall and snowfall at different altitudes are needed to analyze the altitude effects in more detail.

Most samples with high Cl concentrations have lower Br/Cl ratios, some even close to 0 ‰, indicating halite dissolution as a likely source. For high Cl concentrations the distinction between evaporation and salt dissolution can further be nicely made using the plot of ^{18}O vs Cl (Fig. 11). Salt dissolution will cause horizontal lines in the plot showing only increase in Cl and not in ^{18}O. Evaporation on the other hand will show almost vertical lines, affecting ^{18}O much more significantly than Cl, as can be proven by applying the Rayleigh equation for oxygen isotope fractionation. It can be derived from the plot that, among samples which were analyzed for ^{18}O, several are only affected by salt dissolution (E4, E11, W36), some only by the evaporation effect (M20, Mc41) and others seem to be affected by both processes (Rdat wadi and E7). The samples affected by salt dissolution correspond to those with the lowest Br/Cl ratio. The evaporation signal of the Rdat wadi could be explained by a direct evaporation effect on the sampled water. For the groundwater samples evaporation may have occurred through capillary rise from shallow depths or indirectly via the infiltration of concentrated surface water. For some wells with large diameter, direct evaporation effect can also not be entirely excluded despite a correct sampling protocol. As E7 plots between the MWLs (Fig. 5) it was discarded from the samples that are affected by evaporation.

In some arid areas the evaporation process may consistently modify initial isotopic composition of groundwater (El Mokhtar et al. 2012, Abderamane et al. 2013), but the impact of this process in the Haouz plain seems to be limited. The limited effect of evaporation despite a semi-arid climate has also been shown by several studies in Morocco and abroad (Bouchaou 2008, 2009; Bouragba et al. 2011; Lapworth et al. 2013). In the present case study, this could be explained by several reasons (i) the relatively large groundwater depth on a large part of the plain (Fig. 12) and (ii) waters are sampled during a winter rainy season experiencing low evaporation. Notwithstanding, the fact that recharge from direct rainfall has proven to be low, indicates that transpiration may play a dominant role in the water loss back to the atmosphere, as this process does not cause any fractionation (e.g., Stigter et al. 1998).

Concerning the source of sulfate, strontium (Sr) is used as it is often associated to gypsum as celestite ($SrSO_4$) (Carré 1975). The good correlation between Sr and SO_4 observed in the Fig. 13 supports the idea that gypsum dissolution is the main process of sulfate contamination. Gypsum is present in the gypsiferous marls of the Senonian which forms the basement of the Eocene aquifer and the top of the Turonian aquifer. Consequently

Fig. 9 Scatter plot of Cl vs SO$_4$ particularly showing the most enriched samples in chloride and sulfate
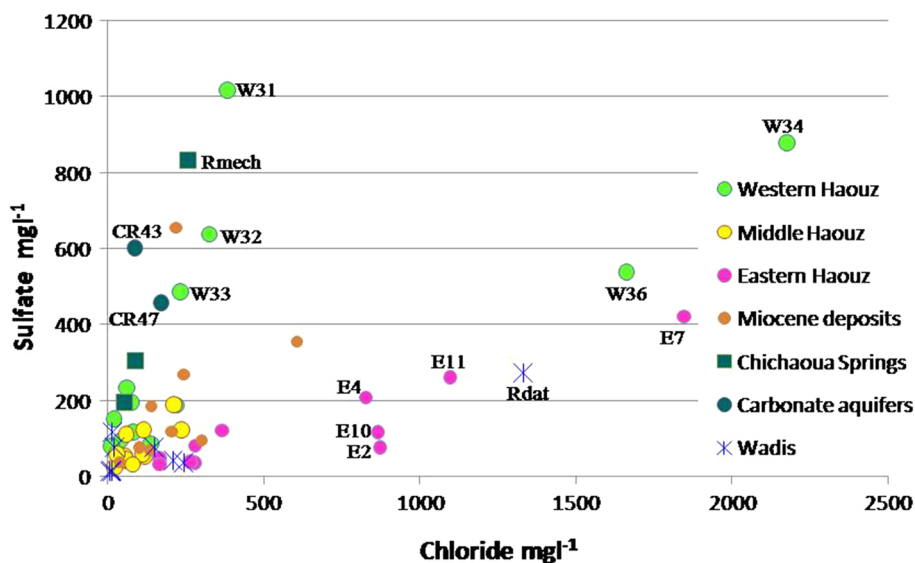
Fig. 10 Scatter plot of Br/Cl ratio vs Cl segregating at low chloride concentration the Western Haouz samples (higher Br/Cl ratio) from Middle and Eastern Haouz samples (lower Br/Cl ratio). High chloride concentrations could be explained by evaporation or Triassic salt contamination
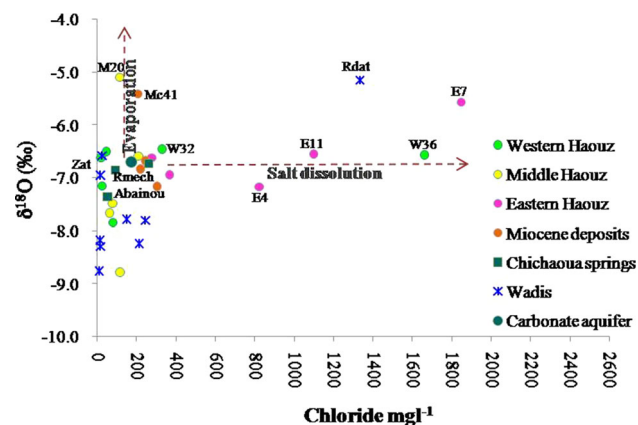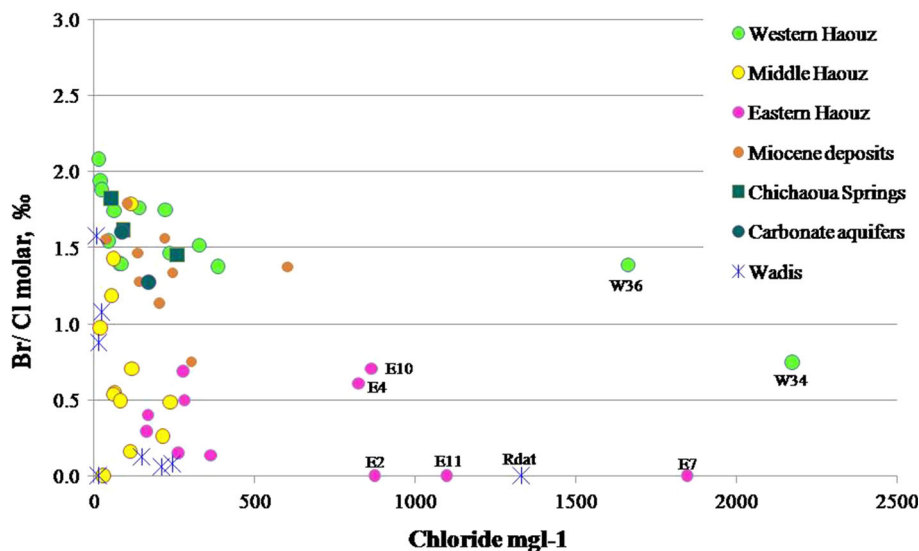
Fig. 11 Plot of ^{18}O vs Cl concentrations in the study area

groundwater in these aquifers could be affected by sulfate contamination.

According to their Ca and Mg content and sulfate enrichment, the springs of Chichaoua (Abainou, Ras El Ain and Rmech) obviously constitute discharge points of a system integrating the carbonate aquifers (Eocene, Cretaceous or Jurassic). The Abainou spring is distinguished by its high flow rate (520 l s^{-1}), lower mineralization and older water (0.6 TU). It could be fed by a larger system containing important reserves. This system could be composed principally by Turonian–Cenomanian aquifer which has a large extent in the west of the study area. The Rmech (55 l s^{-1}) and Ras el Aïn (45 l s^{-1}) springs have lower flow rates. Ras el Aïn has a geochemistry closer to that of

Abainou. Rmech is characterized by a higher sulfate and chloride content and by deuterium depletion. According to its geological location, it could belong to a smaller system which could be related to the Eocene aquifer.

Nitrate contamination

The obtained values for nitrates are used to indicate their distribution in the plain according to guideline threshold values. Nitrate (NO_3^-) is an indicator of groundwater contamination by leaching of (mineral and organic) fertilizers or septic waste, and important for health concerns (e.g., WHO 2011). As cutoff values the drinking water guideline for NO_3^- was chosen (50 mg l^{-1}), as well as half its value (25 mg l^{-1}), a good indicator for groundwater suffering from NO_3^- contamination that could exceed the guideline value at some point in the future.

The maps elaborated by the indicator-geostatistical techniques (Fig. 14) show that nitrate contamination beyond the drinking water limit (50 mg l^{-1}) is not widespread in the Haouz plain, limited to a few, and apparently unconnected locations. Notwithstanding, the spatial configuration of the probability exceeding 25 mg l^{-1} is better structured, particularly in the Eastern Haouz. This could be linked to the existence of a plume due to contaminating activities. The agriculture, as the main activity in the study area, could explain this contamination. However, the existence of wastewater losses from households cannot be excluded, and the use of discrimination techniques such as nitrate isotopes (e.g., Stigter et al., 2011) could be used to distinguish between different sources. Increased monitoring in the more contaminated areas and more representative and frequent (consistent) monitoring is also necessary to timely detect temporal and spatial trends.

Groundwater exploitation and management issues

The main components of irrigation, water supply and exploitation in the Haouz plain are displayed in the Fig. 15. When analyzing water exploitation with the hydrogeological and hydrochemical data, three main management zones of the Haouz plain (East, Middle and West) could be defined (Fig. 15).

The Eastern Haouz

It constitutes the first equipped (early 1970s) perimeter for modern irrigation. The irrigation is supplied by My Youssef dam of the Tassouat Rriver. Nitrate and especially salinity problems are more expressed in the western part of this unit. Consequently, groundwater salinity and the impacts of irrigation both in terms of quantity and quality are the main water management issues. Possibilities of

properly using brackish groundwater should be examined and the irrigation efficiency should be improved. To reduce the risk of nitrate contamination, good agricultural practices need to be implemented in the region. The most promising groundwater restoration measures are targeted towards (i) an increase in nutrient efficiency and (ii) an improvement in nutrient balance in the application of fertilizers, with adequate timings based on crop requirements (e.g., Stigter et al. 2011). Overfertilization is a major problem, since farmers believe it guarantees maximum crop yield and quality, even though adding fertilizer N follows the classical crop response curve for yield-limiting nutrients as presented by Dibb (2000), significantly increasing crop yield only up to a certain point, after which nutrient efficiency drops rapidly. Farmers also largely underestimate the N available from other sources, such as residues from previous crop cycles, soil, or irrigation water. Moreover, the lack of balanced nutrition may also be an important factor, as the presence of other macronutrient elements such as potassium and phosphorus in adequate proportions in soil and fertilizer is essential for N recovery by the crops (e.g.,. Wang et al. 2010).

The middle Haouz

It encompasses the city of Marrakech and its well fields, golf courses and tourist buildings, as well as irrigated agriculture fields. The urban water demand has increased during the last 10 years, mainly driven by a rapid growth of the population in the city of Marrakech (about 1.3 million inhabitants) and by an important growing tourism (about 2 million tourists per year) and real estate activity in Marrakech city and surroundings. Currently, the annual drinking water demand of Marrakech city is about 65 10^6 m^3 $year^{-1}$. The irrigated areas comprise the public perimeters with modern irrigation supplied by dams (Takerkoust and Wirgane), the traditional irrigation perimeters at the piedmont fed by flow derivation from the wadis (Rheraya 1.59 m^3 s^{-1}, Ourika 4.92 m^3 s^{-1}, Zat 3.83 m^3 s^{-1}) and private areas that depend exclusively on groundwater. An inter basin transfer of surface water via the "Canal of Rocade" from the neighboring basin of Oum Er Rbia is used for modern irrigation and drinking water supply. The groundwater is generally of good quality and easy access. Despite consistent surface water supplies (wadis and dams) this is the area where groundwater is most overexploited due to the large water demand. Groundwater decrease rates could vary from 1 to 3 m $year^{-1}$ for the most overexploited area during dry periods (Fakir et al. 2010). Therefore, in the Middle Haouz the challenge is to reduce groundwater abstraction for irrigation, to preserve a part of the available resources for non-irrigation uses and eventually to restore the depleted groundwater reserves. Concerning the last
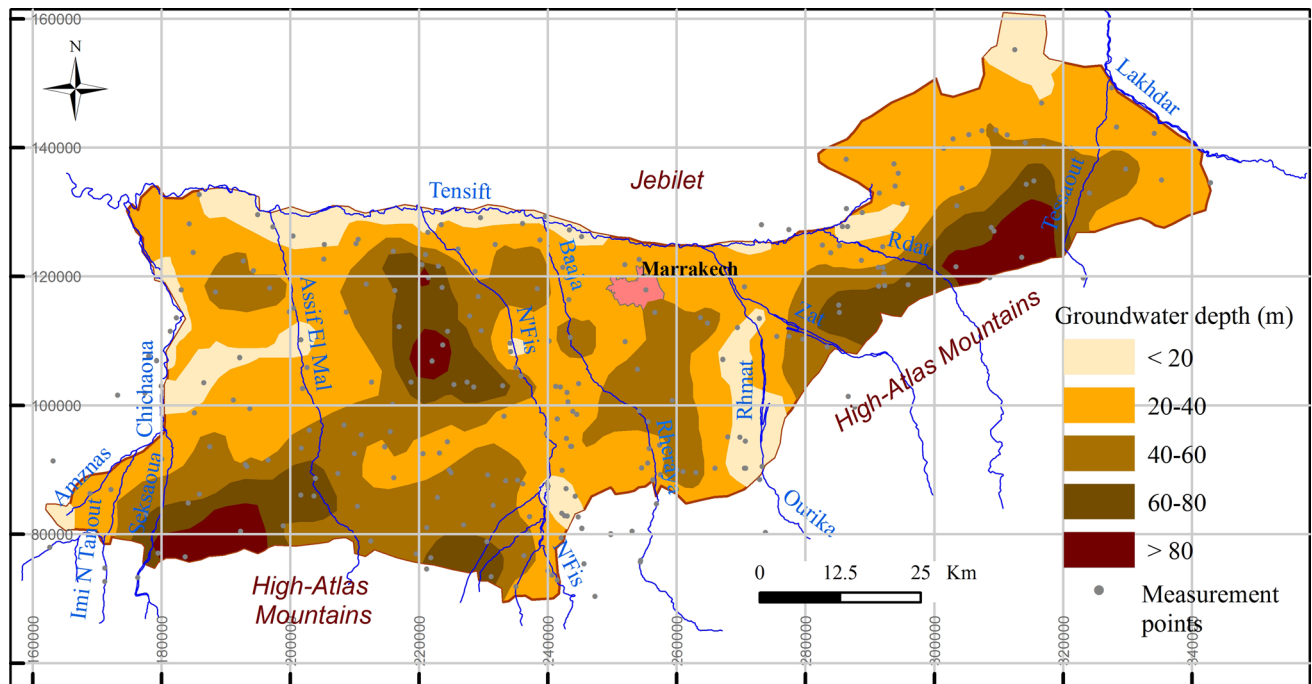
Fig. 12 Alluvial groundwater depth (2011). The groundwater depth is generally greater than 20 m, this could limit the effect of evaporation on groundwater
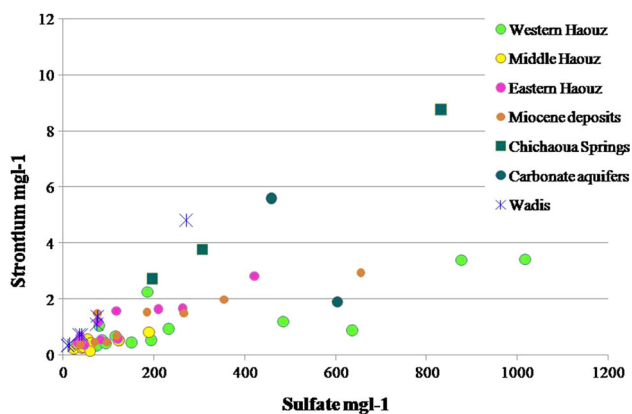
Fig. 13 Scatter plot of SO_4^{2-} vs Sr. The good correlation between these elements suggests the gypsum origin of sulfate

point managed aquifer recharge is an option to be studied and integrated into the water resources management strategy. Indeed, due to the wadis–alluvial aquifer interaction, floods could be used for artificial recharge. Treated wastewater could also be potential source as long as ecological demands in the wadis and certain water quality standards in the treated wastewater would be guaranteed.

The Western Haouz

in addition to the alluvial aquifer, Eocene and Cretaceous deeper aquifers are exploited. The groundwater is generally

of good quality. Up to the 1990s, only traditional irrigation was practiced along the Chichaoua (1.57 m^3 s^{-1}) and Assif El Mal (1.63 m^3 s^{-1}) wadis. The Chichaoua springs also play an important role in irrigation. Over the past 15 years, agriculture activity and consequently irrigation wells have increased in the southern part. In the northern part, because of high salinity, groundwater exploitation is very low and the rainfed cropping is practiced during rainy seasons. The management goal in this zone is to prevent groundwater from experiencing long-term overexploitation. The deeper aquifers should be studied and their role in the water resource sustainability should be defined.
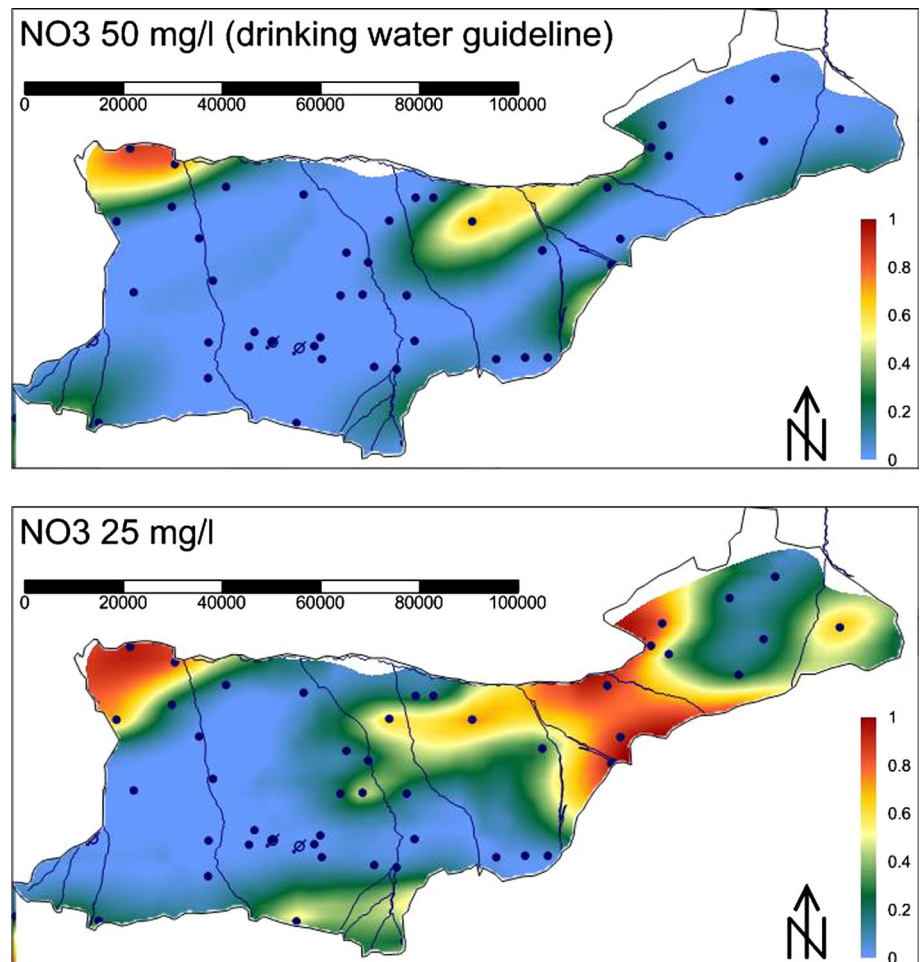
Conclusions

The present study focusing mainly on the alluvial aquifer of the Haouz plain aimed to investigate the origin of recharge and the processes involved in groundwater salinization using hydrochemical and isotopic tracers.

The results show on the one hand an important hydrological influence of the High-Atlas Mountains limiting the area to the south and on the other hand a spatial variability characterizing the aquifer system from east to west.

Within the plain, tritium analyses show the presence of recent groundwater and of a mixing between old and recent groundwater. Stable isotopic data (^{18}O and ^{2}H) indicate that the recharge would be dominated by high-altitude

Fig. 14 Probability maps of exceeding the drinking water guideline for NO_3^-

meteoric water originating from the High-Atlas Mountains. The recharge water is transferred from the mountains to the plain by the wadis that cross the plain from south to north.

Fresh groundwater is widely present and characterized by the predominance of Ca–Mg–Na–HCO_3^-. This indicates that mineralization is marked primarily by carbonate dissolution (from limestone and dolomite rocks) and second by silicate mineral weathering (from the alluvial deposits). However, chloride and sulfate enrichment is responsible for high groundwater salinities (EC > 2000 μS cm^{-1}) observed in the Eastern Haouz and the north part of the Western Haouz. As shown by ^{18}O, chloride and strontium tracers, this enrichment could be linked to the influence of Triassic terrains containing halite in the east and of Senonian carbonate deposits containing gypsum in the west. Evaporation effect is also detected. Furthermore, Br/Cl ratios separate groundwater of Middle and Eastern Haouz from the one of Western Haouz. This may be related to the origin of recharge water, though more analyses are required in this frame.

The springs of Chichaoua wadi which yield around 600 l s^{-1} at the western limit of the study area, have a carbonate facies and are marked by sulfate enrichment. These features indicate that the springs could have their origin in the carbonate aquifers. The tritium value (0.6 TU) of Abainou spring (520 l s^{-1}) could indicate a long residence time of its groundwater.

Nitrate contamination is detected and could be related to the agricultural activity in the eastern part of the Haouz.

Concerning the water management, there is a need to actively manage the groundwater resources to support both the existing and the growing economic activities. Different management actions should be taken with respect to the current water resources status and to the water uses. In this framework it is necessary to control groundwater abstraction, safeguard groundwater quality, optimize irrigation and enhance mountain-front recharge. On the other hand, the presence of salinized groundwater in the Haouz plain asks for the assessment of how to properly use these waters for drinking, irrigation and crop production.

Further investigations are required to improve the knowledge of the aquifer system of the Haouz plain. The main tasks are establishing the geological and hydrodynamic models of Western Haouz, achieving a greater
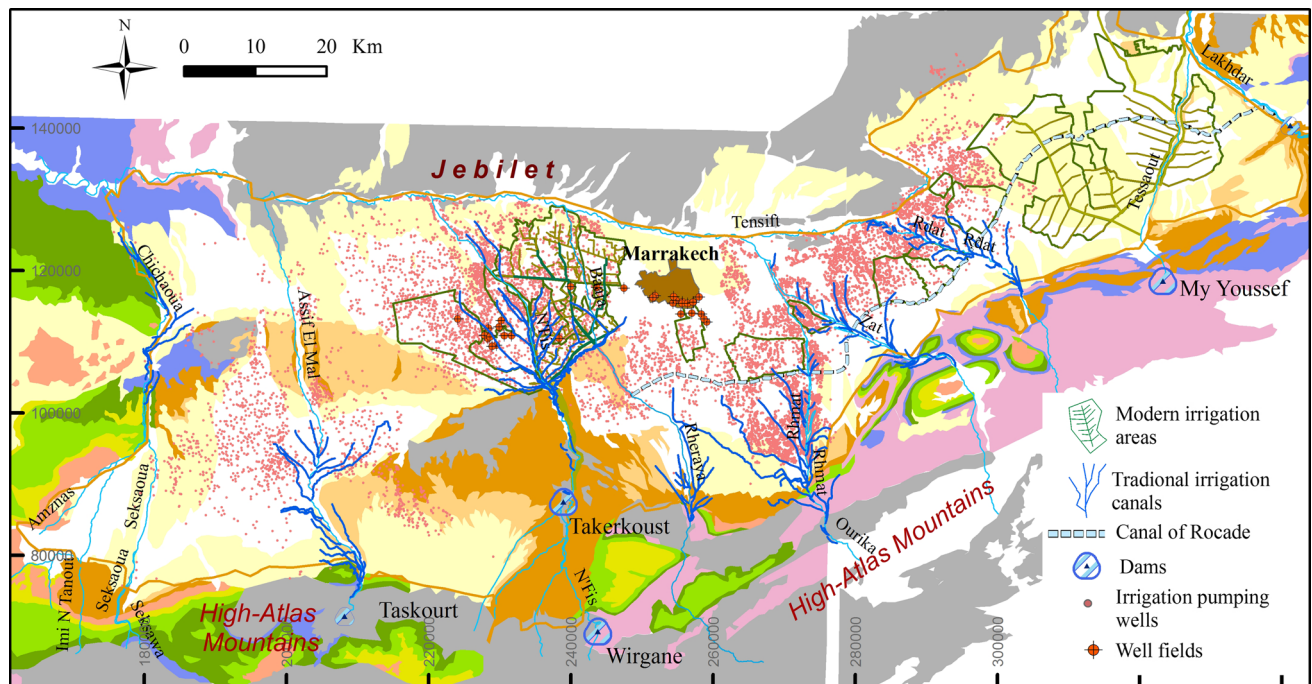
Fig. 15 Water exploitation in the Haouz plain. Despite a various surface water supplies (wadis, dams, interbasin water transfer insured by rocade canal) and complex surface water irrigation network (traditional and modern), the groundwater pumping is widespread, threatening the water resources sustainability in the Haouz plain

isotopic characterization of rainfall and groundwater and assessing recharge amounts both from rivers floods and irrigation return flow.

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