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ORIGINAL ARTICLE

Estimate of regional groundwater recharge rate in the Central Haouz Plain, Morocco, using the chloride mass balance method and a geographical information system

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Abstract Located in the extreme northwest of Africa, the Kingdom of Morocco is increasingly affected by drought. Much of the country is characterised by an arid to semi-arid climate and the demand for water is considerably higher than the supply, particularly on the Haouz Plain in the centre of the country. The expansion of agriculture and tourism, in addition to industrial development and mining, have exacerbated the stress on water supplies resulting in drought. It is therefore necessary to adopt careful management practices to preserve the sustainability of the water resources in this region. The aquifer recharge rate in the piedmont region that links the High Atlas and the Central Haouz Plain was estimated using the chloride mass balance hydrochemical method, which is based on the relationship between the chloride concentrations in groundwater and rainwater. The addition of a geographical information system made it possible to estimate the recharge rate over the whole 400 km^2 of the study area. The results are presented in the form of a map showing the spatialized recharge rate, which ranges from 13 to 100 mm/year and the recharge percentage of the total rainfall varies from 3 to 25 % for the hydrological year 2011–2012. This approach will enable the validation of empirical models covering areas >6200 km^2, such as the Haouz nappe.

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Introduction

Water is a limiting factor in semi-arid zones affected by repeated droughts. The evaluation and optimum management of this resource are therefore essential in regions such as the Haouz Plain, Morocco. The water supplies in this region are stressed as a result of a high and unconstrained demand, complicated by problems with water quality associated with the development of industry and mining, together with pollution from agriculture and urbanization.

The Mio-Plio-Quaternary nappe of the Haouz Plain provides more than 400 million m^3 of water and this water is used to irrigate an area covering >200,000 ha. In years of drought, the volume of water required for irrigation is estimated to be >1300 million m^3/year (Abourida et al. 2008). It is therefore very important to have a good understanding of the recharge rate of aquifers. Several different methods can be used to determine this recharge rate, including hydrochemical approaches. Hydrochemistry is becoming increasingly important in solving problems in hydrology and hydrogeology (Eriksson 1985; Adelana and MacDonald 2008) and several researchers have used hydrochemical (Allison et al. 1985; Adar et al. 1988; Adar and Neuman 1988; Al-Bassam and Al-Rumikhani 2003; Stigter et al. 2006; Fernandes et al. 2009; Hagedorn 2015) and geochemical (Holland 1972; Dissanayake 1991; Glynn and Plummer 2005; Xiao et al. 2012) approaches to address issues related to water management. This study used a hydrochemical method to calculate the recharge rate of aquifers in the Haouz Plain, Morocco.

The aquifer recharge rate is a crucial piece of data in hydrogeology and is key to the improved understanding and management of water resources. The elements used are observations of the behaviour, in the groundwater, of hydrochemical tracers, and major and minor ions subject to very sophisticated analyses.

The objective of this work was to estimate the infiltration recharge rate using the chloride mass balance (CMB) method developed by Eriksson and Khunakasem (1969), also called the chloride budget technique. This method has been successfully applied to aquifers in every continent, including: Africa (Edmunds et al. 1988; Takounjou et al. 2010; Diouf et al. 2013), Asia (Ting et al. 1998; Subyani 2004; Liu et al. 2009; Marei et al. 2010; Huang and Pang 2010), Europe (Lo Russo et al. 2003; Alcalá and Custodio 2014), Australia (Allison and Hughes 1978; Guan et al. 2009) and America (Sophocleous 1991; Scanlon 1991; Murphy et al. 1996; Nolan et al. 2007). It can be used in both the saturated and unsaturated zones (Edmunds et al. 2002) and is applicable in arid (Gee and Hillel 1988; Fouty 1989), semi-arid (Wood et al. 1997; Subyani and Şen 2006; Rödiger et al. 2014) and humid climates (Saghravani et al. 2014). However, it has not yet been used in Morocco.

Wood (2014) has highlighted the point that this method in the very specific case of a steady-state, chemically homogeneous and isotropic aquifer with no other sources of chloride other than precipitation. With a constant spatial and temporal concentration of chloride anions present in precipitation, a single sample of groundwater would therefore be sufficient to estimate the overall recharge rate of the whole aquifer. However, with a heterogeneous aquifer, which is the case in almost all natural aquifers, the density of sampling is critical in achieving an unbiased estimate of the average chloride concentration and the average recharge flow-rate. The representativeness of these concentrations then becomes an important issue.

The novelty of the work reported here lies in the use of geomatics through the development of a geographical information system (GIS) that spatializes variables by interpolating data samples. Each point represents a specific data pair, which makes it possible to apply the relation while retaining the reliability of the input data. The study area is a piedmont zone of the Central Haouz Plain. It has a semi-arid climate and contains the sub-basins of the Rheraya, Issil and Ourika rivers.

The principal and major objective of this study was to estimate the recharge of this piedmont region. A broader aim is that the results can be used to validate large-scale empirical models of areas exceeding 6200 km^2, such as the Haouz nappe.

Materials and methods

Study area

The study area is located between 7°46′42″W and 7°57′55″W and 31°19′10″N and 31°31′10″N (Fig. 1b). It is a piedmont zone covering 400 km^2. Most of the region is made up of Quaternary alluvium, Permo-Triassic sandstone formations, marly limestone continental facies Senonian age, with rocky outcrops to the south of the region and rugged areas to the southeast (Fig. 1c). (Piqué et al. 2007). There is no volcanic activity in the region. The distance from the western perimeter of the study area and the Atlantic Ocean is 200 km (Fig. 1a, b). There is no contamination by these waters from this effect.

The altitude of the piedmont ranges from 683 to 1358 m. This zone is crossed by the Ourika and Rheraya rivers and is the source of the Issil. Most of this hydrographic system is dry (Fig. 2), except during snowmelt or following exceptional rainfall. The area is characterised by a semi-arid climate. The average monthly temperatures over a 30-year period have varied between 18.5 and 20.5 °C; the coldest month is January (11–13 °C) and the hottest months are July and August (25–27 °C) (courtesy of ABHT: Tensift Basin Agency, Marrakesh, Morocco).

In the south of the region, near the rivers, the elevation of the potentiometric surface is 3 m; this increases to up to 60 m at points in the north distant from any rivers (Ait El Mekki 2010). According to the piezometric map (Fig. 1c) there is no interaction between surface water and groundwater at the level of the three rivers for the hydrologic year 2011–2012. The generalized water table is important both in terms of volume and function. It is made up of Mio-Plio-Quaternary alluvium in the form of detritus resulting from the erosion of the Atlas chain by the various rivers.

Chloride mass balance method

The CMB method uses chloride anions to calculate the recharge rate. The chloride anions are derived from both surface waters and groundwater, and from precipitation.

The method, developed by Eriksson and Khunakasem (1969), has been described by many researchers (Dettinger 1989; Wood and Sanford 1995; Bazuhair and Wood 1996; Wood 1999; Subyani 2004; Gee et al. 2005; Somaratne and Smettem 2014) and has been implemented in various climates and on all continents. It is based on the assumption that the only source of chloride anions in an unsaturated zone is precipitation. As few plants can use this anion, the concentrations of chloride increase in the soil until the aquifer is reached. The recharge rate therefore decreases as the chloride concentration increases, i.e. the higher the soil concentration, the lower the recharge rate.

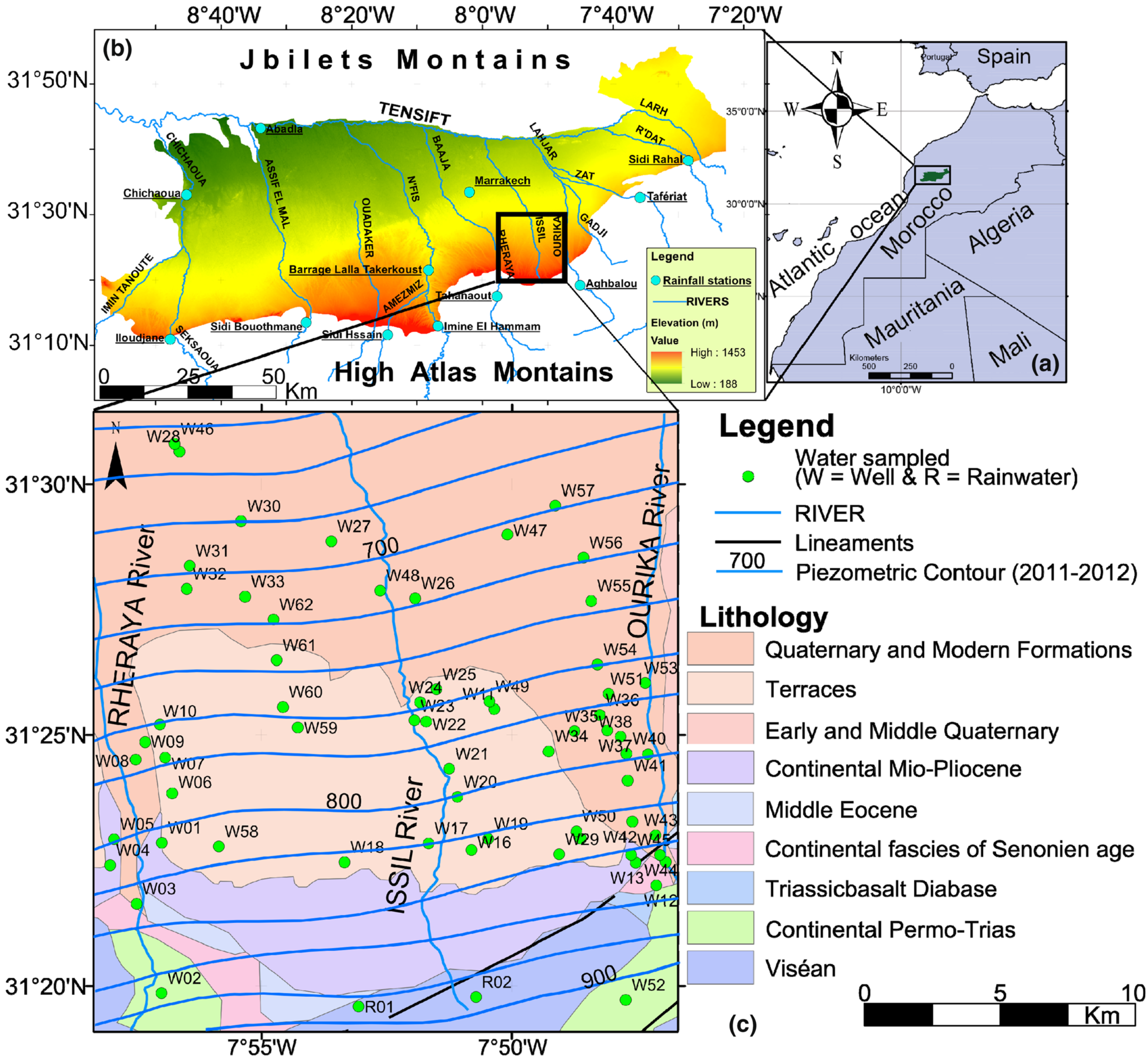

Fig. 1 Map of the study area

The conditions for the use of this method are as follows:

- there are sufficient chloride anions present in precipitation;
- there is no other source of chloride in the ground or in the aquifer (e.g. from urban or industrial waste, mining or agriculture);
- the chloride concentrations in rainwater are stable (i.e. there is no acid rain).

The recharge from rainwater can be calculated using (Eq. 1):

$$R = \frac{P \times C_p}{C_i} - \frac{Q \times C_q}{C_i} \quad (1)$$

where R the effective recharge rate (L^3 T^{-1}), P the annual precipitation (L^3 T^{-1}), C_p the chloride concentration in rainwater (ML^{-3}), C_q the average chloride concentration in runoff (ML^{-3}), C_i the concentration of groundwater chlorides (ML^{-3}) and Q the average runoff (L^3 T^{-1}).

In general, in this type of semi-arid climate, the runoff tends to evaporate or to infiltrate downstream of the mountains. It can therefore be considered to be negligible (Dettinger 1989) and Eq. (1) simplifies to:

$$R = P \times \frac{C_P}{C_i} \quad (2)$$

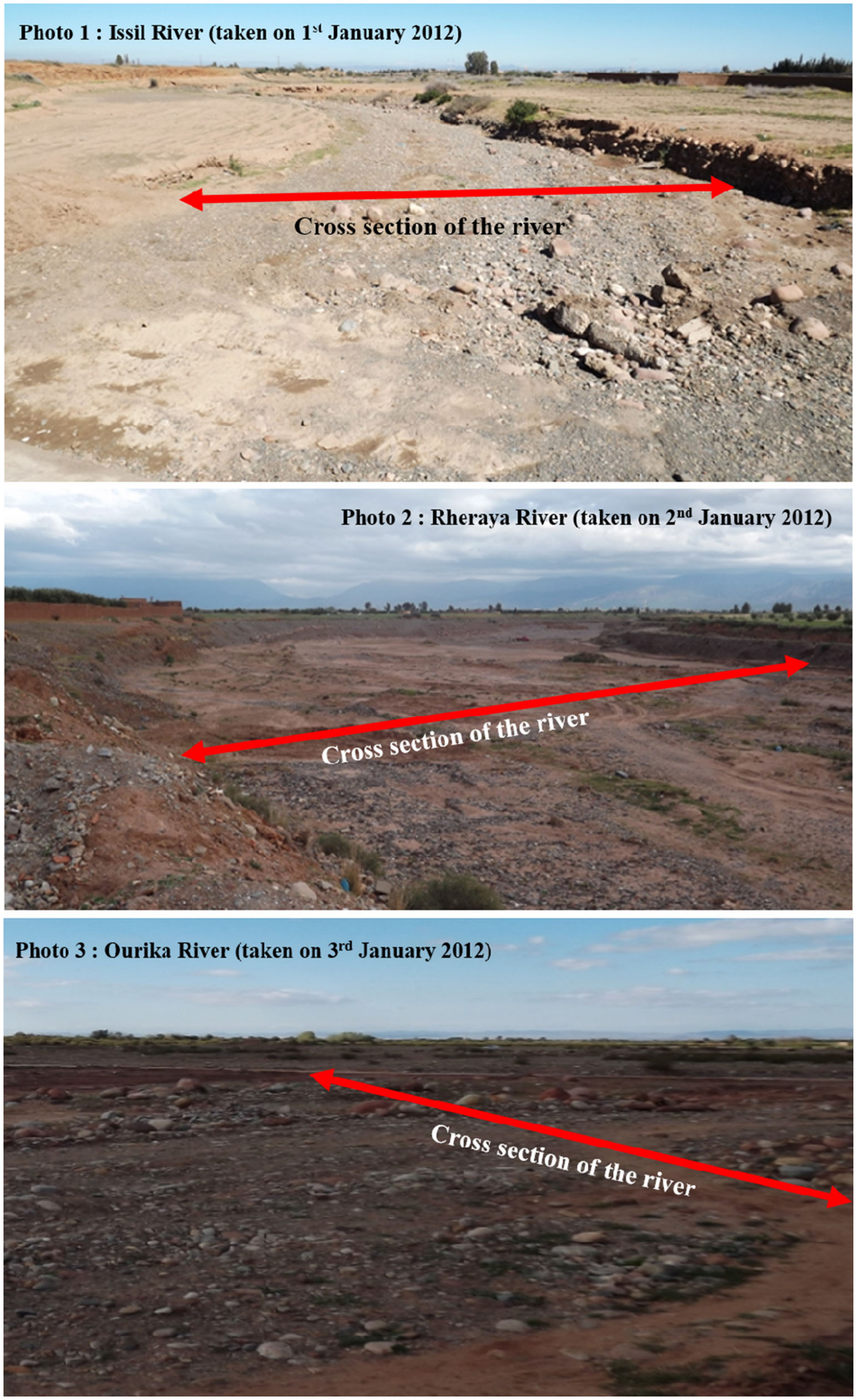

Fig. 2 Photos of rivers: Issil, Rheraya and Ourika

Determination of variables

Determination of annual effective precipitation

The effective daily rainfall was measured for the hydrological cycle 2011–2012 using data from 12 rainfall stations distributed throughout the Haouz Plain (Fig. 1b).

Determination of concentrations

Rainwater was sampled twice, in November and December 2011. Groundwater was sampled from 62 wells evenly distributed over the study area in a piezometric survey carried out in January (the middle of the hydrological year 2011–2012 and a period that coincides with the start of high water levels) (Fig. 1c).

Physical parameters (pH, conductivity and temperature) were measured on-site using a Yokogawa analyzer. Laboratory samples were collected using a rigorous protocol. Two samples were collected at a time: the first was stored in 500-ml polyethylene bottles for the determination of hydrogen carbonate anions and the second was placed in 60-ml tinted glass vials for analysis by ion-exchange chromatography. All the samples were stored in the field in an ice-box and then in a laboratory refrigerator at 3–4 °C until analysis.

The chloride anions were determined by ion-exchange chromatography using a Dionex ICS-1100 column. These analyses were carried out at the Analysis and Characterization Centre at the Faculty of Sciences Semlalia; Cadi Ayyad University (CAC, FSSM, UCA Marrakesh, Morocco).

Spatialization of rainfall and chloride concentrations

Several researchers (Somaratne and Smettem 2014) have confirmed the validity of the CMB method used punctually or in a chemically stable homogeneous aquifer. However, natural aquifers are heterogeneous, with wide chemical variations. Therefore, the method is not considered to be applicable on a regional scale, which questions the usefulness of Eq. (2). However, if the three parameters of Eq. (2) are spatialized, it is then possible to apply the method over large areas. In the recharge map that is created, each pixel represents a single measurement of rainfall and chloride concentration.

The various data points were transformed into isovalue data layers through inverse distance weighting (IDW) interpolation (Lu and Wong 2008). The data layer for the 2011–2012 rainfall distribution was obtained through IDW interpolation of data from the 12 rainfall stations (courtesy of ABHT). The groundwater chloride layer was constructed using data from 62 wells. ArcGIS software (version 10.2) was used to develop the GIS. Eqn (2) was calculated using the spatial analyst tools module based on spatialized variables in raster format data layers.

Results

Precipitation

The data from the 12 stations show an overall average rainfall of about 317 mm/year (Fig. 1). The lowest value was at the Abadla station (173 mm/year) and the maximum was at the Tahanaout station (519 mm/year). In the overall study area, the minimum and maximum values were 281 and 512 mm/year, respectively. The spatial IDW interpolation makes it possible to map the rainfall distribution (Fig. 3). The map in Fig. 3 corresponds to the variable P in Eq. (2).

Chloride concentration (rainwater and groundwater)

Table 1 gives the results obtained for the measurement of the chloride concentrations. The November and December rainwater concentrations are both very close to 11.5 mg L^{-1} (C_p in Eq. 2). The groundwater concentration varies from 14 to 361 mg L^{-1}. The interpolation can be used to produce the concentration distribution map (Fig. 4). The map in Fig. 4 corresponds to the variable C_i in Eq. (2).

Design of the regional map

Following the preparation of the spatialized variables in data layers in raster format, the application of Eq. (2) led to the development of the regional recharge map. Minimum and maximum values were 12 and 100 mm/year,

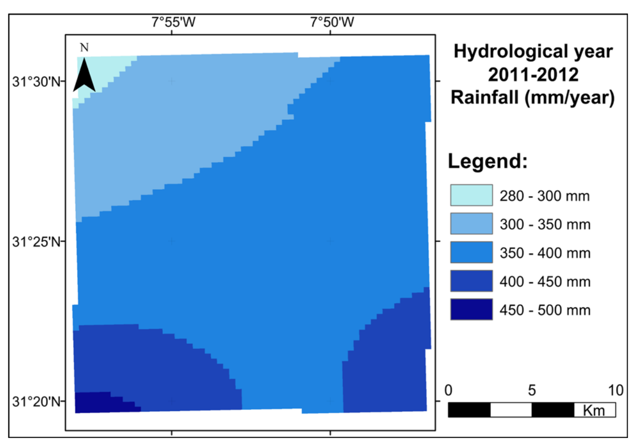

Fig. 3 Rainfall map for the hydrological year 2011–2012 in the Rheraya, Issil and Ourika river sub-basins (in mm/year)

Table 1 Chemical composition of rain and groundwater samples in the study area

No.	Nature	Water type	Date	Longitude[a] (°)	Latitude[a] (°)	Altitude (m)	Cl^- (mg L^{-1})
R01	Rainfall	Rw	11/2011	−7.88400	31.32600	1027	11.5105
R02	Rainfall	Rw	12/2011	−7.84500	31.33200	1009	11.4849
W01	Well	Gw	01/2012	−7.94971	31.38079	880	289.8025
W02	Well	Gw	01/2012	−7.94984	31.33088	980	270.0859
W03	Well	Gw	01/2012	−7.95820	31.36055	906	264.8087
W04	Well	Gw	01/2012	−7.96697	31.37342	904	271.2423
W05	Well	Gw	01/2012	−7.96560	31.38208	851	360.6405
W06	Well	Gw	01/2012	−7.94634	31.39724	841	321.5109
W07	Well	Gw	01/2012	−7.94857	31.40911	855	209.0568
W08	Well	Gw	01/2012	−7.95852	31.40847	796	147.4853
W09	Well	Gw	01/2012	−7.95535	31.41432	805	191.1957
W10	Well	Gw	01/2012	−7.95036	31.42009	810	163.0371
W11	Well	Gw	01/2012	−7.83921	31.42530	734	25.7170
W12	Well	Gw	01/2012	−7.78525	31.36671	906	20.5686
W13	Well	Gw	01/2012	−7.79217	31.37428	882	24.7632
W14	Well	Gw	01/2012	−7.78221	31.37445	871	96.0487
W15	Well	Gw	01/2012	−7.81035	31.38225	875	51.8383
W16	Well	Gw	01/2012	−7.84680	31.37844	852	145.9234
W17	Well	Gw	01/2012	−7.86105	31.38063	836	92.5382
W18	Well	Gw	01/2012	−7.88906	31.37440	882	27.4482
W19	Well	Gw	01/2012	−7.84115	31.38212	837	165.8190
W20	Well	Gw	01/2012	−7.85140	31.39612	786	116.9393
W21	Well	Gw	01/2012	−7.85412	31.40541	798	117.9560
W22	Well	Gw	01/2012	−7.86185	31.42110	750	98.4816
W23	Well	Gw	01/2012	−7.86570	31.42153	732	149.6134
W24	Well	Gw	01/2012	−7.86378	31.42747	788	88.6706
W25	Well	Gw	01/2012	−7.85838	31.43182	722	171.6162
W26	Well	Gw	01/2012	−7.86557	31.46216	677	75.0355
W27	Well	Gw	01/2012	−7.89336	31.48095	665	94.9147
W28	Well	Gw	01/2012	−7.94388	31.51082	622	184.0986
W29	Well	Gw	01/2012	−7.81757	31.37695	872	87.4206
W30	Well	Gw	01/2012	−7.92334	31.48767	646	195.6960
W31	Well	Gw	01/2012	−7.94052	31.47293	656	97.4012
W32	Well	Gw	01/2012	−7.94151	31.46521	673	100.2156
W33	Well	Gw	01/2012	−7.92207	31.46269	670	187.7759
W34	Well	Gw	01/2012	−7.82113	31.41121	772	35.7094
W35	Well	Gw	01/2012	−7.81244	31.41794	764	25.9241
W36	Well	Gw	01/2012	−7.80407	31.42332	761	56.2204
W37	Well	Gw	01/2012	−7.80164	31.41812	777	58.9769
W38	Well	Gw	01/2012	−7.79711	31.41600	784	57.3124
W39	Well	Gw	01/2012	−7.78810	31.41023	787	32.4079
W40	Well	Gw	01/2012	−7.79524	31.41043	792	13.9901
W41	Well	Gw	01/2012	−7.79476	31.40147	817	46.1923
W42	Well	Gw	01/2012	−7.79329	31.38787	847	104.9926
W43	Well	Gw	01/2012	−7.78559	31.38334	852	107.6751
W44	Well	Gw	01/2012	−7.78400	31.37676	868	88.6856
W45	Well	Gw	01/2012	−7.79374	31.37682	874	23.2708
W46	Well	Gw	01/2012	−7.94552	31.51331	600	154.8350

Table 1 continued

No.	Nature	Water type	Date	Longitude[a] (°)	Latitude[a] (°)	Altitude (m)	Cl^- (mg L^{-1})
W47	Well	Gw	01/2012	−7.83488	31.48335	636	81.5666
W48	Well	Gw	01/2012	−7.87715	31.46463	659	47.2504
W49	Well	Gw	01/2012	−7.84076	31.42779	744	18.2450
W50	Well	Gw	01/2012	−7.81193	31.38467	860	38.5559
W51	Well	Gw	01/2012	−7.80113	31.43031	760	71.4605
W52	Well	Gw	01/2012	−7.79545	31.32860	1172	39.3922
W53	Well	Gw	01/2012	−7.78898	31.43396	748	38.4962
W54	Well	Gw	01/2012	−7.80485	31.44003	736	79.0671
W55	Well	Gw	01/2012	−7.80694	31.46126	698	99.9467
W56	Well	Gw	01/2012	−7.80955	31.47558	674	80.0577
W57	Well	Gw	01/2012	−7.81889	31.49285	645	48.1516
W58	Well	Gw	01/2012	−7.93084	31.37957	870	287.6349
W59	Well	Gw	01/2012	−7.90446	31.41916	753	19.0713
W60	Well	Gw	01/2012	−7.90944	31.42594	724	87.4032
W61	Well	Gw	01/2012	−7.91156	31.44152	707	86.4914
W62	Well	Gw	01/2012	−7.91261	31.45505	681	75.8798

Rw rainwater, *Gw* groundwater

[a] Coordinates in decimal degrees (coordinates system: GCS Merchich Degree)

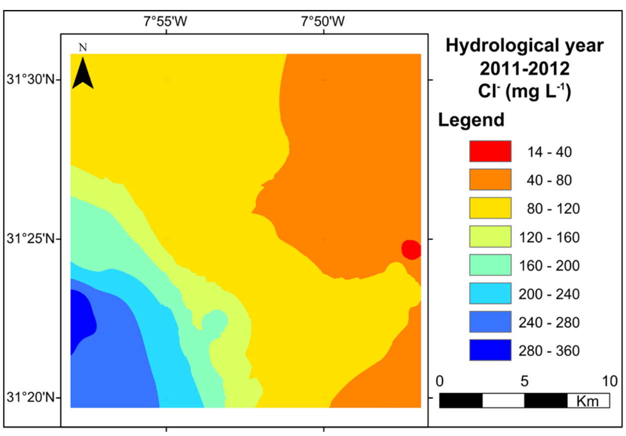

Fig. 4 Distribution of chloride in groundwater (mg L^{-1}) for the hydrological year 2011–2012 in the Rheraya, Issi and Ourika river sub-basins

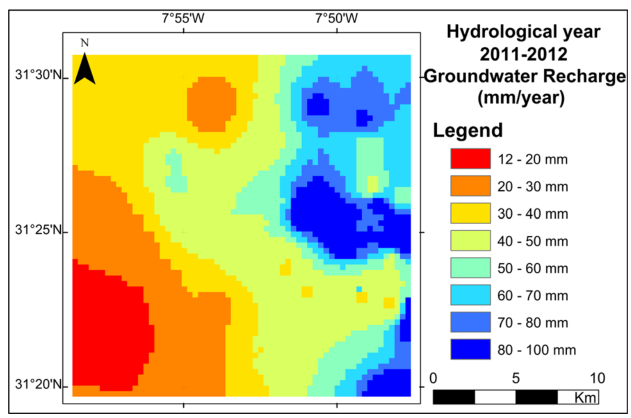

Fig. 5 Spatialized groundwater recharge map for the hydrological year 2011–2012 in the Rheraya, Issil and Ourika river sub-basins (in mm/year)

respectively (Fig. 5), while the percentage of recharge due to rainfall varies from 3 to 25 % (Fig. 6).

Discussion

The choice of study area was based on a number of key criteria. There was no industrial activity, urban discharge, marine intrusion, or volcanic activity, which eliminates any potential contamination from these sources; in addition, there was no agricultural land and therefore no pollution from chemical fertilizers or pesticides. The area was therefore almost entirely free from anthropogenic influences, with the exception of a few, very small, rural populations of shepherds.

The Atlantic coast is at a minimum of 200 km from the sampled wells, which are at an altitude of between 683 and 1358 m. Seawater has no influence.

The climate of the region is semi-arid. Most of this hydrographic system is dry except following exceptional rainfall. Rainfall in the hydrologic year 2011–2012 was not high (<512 mm/year). This intensity is insufficient to create a rise in the water level leading to a concentrated

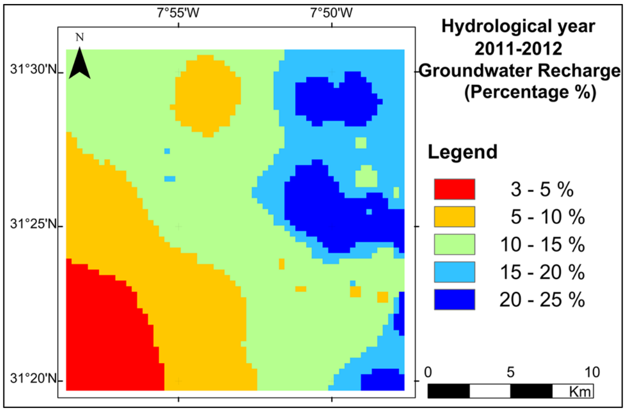

Fig. 6 Spatialized groundwater recharge map for the hydrological year 2011–2012 in the Rheraya, Issil and Ourika river sub-basins (in %)

recharge that would be a second source for the nappe. This observation is confirmed by hydroisohypses lines showing that drainage is generalized throughout the region (Fig. 1c). The latter figure shows that current flows and the drainage axes in the rivers are somewhat parallel. These lines are neither divergent (dismissing the idea of a concentrated recharge at the level of the river), nor convergent (suggesting exfiltration from groundwater). Consequently, there is only diffuse recharge, which is quantized in this study.

97 % of chloride samples are below around 300 mg L^{-1} which is very normal for groundwater in this region. On the other hand, two samples exceed this threshold (321 and 360 mg L^{-1}, respectively). Both wells are located in the extreme southwest of the region, where the context does not favour infiltration; as a result much of the rainwater evaporates and what remains has poor access to the nappe with a higher concentration of chlorides. These conditions concentrate the groundwater in this area and will be discussed later.

According to Wood (2014), the CMB is only effective in estimating the regional recharge rate if the aquifer is both homogeneous and isotropic. However, the addition of a GIS makes it possible to apply the method to a heterogeneous aquifer based on the spatialization of the measured parameters.

Interpolation of the data transforms the point variables into spatial components in raster format as each pixel in the raster has its own value and represents a point recharge rate. It is therefore possible to use Eq. (2). The data from the pixels can be used to create a regional recharge map.

The recharge map created in this way revealed a transition running from east to west. It illustrates very different behaviour in the three basins where the Issil marks a transitional region between the Ourika and Rheraya, and the recharge rates are between 40 and 50 mm/year (10–15 %). The Rheraya basin, located in the east, has very low recharge rates of <20 mm/year (<5 %) in the south, increasing to 30–40 mm/year (10–15 %) towards the north. The Ourika basin sees intense infiltration of 40–100 mm/year (10–25 %); most of its watershed has a recharge rate >80 mm/year (>20 %).

The spatial distribution of the recharge rate is the result of the effect of several different parameters, including the lithology, slope gradient, rock fracturing, land use and soil type. The lithology directly affects the permeability of the rocks and therefore the rate of infiltration. The geology varies in the three basins (Dauteloup 1958; Piqué et al. 2007). The Rheraya basin has a low permeability compared with the rest of the region and consists of continental Permo–Triassic sandstone formations, marly limestone continental facies of Senonian age, and multiple ferromagnesian rocky outcrops that are almost impermeable. The part of the Ourika basin in the study area is composed of middle Eocene and continental Miocene formations dominated by early-to-middle Quaternary and modern formations, all highly permeable. To the north, up to 80 m of breccia conglomerate promotes infiltration. In addition, the very friable brown soils, which cover almost the entire basin, promote recharge. Apart from its lithological and soil characteristics, lineaments correspond to fault zones and fractures with secondary porosity and high permeability. These lineaments are very important as they promote the passage of water towards the aquifer. Finally, the existence of NE–SW-oriented fractures downstream of the Ourika basin favour recharge as they are perpendicular to the flow of rainwater running from the High Atlas to the adjacent sub-basins.

Conclusion

The development of a recharge rate map for the hydrological year 2011–2012 for the three basins of the Central Haouz Plain revealed three different zones: a zone with very low potential (<20 mm/year); a low recharge zone (30–50 mm/year); and a medium recharge zone (50–100 mm/year). This map of recharge rates over an area of 200 km^2 is a very important tool for the validation of models based on empirical methods. The models can be applied to large areas such as the Haouz Plain (6200 km^2), which has an average width of about 40 km and is oriented N–S with an average length of 150 km in an E–W direction. It remains difficult to use the CMB method over such a large area as a result of the influence of human activity on chloride levels and, in this situation, empirical methods must be used. However, these empirical models must be validated as they provide methods for decision support. This study shows that validation is possible using a direct method that combines prospecting and field surveys supplemented by chemical analyses.

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