ATLAS of Isotope Hydrology

MOROCCO

Centre National de l'Energie, des Sciences et des Techniques Nucléaires Maroc

IAEA
International Atomic Energy Agency
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Secrétariat d'Etat auprès du Ministère de l'Energie, des Mines, de l'Eau et de l'Environnement chargé de l'Eau et de l'Environnement Maroc

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Printed by the IAEA in Austria
December 2010
STI/PUB/1480

IAEA Library Cataloguing in Publication Data

Atlas of isotope hydrology — Morocco. — Vienna:
International Atomic Energy Agency, 2010.
p. ; 30 cm.
STI/PUB/1480
ISBN 978-92-0-111010-7
Includes bibliographical references.

1. Groundwater – Atlases – Morocco.
2. Radioactive tracers in hydrogeology – Maps – Morocco. I. International Atomic Energy Agency.

IAEAL 10-00656

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CONTENTS

FOREWORD

The sustainability of groundwater resources for drinking water supplies, agriculture, and industry is a prime concern in countries dominated by arid and semi-arid climates such as Morocco. The growing demand for groundwater coupled with impacts from land use and climate change make sustainability an even more important water management goal. In order to make sound decisions about water use and protection of water quality, water managers and policy makers must have a sound understanding of such factors as the location and amount of groundwater recharge and groundwater ages. Isotope methods can be essential for understanding how groundwater systems work in large dry land basins and yield critical insights that standard hydrological or geochemical methods cannot provide. Stable isotopes of the water molecule along with tritium and carbon-14 are effective tracers of the hydrological cycle and have proven to be effective in helping Morocco better understand its water resources and manage them more efficiently.

For many years the Morocco State Secretary in charge of Water and Environment, the Morocco National Centre of Nuclear Energy, Sciences and Technology (CNESTEN), and the IAEA have worked together to characterize groundwater basins in Morocco using isotope and nuclear methods. Ten different groundwater investigation projects have been conducted using IAEA and/or Ministry support, and this Atlas summarizes the data and findings of these basin investigations. The Atlas demonstrates how isotope compilations can be used as a national and international resource for sustainable groundwater management, and should help promote increased utilization of isotope methods in other countries.

BACKGROUND AND PURPOSE

Morocco is characterized by a semi-arid to arid climate, excluding a humid zone in the North. This climatic constraint requires the application of new technologies to supplement conventional hydrological methods, in order to improve water resources assessment and management in Morocco. Among these technologies, isotope techniques, which are based on the natural tracing of water and its dissolved components, have not been utilized to the extent that they should. This Atlas is intended to promote increased use of these techniques. The Atlas describes the use of isotopic and related hydrological tracers in Morocco and demonstrates their effectiveness for obtaining essential hydrological information. Sometimes, such information is unobtainable by other techniques.

Isotope tracers can be divided into two great groups which correspond respectively to stable isotopes (^{18}O, ^{2}H, ^{13}C, ^{15}N, ^{34}S, etc.) and radioactive isotopes (^{3}H, ^{14}C, ^{36}Cl, etc.). The first group is generally used to determine the origin of water; to estimate mixing proportions of surface water and groundwater or between different aquifers; to identify recharge zones; or to understand the origin of dissolved salts. The second group is especially used to determine 'the age of water' which provides unique information about aquifer recharge, replenishment rates and groundwater dynamics.

This Atlas is the result of a collaborative effort by the State Secretary in charge of Water and Environment of Morocco (SEEE), the National Centre of Nuclear Energy, Sciences and Technology (CNESTEN) and the International Atomic Energy Agency (IAEA). This is a compilation of studies conducted by the SEEE and the CNESTEN [1–5] and those in collaboration between SEEE, CNESTEN and the IAEA through the implementation of technical cooperation projects and coordinated research projects [6–13]. Requests for information on the Morocco isotope database should be referred to the Head of Water and Climate Unit of CNESTEN.

The Atlas and its associated database include:

(1) Isotope and related meteorological information collected in seven meteorological stations in Morocco, where deuterium, oxygen-18 and tritium have been measured on a monthly or daily basis;

(2) Isotope data summaries and plots from surface and groundwater samples collected from ten studies representing eight different basins in Morocco, where basic hydrochemistry, tritium, carbon-14, carbon-13, deuterium and oxygen-18 were determined;

(3) Interpolation maps of the spatial distribution of groundwater isotopes for each project/basin (based on well, borehole, and spring sampling). Such maps are useful for understanding groundwater characteristics such as flow directions and the influences of different recharge areas in the basin.

The major objectives of this Atlas are:

(1) Compilation of existing hydrogeochemical data into a national isotope database;

(2) Provision of short syntheses describing key interpretations and conclusions regarding the hydrology of certain aquifer units in Morocco based on isotope results;

(3) Development of isotope maps using geostatistical methods and GIS tools to visualize the spatial variability of groundwater isotopes in studied basins across Morocco;

(4) Provision of a valuable contribution for national and international scientific and practical applications involving the water cycle, climatology, and ecology.

The technical officers responsible for the preparation of this Atlas were: H. Marah of the CNESTEN and N. Zine of the Morocco Ministry of Energy, Water and Environment, and B. Newman of the IAEA Division of Physical and Chemical Sciences. A list of contributing authors is presented on page 67.

STRUCTURE OF THE ATLAS

This Atlas presents the main hydrological results obtained in ten projects/basins in which isotope hydrology studies have been carried out. Each project begins with a title page for the project area and/or basin. The summary presented for each study area contains the following elements:

The first element shows a physiographic map of the area, as described below, which includes sampling locations and water types. Nearby cities, towns and settlements, and other geographical features are also shown.

The second element is a project background section that presents the general geographical and climate conditions of the area as well as the particular objectives of the isotope hydrology study.

The third element is a table summarizing the isotope data. For each water and isotope type, the table includes the number of samples analysed, the mean isotope value and its standard deviation. If precipitation data were collected as part of the study, then the mean and standard deviations of the stable isotope results are also included. Climatic and isotope diagrams showing the annual distribution of amount of precipitation mean air temperature and oxygen-18 contents in precipitation are also included.

The fourth element is a scatter plot showing oxygen-18 versus deuterium of samples analysed for the project. Different water types are indicated in the map legend and in the summary data table. The Global Meteoric Water Line, GMWL ($\delta^{2}H=8\cdot\delta^{18}O+10$), is included in the plot for reference.

The fifth element includes interpolated maps of the isotope values for groundwater in the basin. The maps were generated by using a tension spline method of the available groundwater isotope data and show the general trends within the project area. Caution should be used when interpreting these maps because some have been generated using combined data from multi-level aquifer systems and/or springs. Combined data interpolations were generated because the spacial distribution of samples did not permit interpolations of individual aquifers.

The sixth element includes a brief summary of the results obtained for the project and highlights key isotope results and how they relate to the project objectives.

ELEMENTS OF THE PROJECT MAPS

Maps of the study areas were prepared using the 'traditional' physiographical representation with altitude information displayed using blended hypsometric tints (Fig. 2), bearing in mind that altitude is usually a key factor controlling the isotope content of precipitation and thus the oxygen-18 and deuterium contents of surface water and groundwater.

The choice of hypsometric colours is uniform throughout the whole Atlas and largely follows established colour schemes [14] (Fig. 1). Green colours are used to represent low lying areas while yellow, orange and brown tones indicate middle to higher altitudes. Selected index contour lines are meant to assist the reader in identifying elevation. Several peak elevation features provide information on maximum elevation within the study area. Finally, the underlying shaded relief aims to increase the plasticity of visualization. In addition to terrain, the project maps display two important factors related to water resources:

The surface hydrography network is represented by selected rivers and streams, as well as by standing water bodies: perennial lakes and reservoirs are included alongside ephemeral water bodies and, in some areas, wetlands and frequently inundated floodplains.

Finally, project maps reveal the location of sampling sites (for which summary statistics and standard isotope plots are given in the next plate).

ELEMENTS OF THE ISOTOPE MAPS

Presenting the spatial distribution of the isotopic content of groundwater resources is a key issue in making isotopic hydrology understandable to the general public. This can be achieved best by presenting this information in a continuous form such as in interpolated isotope maps.

The basic isotope information itself is limited to point data due to the fact that sampling is commonly conducted via individual wells and springs. Hence, the particular challenge in mapping is to apply geostatistical tools to elaborate the spatial extension of the ranges of isotope values based upon the single data points.

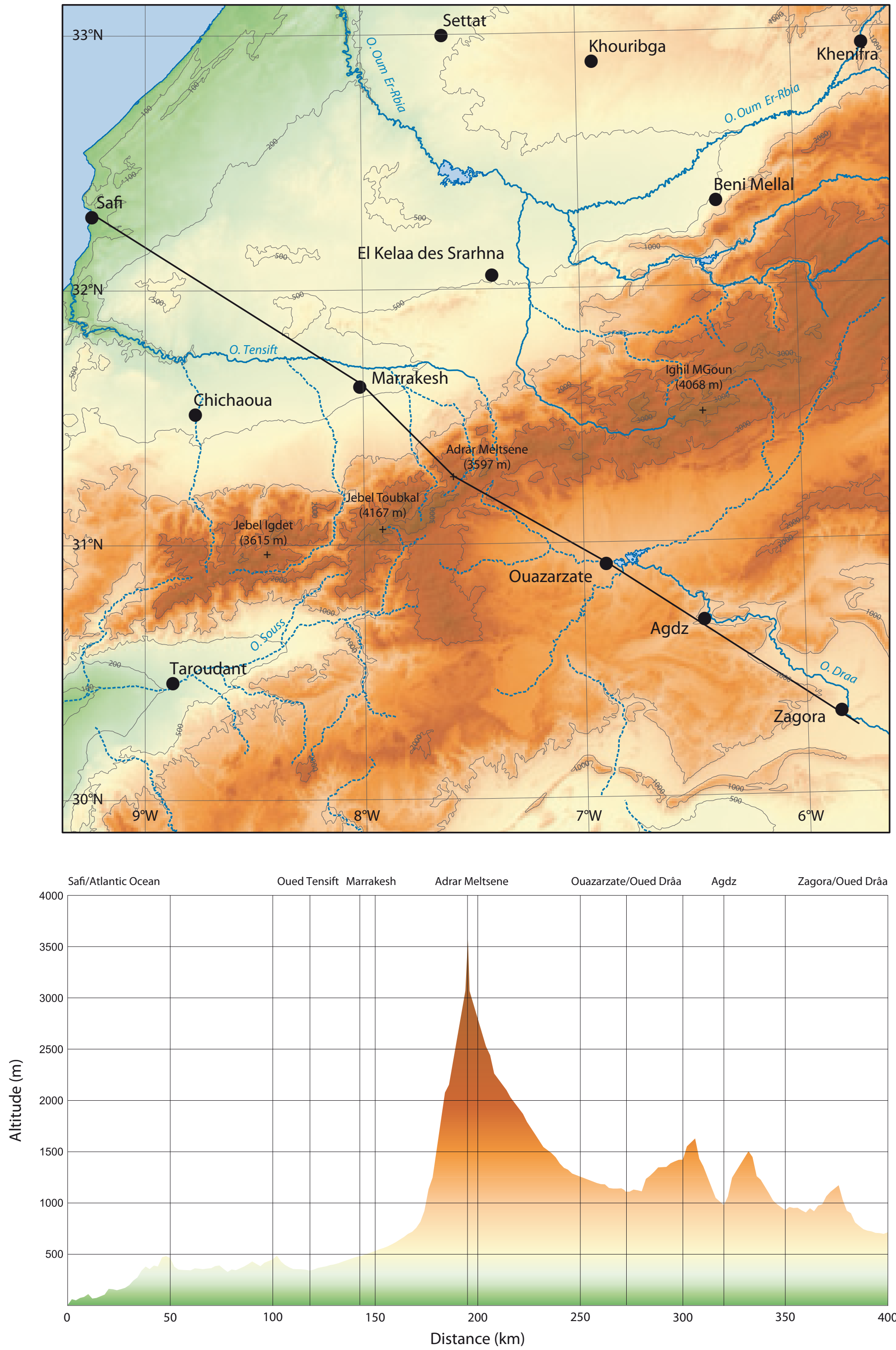

FIGURE 1. Altitude profile from the Atlantic Coast to the Atlas Mountains showing the physiographical colour scheme and location map of the profile.

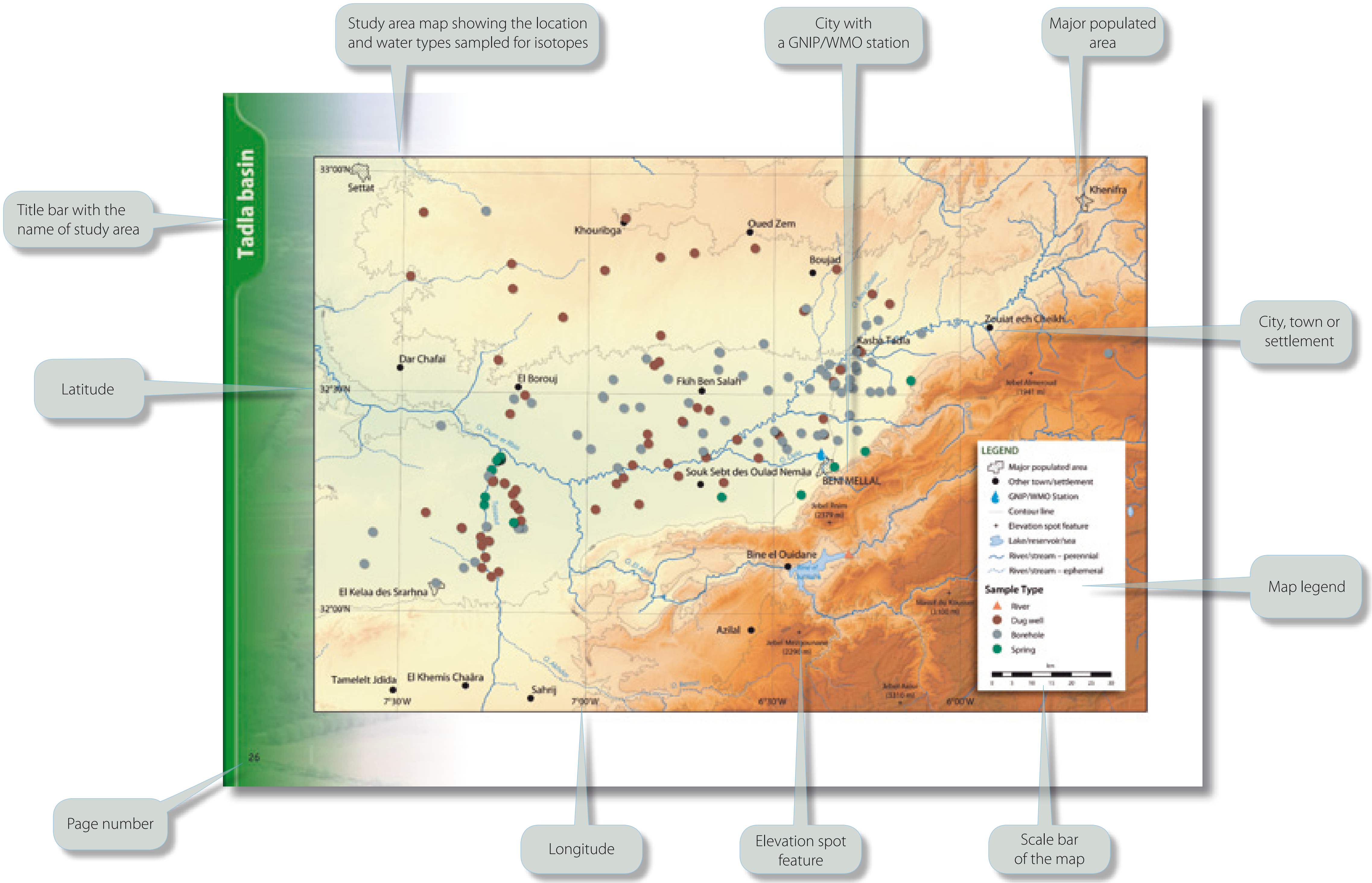

FIGURE 2. Elements of the project page.

Whereas kriging has often been used in the hydrosciences [15, 16], this Atlas experimentally uses regularized tension splines [17, 18]. A spline is a curve that determines its curvature properties by itself based upon the sampling points' values and some pre-set rigidity parameters. This approach excels through its simple parameterization: the most important parameters are the tension (as a measure of rigidity; imagine the behaviour of a steel plate versus that of a rubber membrane) and a smoothing number. Although not used here, a θ (theta) parameter can be applied to account for anisotropy. The tension and smoothing factors of the splines used for each interpolation map, as well as the root mean square error (RMSE), which indicates the goodness of fit between the modelled and the measured values, are shown for each interpolation map.

To generate the isotope maps, interpolation results were rendered into classes as shown in each isotope map:

- Class width for $\delta^{18}O$ is 0.5‰; the colour ramp ranges from blue (lower isotope values) to red (higher isotope values).
- Class width for tritium (^{3}H) largely follows an exponential scale to reflect the differences in present-day low tritium contents versus higher tritium contents during the 1960s and 1970s, shortly after the bomb peak. The scale is coloured from green (young waters) to red (old waters).
- For carbon-14 (^{14}C), a class width of 10 pMC was chosen, ranging from less than 15 pMC (old waters) to 85 pMC (young waters). Again, a green to red colour scale is applied.

Finally, a distance criterion was applied to the data to avoid interpolation in data-scarce areas and to avoid the impression of existence of continuous isotope data where no actual data is available to support such visualization.

ANALYTICAL METHODS

The basic methods of sampling and analyses are described below. The reader is referred to Ref. [19] for more specific information on isotope sampling and analysis. Water samples were collected from surface water, groundwater, springs and precipitation in various parts of Morocco and analysed for their chemical and isotopic compositions. Temperature, pH, conductivity and total alkalinity were measured in the field. Chemical analyses of major elements and isotope analyses for ^{14}C, ^{13}C, ^{3}H, ^{18}O and ^{2}H were measured at the Water and Climate Unit, CNESTEN and the IAEA Isotope Hydrology Laboratory in Vienna.

In order to carry out these missions CNESTEN has installed, with technical assistance from the IAEA, an Isotope Hydrology Laboratory equipped with the following analytical instruments:

- Mass spectrometer for the determination of stable isotopic ratios of H, C, N and O in water, carbonate and organic matter;
- Water equilibration system for the measurement of ^{18}O and ^{2}H in water;
- Gas chromatograph system attached to an element analyser CarloErba 'NC2500' and a mass spectrometer for measurement of isotopic ratios of ^{13}C, ^{18}O and ^{15}N in organic matter;
- Electrolytic enrichment lines for ^{3}H (40 cells of 500 mL);
- Benzene synthesis line for radiocarbon dating;
- Liquid scintillation counter (LSC, Quantulus 1220);
- Ion chromatograph Dionex DX-120 with Conductivity Detector and AS40 Automatic Sampler.

Radiocarbon analysis

For hydrogeological applications, radiocarbon or carbon-14 activity is expressed as a percentage of modern carbon (pMC). The activity of modern carbon is 95% of the specific activity of the carbon of NBS oxalic acid supplied by the US National Institute of Standards and Technology (NIST). One hundred per cent modern carbon (pMC) corresponds to a carbon-14 specific activity of 13.56 ± 0.07 disintegrations per minute per gram of carbon. Measurement of carbon-14 activity is generally carried out by decay counting using liquid scintillation spectrometry or, more recently, by measurement of atoms using accelerator mass spectrometry (AMS) methods.

The benzene synthesis sample preparation approach and liquid scintillation counting (LSC) were used to determine the amount of modern carbon in groundwater samples. Carbon containing material precipitated from groundwater in the field is converted in the laboratory first into carbon dioxide gas, and then into high purity benzene through a benzene synthesis process. The benzene is measured for ^{14}C activity using LSC, and the result is compared to NIST standards. Minimum detectable activity (MDA) in the CNESTEN laboratory corresponds to an age of about 43 000 years.

Tritium analysis

Tritium concentration is expressed in tritium units (TU). One TU is defined as one atom of ^{3}H per 10^{18} atoms of ^{1}H, which is equivalent to an activity of 0.11919 Bq or 3.193 pCi per litre of water. The half-life of tritium is 12.32 years (4500 days ± 8 days). Due to this relatively short half-life, tritium has been used in hydrogeology as an excellent environmental tracer to identify modern recharge in aquifer systems. Tritium content is measured by counting its radio active decay, using liquid scintillation spectrometers. Due to very low levels of tritium in natural waters, electrolytic enrichment of tritium is done before counting the radioactive decay.

The analytical uncertainty for tritium analysis is usually reported with each measurement. Current analytical methods involving electrolytic enrichment followed by liquid scintillation counting provide uncertainty values of the order of ±0.3 TU for tritium levels lower than 5 TU.

Minimum detectable concentration (MDC) in our laboratory is less than 0.3 TU.

Stable isotope analysis

Oxygen-18 and deuterium contents in water samples are expressed as δ values ($\delta^{18}O$, $\delta^{2}H$), which are permil (‰) deviations from an internationally accepted standard. The δ unit is defined as:

$$\delta(‰) = \frac{R_{sample} - R_{VSMOW}}{R_{VSMOW}} \times 10^3$$

where R is the isotope ratio $^{2}H/^{1}H$ or $^{18}O/^{16}O$.

In the case of water, the internationally accepted standard is called Vienna Standard Mean Ocean Water (VSMOW). The ^{2}H and ^{18}O isotope ratios are determined by mass spectrometric methods.

To measure ^{18}O and ^{2}H in water, samples were prepared by equilibration with gaseous hydrogen (for $\delta^{2}H$) and carbon dioxide (for $\delta^{18}O$) and run on an automated dual inlet isotope ratio mass spectrometer system. Precision in the CNESTEN laboratory is better than ±0.1‰ and ±1.5‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively.

To measure the $\delta^{13}C$ of dissolved inorganic carbon (DIC), samples were prepared by precipitation with strontium chloride solution, followed by filtration and purification, and finally by acidification of the strontium carbonate. The resulting CO_2 was analysed using an automated dual inlet isotope ratio analysis system. Results are expressed as permil (‰) deviations from Vienna Pee Dee Belemnite (VPDB) standard. Precision of the CNESTEN laboratory is approximately ± 0.1‰.

Chemical analyses

Laboratory chemical analyses were performed using ion chromatography with conductivity detection. Water samples were analysed for cations (lithium, sodium, ammonium, potassium, magnesium and calcium) and anions (fluoride, acetate, chloride, nitrite, bromide, nitrate, phosphate and sulphate). Precision of the CNESTEN laboratory is better than 5%.

STABLE ISOTOPE COMPOSITION OF PRECIPITATION OVER MOROCCO

The basis for the application of oxygen-18, deuterium and tritium in hydrology is the analysis of the spatial and temporal variations of the concentration of these isotopes in the different water bodies and its comparison with the isotope signal of precipitation as the ultimate source of recharge to aquifers, rivers, lakes, etc. The isotope signal of present-day precipitation over Morocco can be estimated through the evaluation of available oxygen-18, deuterium and tritium analyses carried out on precipitation samples collected in a number of monitoring stations across the country.

Precipitation samples for isotope analyses have been systematically collected in seven meteorological stations as part of studies conducted (national projects, CRPs or technical cooperation) [1–13] and the operation of a monitoring station included in the Global Network of Isotopes in Precipitation (GNIP). Table 1 presents the geographical coordinates, the sampling period and the mean values of certain climatic parameters, together with the arithmetic and amount-weighted mean values for oxygen-18 and deuterium for selected stations used to collect precipitation samples on monthly basis. Table 2 presents a similar statistical summary for selected meteorological stations in which samples for isotope analyses were collected on an event basis [10, 13, 19]. The estimated characteristic isotope values for the two stations listed in both tables are similar.

The available isotope information illustrates the range of isotope variability across Morocco, as a result of the influence of air masses originating over the North Atlantic and the Western Mediterranean areas and the altitude effect resulting in more isotopically depleted rains in stations located at higher elevation.

The seasonal distribution of precipitation in four monitoring stations (Fes Sais, Beni Mellal, Bab Bou Idir and Rabat–CNESTEN) is similar, with the rainy period concentrated in the winter months. Seasonal distribution of isotope contents in precipitation shows the expected isotopically more negative values in the winter months as shown in the project pages for the Fes Sais station.

The isotope contents in precipitation in four Moroccan stations stations (Beni Mellal, Fes Sais, Bab Bou Idir and Rabat–CNESTEN) have been included in GNIP and are available on-line, as well as the remaining stations included in the GNIP database, through the IAEA’s web site: www.iaea.org/water.

TABLE 1. ISOTOPE CONTENTS OF PRECIPITATION IN SELECTED STATIONS COLLECTING MONTHLY COMPOSITE SAMPLES

Station name	Station index	Latitude	Longitude	Altitude (m)	Sampling period	Mean annual temp (ºC)	Annual precipitation (mm)	Oxygen–18 (‰)		Deuterium (‰)		Deuterium–excess (‰)	
								Average	Weighted mean	Average	Weighted mean	Average	Weighted mean
BAB BOU IDIR	6012501	34º13´ N	04º00´ W	1500	2001–2002	17.6	801	−7.33	−7.77	−37.3	−42.2	21.3	20.0
BENI MELLAL	6019100	32º22´ N	06º24´ W	468	2001–2002	17.6	720	−5.50	−5.23	−30.4	−29.0	13.5	12.8
FES SAIS	6014100	33º58´ N	04º59´ W	571	1994–2004	16.6	691	−4.31	−5.25	−24.0	−29.8	10.5	12.2
RABAT–CNESTEN	6013501	34º46´ N	06º46´ W	75	2001–2002	17.2	556	−4.08	−4.71	−19.5	−22.1	13.1	15.5

TABLE 2. ISOTOPE CONTENTS OF PRECIPITATION IN SELECTED STATIONS COLLECTING EVENT-BASED RAIN SAMPLES

Station name	Station index	Latitude	Longitude	Altitude (m)	Sampling period		Oxygen-18 (‰)			Deuterium (‰)			Deuterium-excess (‰)		
							n	Av.	W. m.	n	Av.	W. m.	n	Av.	W. m.
BENI MELLAL	6019100	32º22´ N	06º24´ W	468	2000-10-12	2003-04-16	63	−5.08	−5.58	63	−24.9	−27.9	63	15.7	16.7
RABAT-CNESTEN	6013501	34º46´ N	06º46´ W	75	2000-11-15	2003-04-19	98	−4.02	−4.81	98	−19.3	−24.8	98	12.9	13.8

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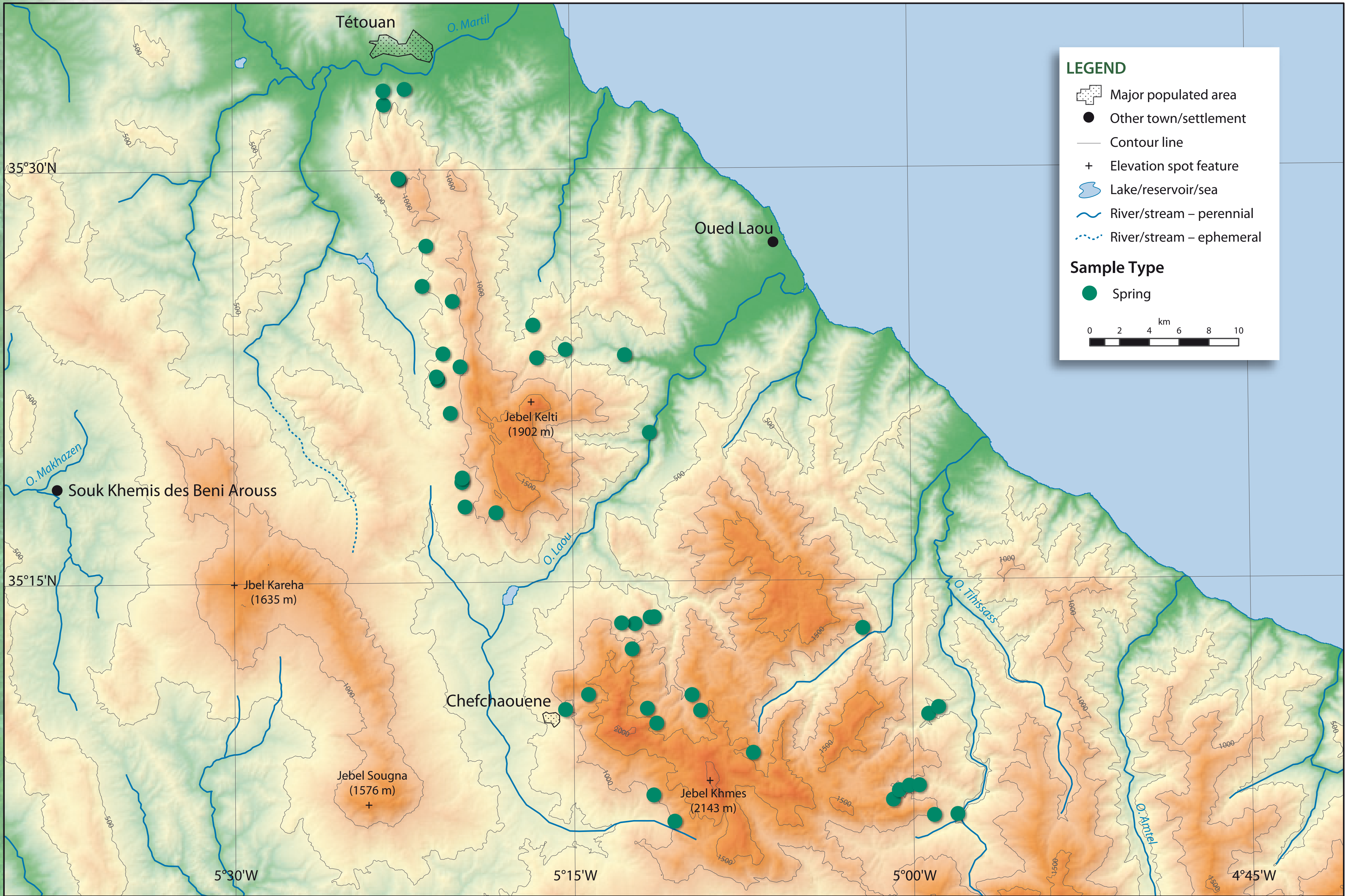
Rif limestone chain


Tétouan
O. Martil
35°30'N
Oued Laou
Jebel Kelti
(1902 m)
O. Makhazen
Souk Khemis des Beni Arouss
O. Laou
35°15'N
Jbel Kareha
(1635 m)
O. Tihissass
Chefchaouene
Jebel Sougna
(1576 m)
Jebel Khmes
(2143 m)
O. Amtel
5°30'W
5°15'W
5°00'W
4°45'W
LEGEND
Major populated area
Other town/settlement
Contour line
Elevation spot feature
Lake/reservoir/sea
River/stream – perennial
River/stream – ephemeral
Sample Type
Spring
km
0 2 4 6 8 10

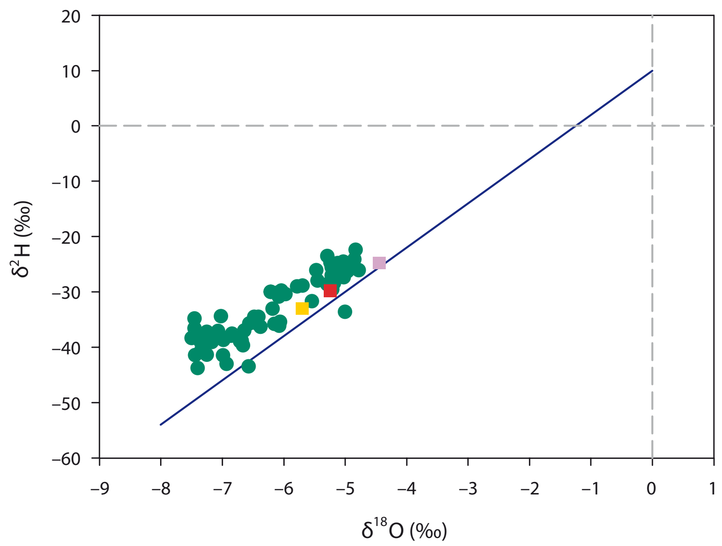
Study area: Rif limestone chain/Loukkos basin
Sampling period: 2003

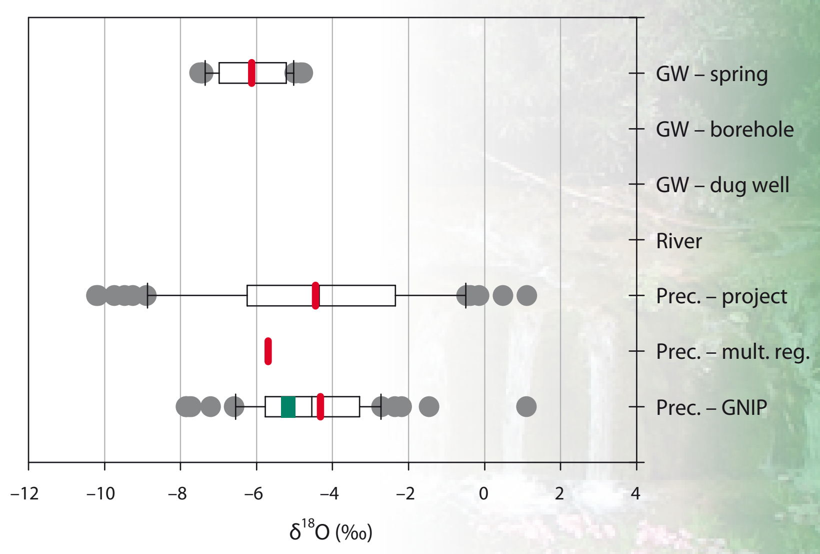
Background

The Rif limestone chain and Loukkos basin are located at the northern end of Morocco. The basin has an area of about 1240 km² and is bounded by Sebta in the north and Al Hoceima in the east. The climate is influenced by both the Atlantic Ocean and the Mediterranean sea. It is the principal limestone chain in Morocco.

Sixty-seven springs were sampled in five areas; El Haouz (average altitude 400 m), Jebel Dersa (average altitude 350 m), Wadi Lao (average altitude 800 m), West Jbel Lakrâa (average altitude of 1300 m) and East Jbel Lakrâa (average altitude of 1100 m).

The objective of this work was to calculate the residence time of water in the springs and to establish an oxygen-18 altitude gradient using stable isotope data. These results were used to delimit the spring recharge areas. The results contributed to the improvement of water management in the Rif area.





Precipitation		$\delta^{18}O$ (‰) n	Median	Mean ± St. dev.	δ^2H (‰) n	Median	Mean ± St. dev.	Tritium (TU) n	Mean ± St. dev.	Annual prec. (mm)	Temperature (°C)
GNIP station FES SAIS	■ (red)	60	−4.55	−5.24	60	−23.3	−29.8			457	17.4
Interpolation – multiple reg.	■ (yellow)			−5.70			−33.0				
Project	■ (pink)	60	−4.35	−4.45 ± 2.8	60	−20.8	−24.8 ± 18.4				

Surface waters		$\delta^{18}O$ n	Median	Mean ± St. dev.	δ^2H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.
Lake/reservoir/sea	▲								
River	▲								

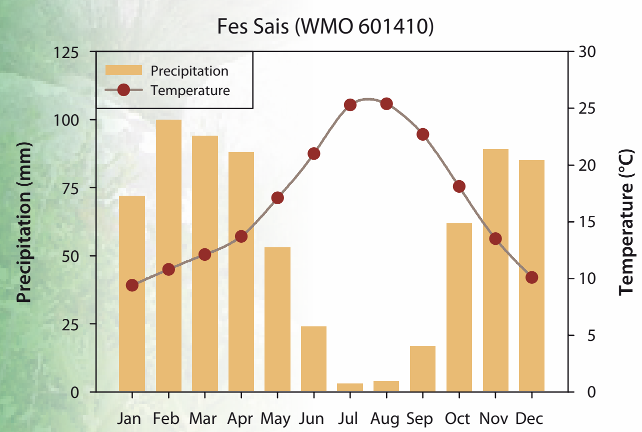
Groundwaters		$\delta^{18}O$ n	Median	Mean ± St. dev.	δ^2H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.	^{14}C (pMC) n	Mean ± St. dev.	$\delta^{13}C$ (‰) n	Mean ± St. dev.
GW–Borehole	●												
GW–Dug well	●												
GW–Spring	●	67	−6.15	−6.13 ± 0.9	67	−33.6	−32.7 ± 6.0	29	3.8 ± 1.0	9	90.7 ± 5.6	9	−13.4 ± 1.6

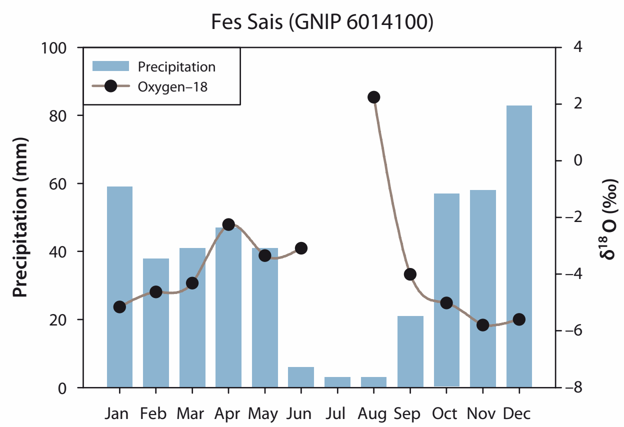
Results

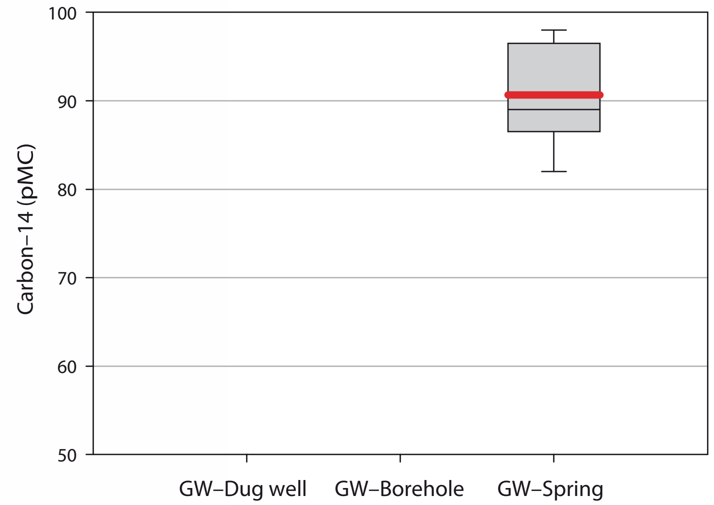
In this study it was important to establish the elevation of recharge for establishing protection zones for springs in the Loukkos basin. Using correlations of stable isotopes based on the well known isotope–altitude gradient, recharge areas were identified. This approach resulted in a $\delta^{18}O$ gradient of −0.26 ‰/100 m, which is similar to those established by other investigators in the south of Europe. These results demonstrate that such an approach can be applied in other regions. The correlation model was used to calculate the mean altitude of the recharge areas for 67 springs. Example results are shown in the table below. The high deuterium excess of many of the spring values (see $\delta^{18}O$ versus $\delta^{2}H$ plot) is likely related to atmospheric precipitation sources from the Mediterranean. Using tritium, the residence times of water in the springs were estimated to be between 5 and 10 years. The oxygen isotope interpolation (A) shows an area of more negative isotope composition in the south central part of the study area. This zone is probably related to higher elevation of the recharge relative to the more northern part of the study area.

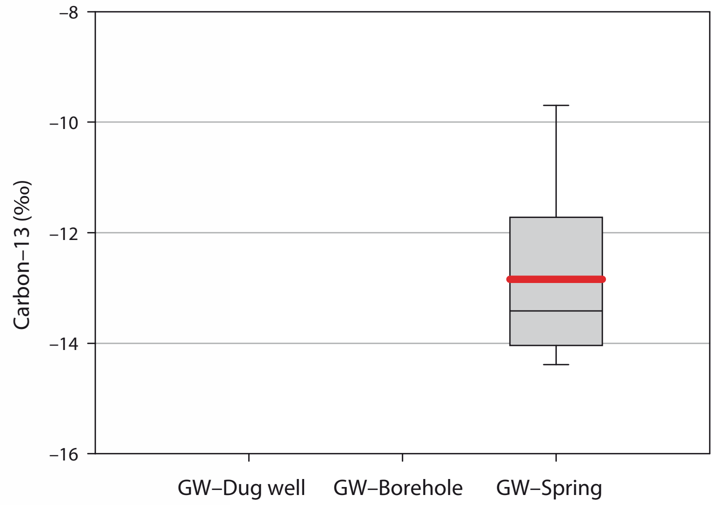
Mean, minimum, and maximum recharge altitudes for different springs in the Rif limestone chain (all values in m).

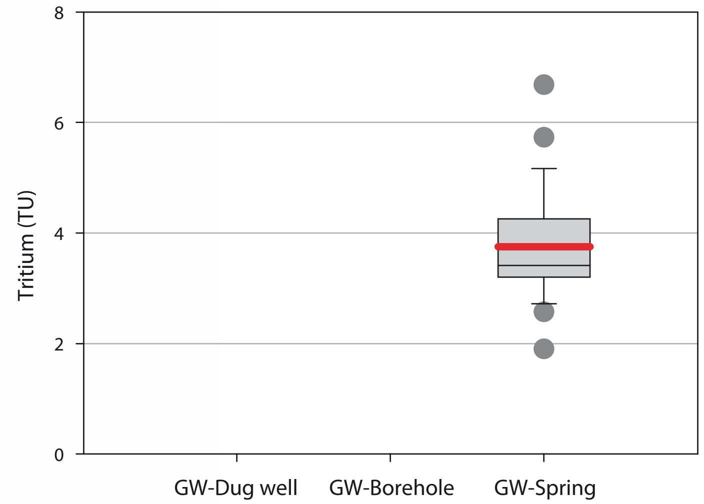
Identification	Mean recharge altitude	Minimum recharge altitude	Maximum recharge altitude
Jble Dersa	367	254	492
Ouest El Haouz	412	235	862
Nord Oued lao	731	319	1035
Ouest Jbel LaKraa	1022	331	1262
Est Jbel Lakraa	1146	923	1281

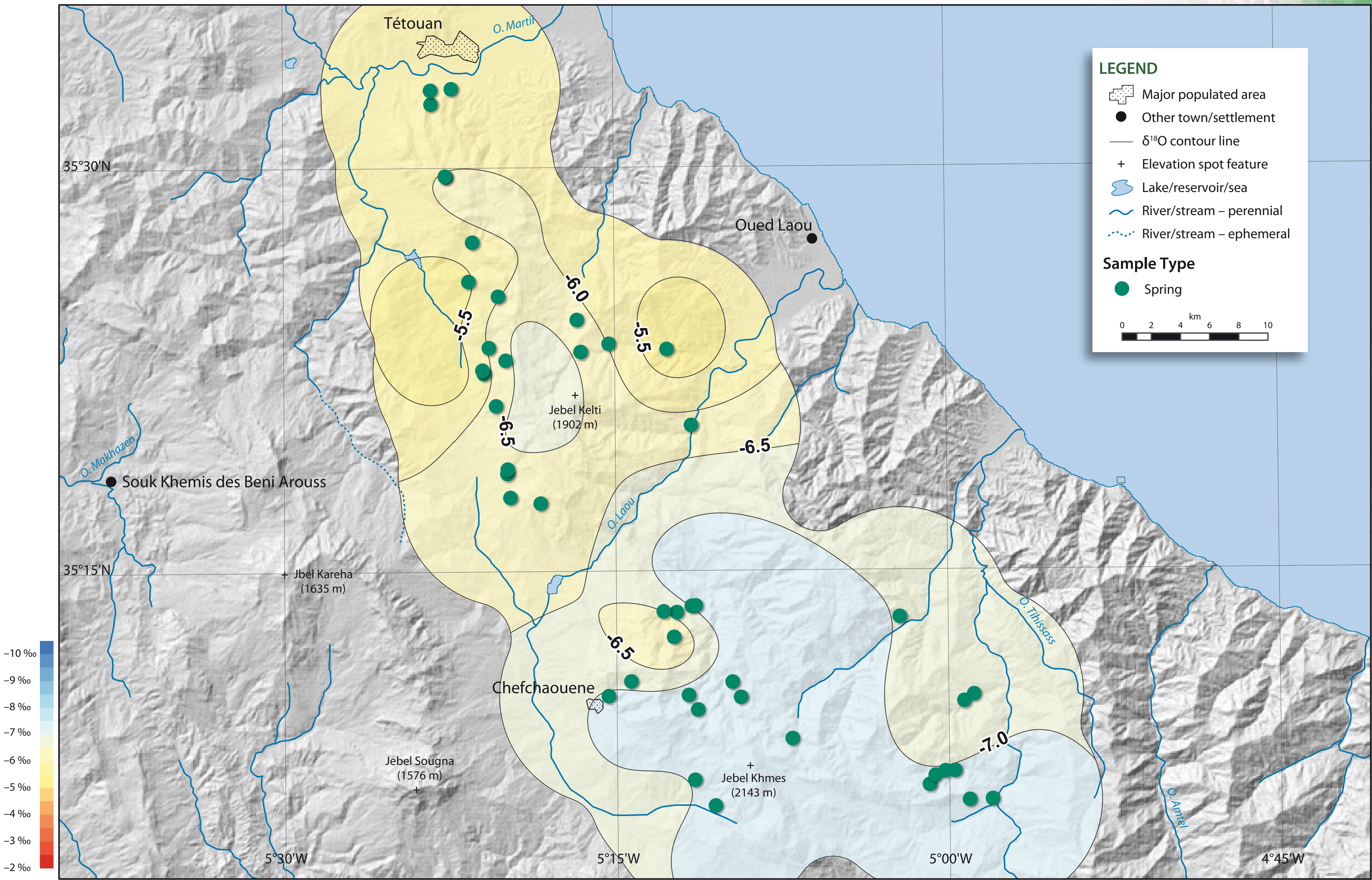








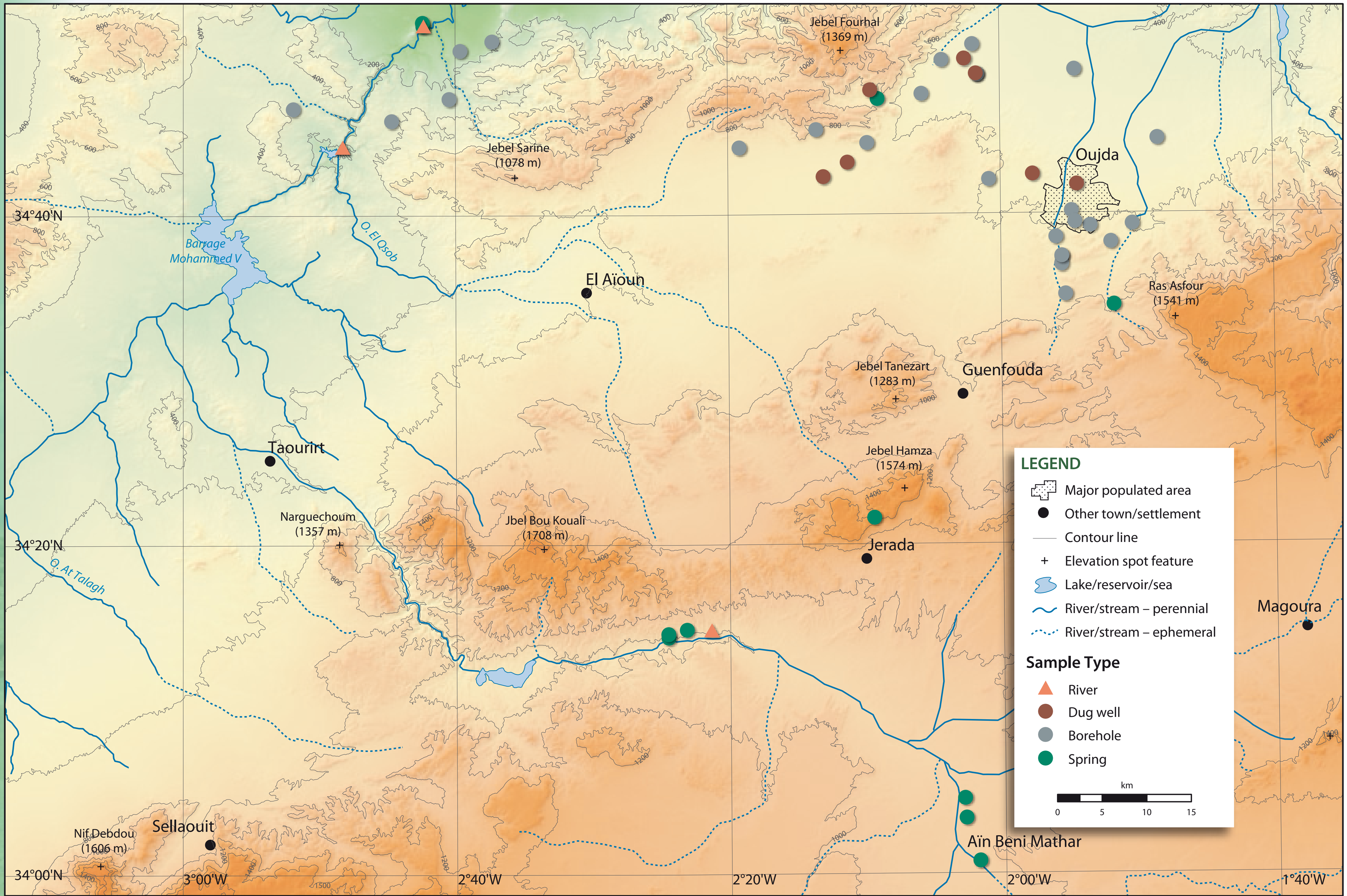




(A) Oxygen-18 interpolation

Tension: 70, Smoothing: 0.5, RMSE: 0.52‰

Moulouya basin – NE


Jebel Fourhal
(1369 m)
Jebel Sarine
(1078 m)
Oujda
34°40'N
Barrage
Mohammed V
O. El Qsob
El Aïoun
Ras Asfour
(1541 m)
Jebel Tanezart
(1283 m)
Guenfouda
Taourirt
Jebel Hamza
(1574 m)
Narguechoum
(1357 m)
Jbel Bou Kouali
(1708 m)
Jerada
34°20'N
O. At Talagh
Magoura
Nif Debdou
(1606 m)
Sellaouit
Aïn Beni Mathar
34°00'N
3°00'W
2°40'W
2°20'W
2°00'W
1°40'W
LEGEND
Major populated area
Other town/settlement
Contour line
Elevation spot feature
Lake/reservoir/sea
River/stream – perennial
River/stream – ephemeral
Sample Type
River
Dug well
Borehole
Spring
km
0
5
10
15

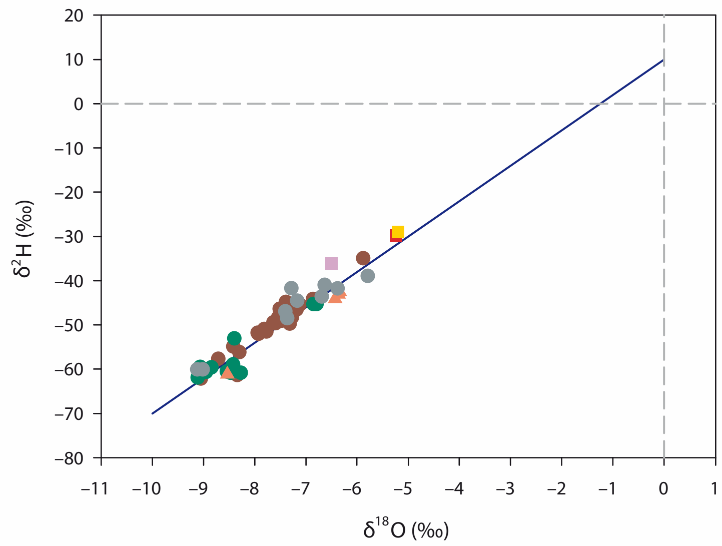
Study area: Moulouya basin – NE
Sampling period: 1999

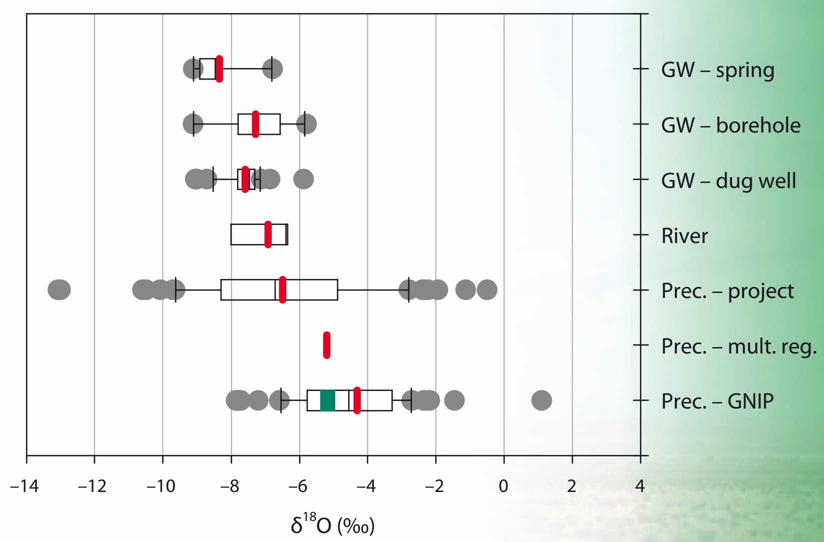
Background

The Moulouya basin covers approximately 74 000 km². This project focused on an area in the north-east part of the basin near Oujda. The area is characterized by an arid and semi-arid climate. Average rainfall amounts to 245 mm/a. Isotope and geochemical studies were undertaken in order to better understand the hydrodynamic functioning of the follwing aquifer units: Angad, Jbel Hamra, Beni Snassen, Bouhria and Beni Mathar.

The specific objectives of the study were:

- To determine if connections exist between the Angad, Bouhria and Beni Snassen aquifers.
- To estimate the altitude of recharge of the Angad, Jbel Hamra and Bouhria aquifers using stable isotopes.
- To measure tritium and radiocarbon for groundwater dating (Beni Snassen aquifer, Beni Mathar aquifer and Angad aquifer).





Precipitation		δ¹⁸O (‰) n	Median	Mean ± St. dev.	δ²H (‰) n	Median	Mean ± St. dev.	Tritium (TU) n	Mean ± St. dev.	Annual prec. (mm)	Temperature (ºC)
GNIP station FES SAIS	■ (red)	60	−4.55	−5.24	60	−23.3	−29.8			457	17.4
Interpolation – multiple reg.	■ (yellow)			−5.20			−29.0				
Project	■ (pink)	70	−6.71	−6.50 ± 2.6	70	−36.8	−36.2 ± 16.8				

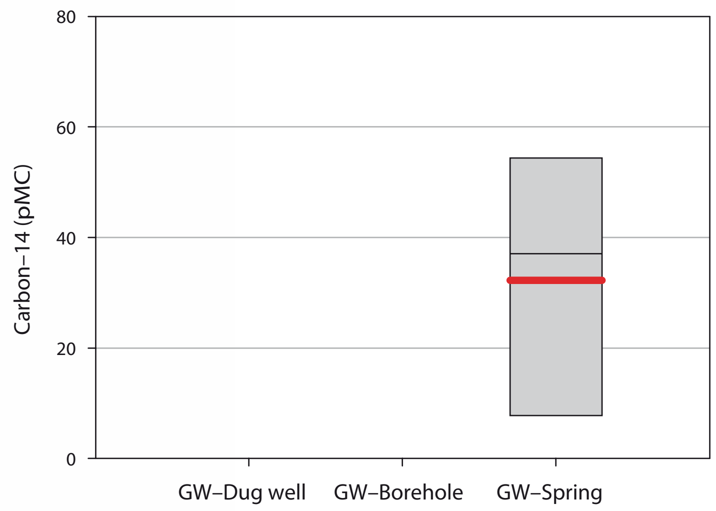
Surface waters		δ¹⁸O n	Median	Mean ± St. dev.	δ²H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.
Lake/reservoir/sea	▲ (yellow)								
River	▲ (orange)	4	−6.40	−6.92 ± 1.1	4	−43.6	−47.7 ± 9.0	3	5.2 ± 1.5

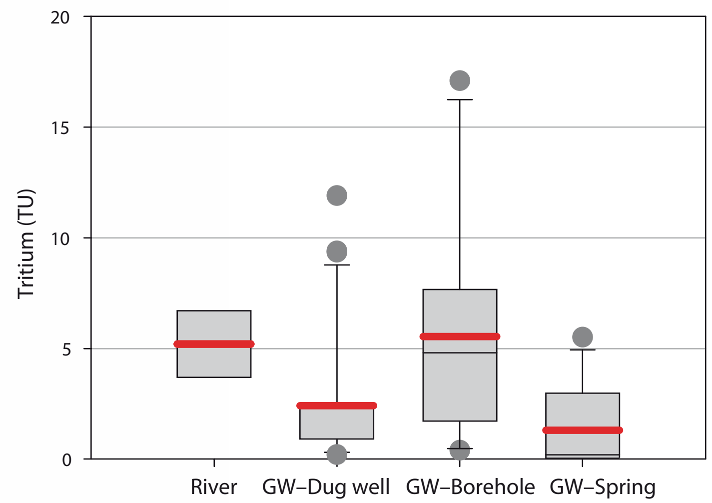
Groundwaters		δ¹⁸O n	Median	Mean ± St. dev.	δ²H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.	¹⁴C (pMC) n	Mean ± St. dev.	δ¹³C (‰) n	Mean ± St. dev.
GW–Borehole	● (grey)	10	−7.23	−7.28 ± 1.1	10	−44.1	−46.7 ± 7.6	10	5.5 ± 4.9				
GW–Dug well	● (brown)	35	−7.47	−7.60 ± 0.6	35	−48.6	−49.6 ± 5.2	35	2.4 ± 2.9	5	32.3 ± 24.3		
GW–Spring	● (green)	12	−8.48	−8.35 ± 0.8	12	−60.1	−57.3 ± 6.0	12	1.3 ± 1.9				

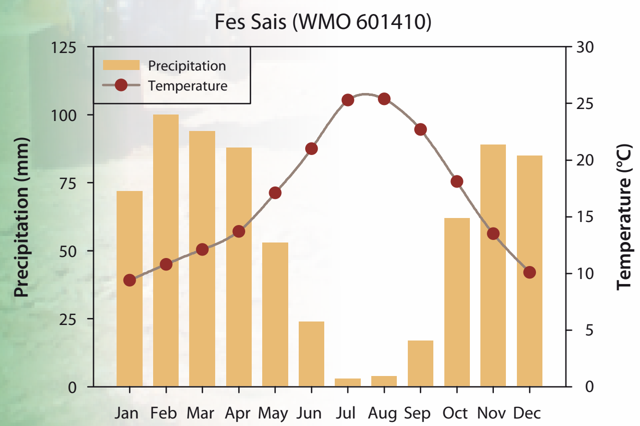
Results

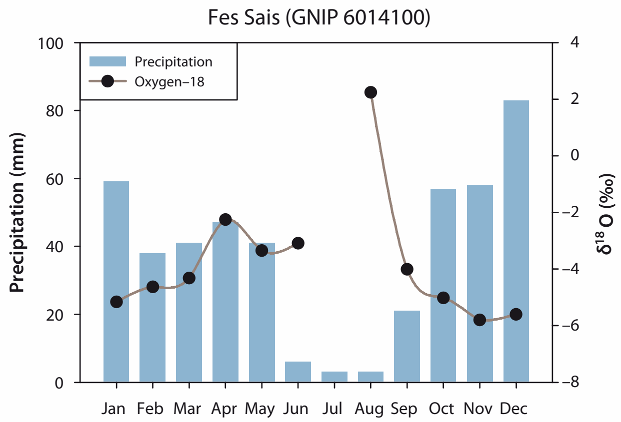
Recharge altitudes estimated using stable isotopes suggest that recharge areas lie between 700 and 1000 m for the Angad aquifer, and between 850 and 1200 m for the Jbel Hamra and Bouhria aquifers. These altitudes are located in the Beni Snassen and Jbel Hamra Mountains. Although it is not apparent from the $\delta^{18}O$ interpolation map (A), which uses combined aquifer data, there does not appear to be a strong connection or mixing between the Angad and Bouhria aquifers, based on the distinct stable isotope signature of these two aquifers. Less negative isotope values in the north from the Angad and more negative values in the south from the Bouhria were observed. However, the isotope signatures of the Angad and Beni Snassen aquifers (north of the study are) are not distinct, suggesting that there may be substantial mixing between the aquifers.

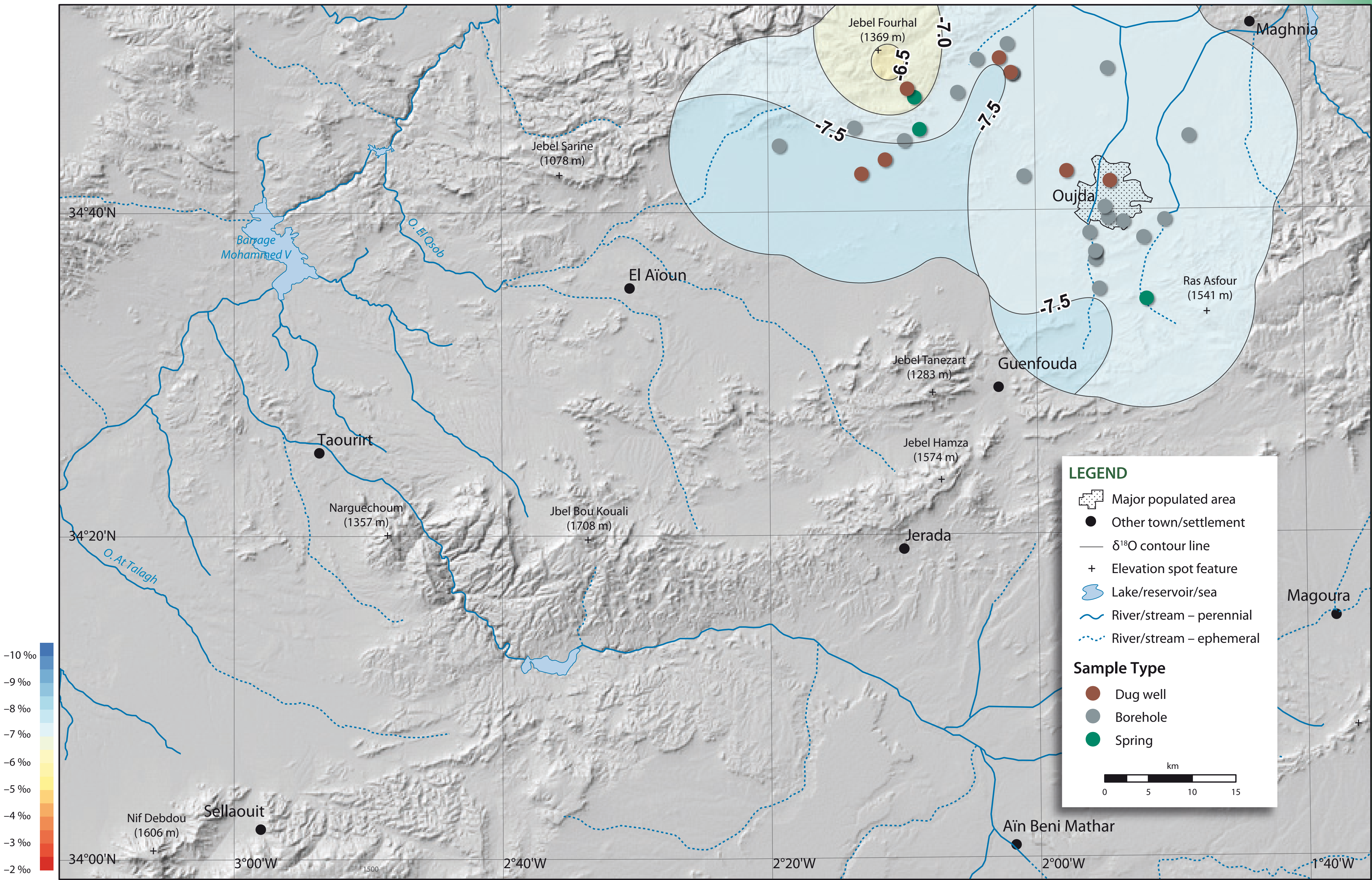
The low tritium and carbon–14 results show that the groundwater of Beni Mathar aquifer is old (<2 pMC; see tritium interpolation map (B)). However, most waters in the Angad and Beni Snassen aquifers are derived from recent recharge based on their tritium and carbon-14 contents.





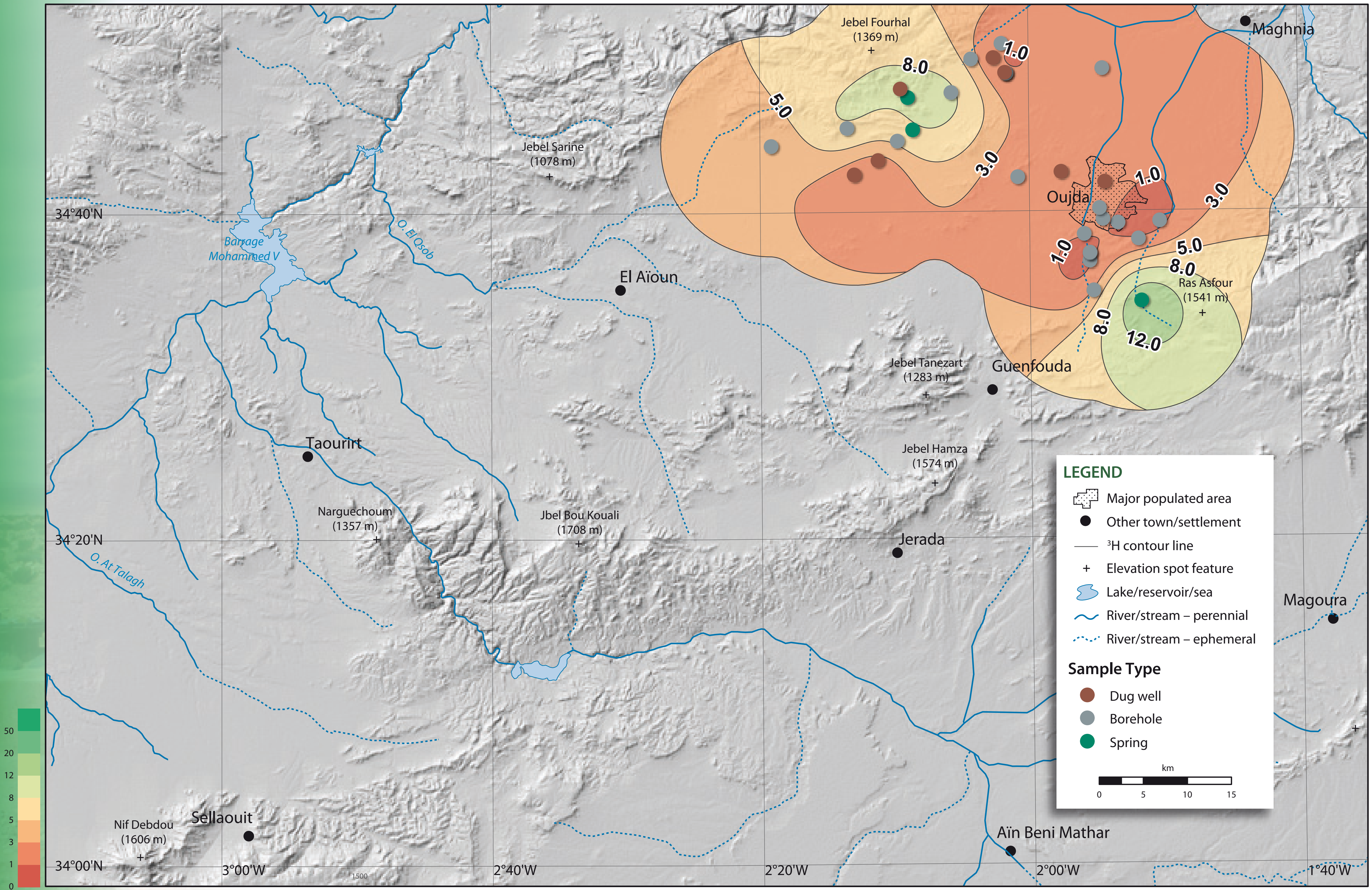






(A) Oxygen-18 interpolation

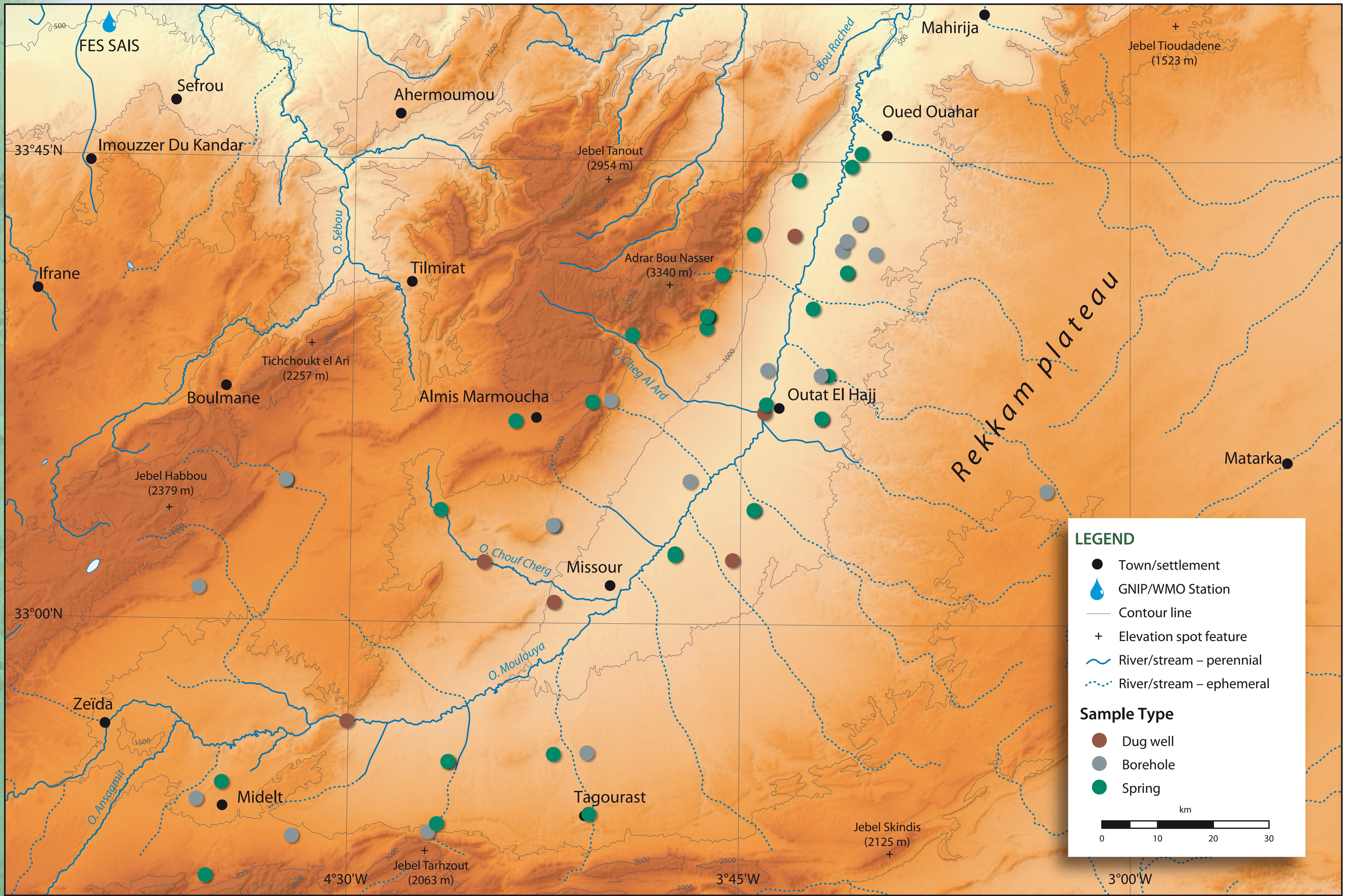
Tension: 100, Smoothing: 0.5, RMSE: 0.79 ‰



(B) Tritium interpolation

Tension: 70, Smoothing: 0.5, RMSE: 0.73 TU

Moyenne Moulouya basin

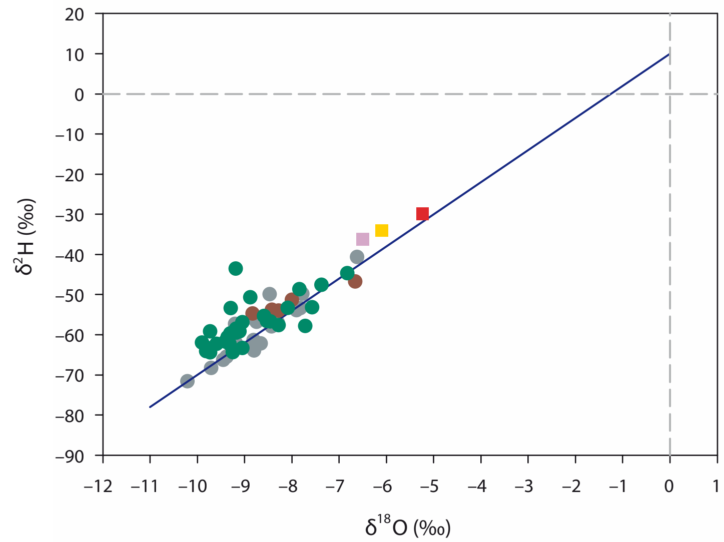

FES SAIS
Sefrou
Ahermoumou
Mahirija
Jebel Tioudadene
(1523 m)
Oued Ouahar
O. Bou Rached
33°45'N
Imouzzer Du Kandar
Jebel Tanout
(2954 m)
O. Sébou
Ifrane
Tilmirat
Adrar Bou Nasser
(3340 m)
Tichchoukt el Ari
(2257 m)
O. Cheg Al Ard
Boulmane
Almis Marmoucha
Outat El Hajj
Rekkam plateau
Matarka
Jebel Habbou
(2379 m)
O. Chouf Cherg
Missour
33°00'N
O. Moulouya
Zeïda
Midelt
O. Ansegmir
Tagourast
Jebel Skindis
(2125 m)
Jebel Tarhzout
(2063 m)
4°30'W
3°45'W
3°00'W
LEGEND
Town/settlement
GNIP/WMO Station
Contour line
Elevation spot feature
River/stream – perennial
River/stream – ephemeral
Sample Type
Dug well
Borehole
Spring
km
0
10
20
30

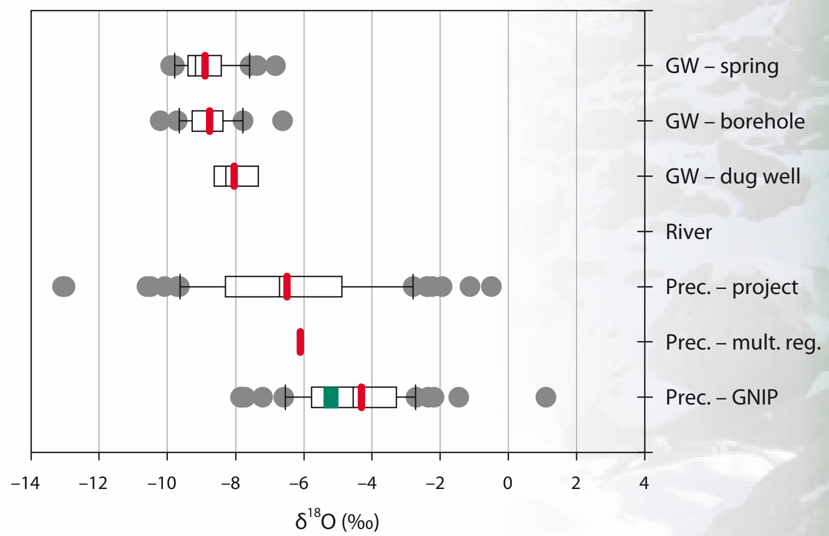
Study area: Moyenne Moulouya basin
Sampling period: 2002–2004

Background

The middle Moulouya (Moyenne) basin project was conducted in the northeast of Morocco. The study area is bounded in the south and the west by the high Atlas Mountains, and by the Rekkam plateau in the east. The middle basin area is about 17 000 km^2. The basin is crossed by the Moulouya River. The annual rainfall is about 200 mm. The principal aquifers are: shallow aquifers in the Quaternary strata which are conglomeratic, sandy and marly; and deeper aquifers (Cretaceous and Dogger), which occur at a depth of 1200 m.

The productivity of the shallow aquifers is very low and the quality is poor. It is insufficient for sustainable development. The deeper aquifers provide water of good quality and are under artesian conditions. Therefore, the potential of the deeper aquifer as a water source was evaluated by understanding the hydrodynamic functioning and relations with potential recharge areas in the middle and the high Atlas Mountains and the Rekkam plateau (where outcrops of the Aaleno-Bajocien strata can be found).



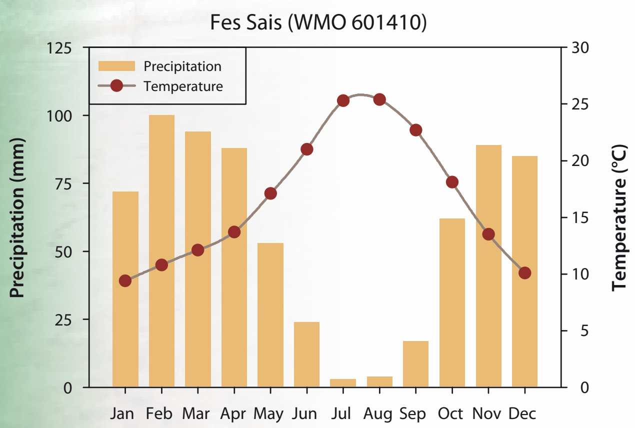


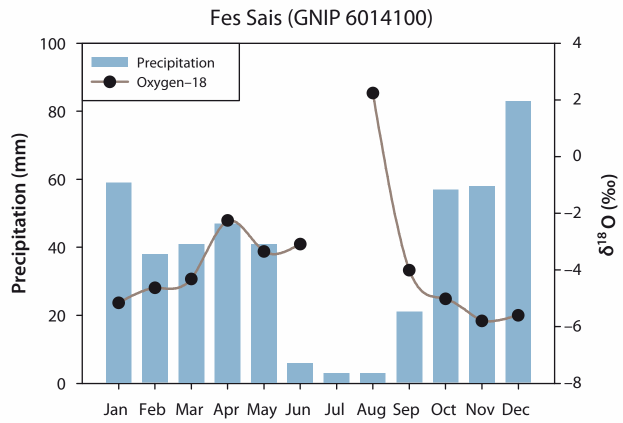
Precipitation		δ18O (‰) n	Median	Mean ± St. dev.	δ2H (‰) n	Median	Mean ± St. dev.	Tritium (TU) n	Mean ± St. dev.		Annual prec. (mm)		Temperature (ºC)
GNIP station FES SAIS	■	60	−4.55	−5.24	60	−23.3	−29.8				457		17.4
Interpolation – multiple reg.	■			−6.10			−34.0						
Project	■	70	−6.71	−6.50 ± 2.6	70	−36.8	−36.2 ± 16.8						
Surface waters		δ18O n	Median	Mean ± St. dev.	δ2H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.				
Lake/reservoir/sea	▲												
River	▲												
Groundwaters		δ18O n	Median	Mean ± St. dev.	δ2H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.	14C (pMC) n	Mean ± St. dev.	δ13C (‰) n	Mean ± St. dev.
GW–Borehole	●	21	−8.81	−8.77 ± 0.8	21	−61.4	−59.3 ± 7.2	23	3.0 ± 4.2	18	27.8 ± 26.0	18	−7.2 ± 3.3
GW–Dug well	●	5	−8.28	−8.04 ± 0.8	5	−53.8	−52.1 ± 3.3	4	6.3 ± 8.2				
GW–Spring	●	30	−9.18	−8.89 ± 0.8	30	−58.9	−57.4 ± 5.8	27	6.5 ± 4.7	24	49.8 ± 29.9	24	−7.0 ± 2.9

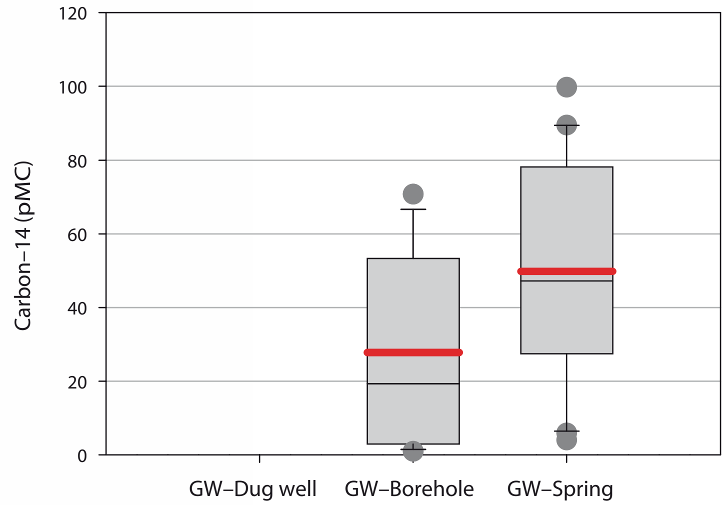
Results

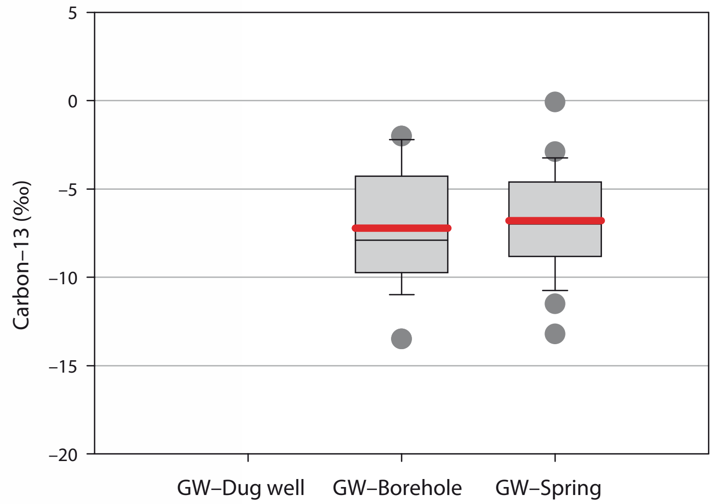
Using stable isotope data, it was concluded that there are some connections between the middle Atlas and the shallow aquifers in the downstream part of the plain because of the similarity in stable isotope composition (see oxygen-18 interpolation map (A)). The similarity between stable isotope values also suggested connections between the high Atlas, the Cretaceous aquifers of the Rekkam plateau to the shallow aquifers in the high part of the plain.

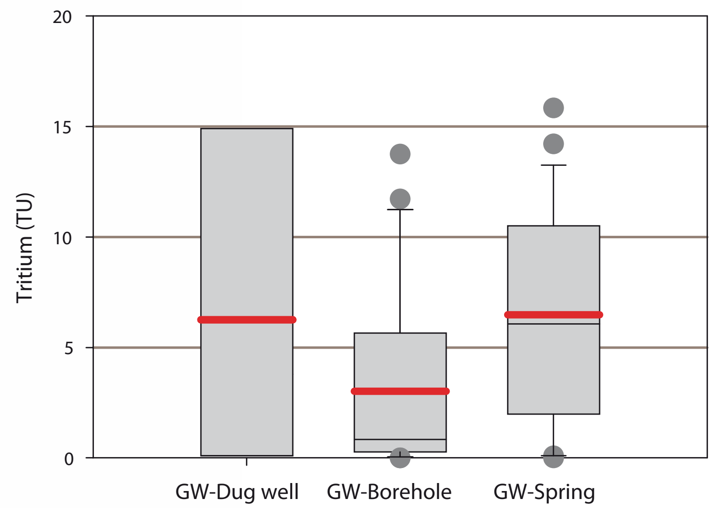
It was not possible to delineate a clear relationship between the deep Dogger aquifer in the basin plain (more negative stable isotopes values) and plateau (more positive stable isotopes values). It appears that the discharge of the Rekkam plateau occurs mainly through the Tissaf spring. Based on the carbon-14 and tritium data, the groundwater age in the north-east part of the Moyenne Moulouya is on the order of thousands of years, suggesting that the recharge is minimal (see carbon-14 interpolation map B). The Oligo-Miocene aquifer, used by the drinking water supply authority (ONEP) to supplement the water drinking supply for the town of Missour, also contains old water (low tritium and carbon-14 contents), which supports the hypothesis of low recharge rates.

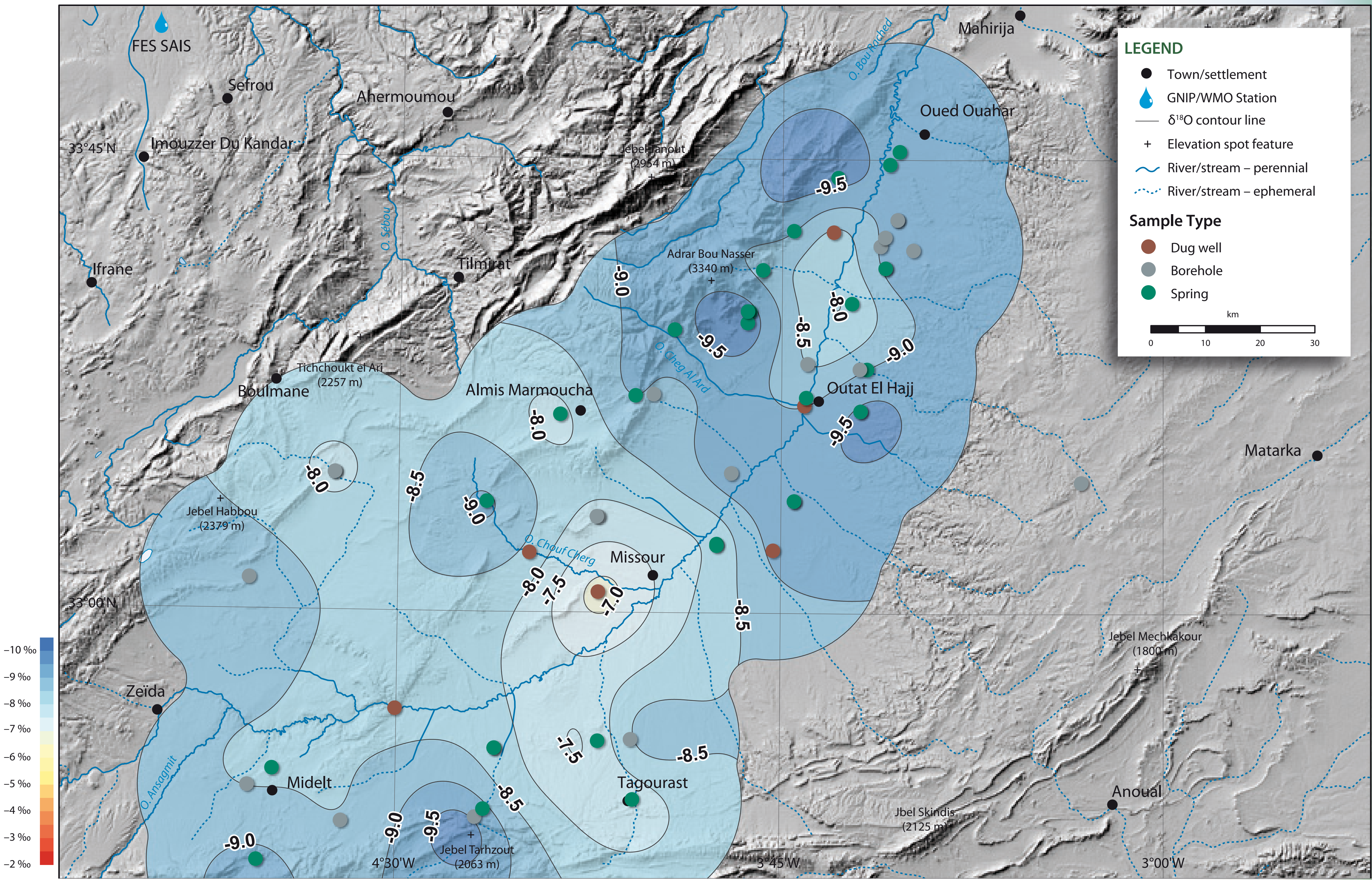






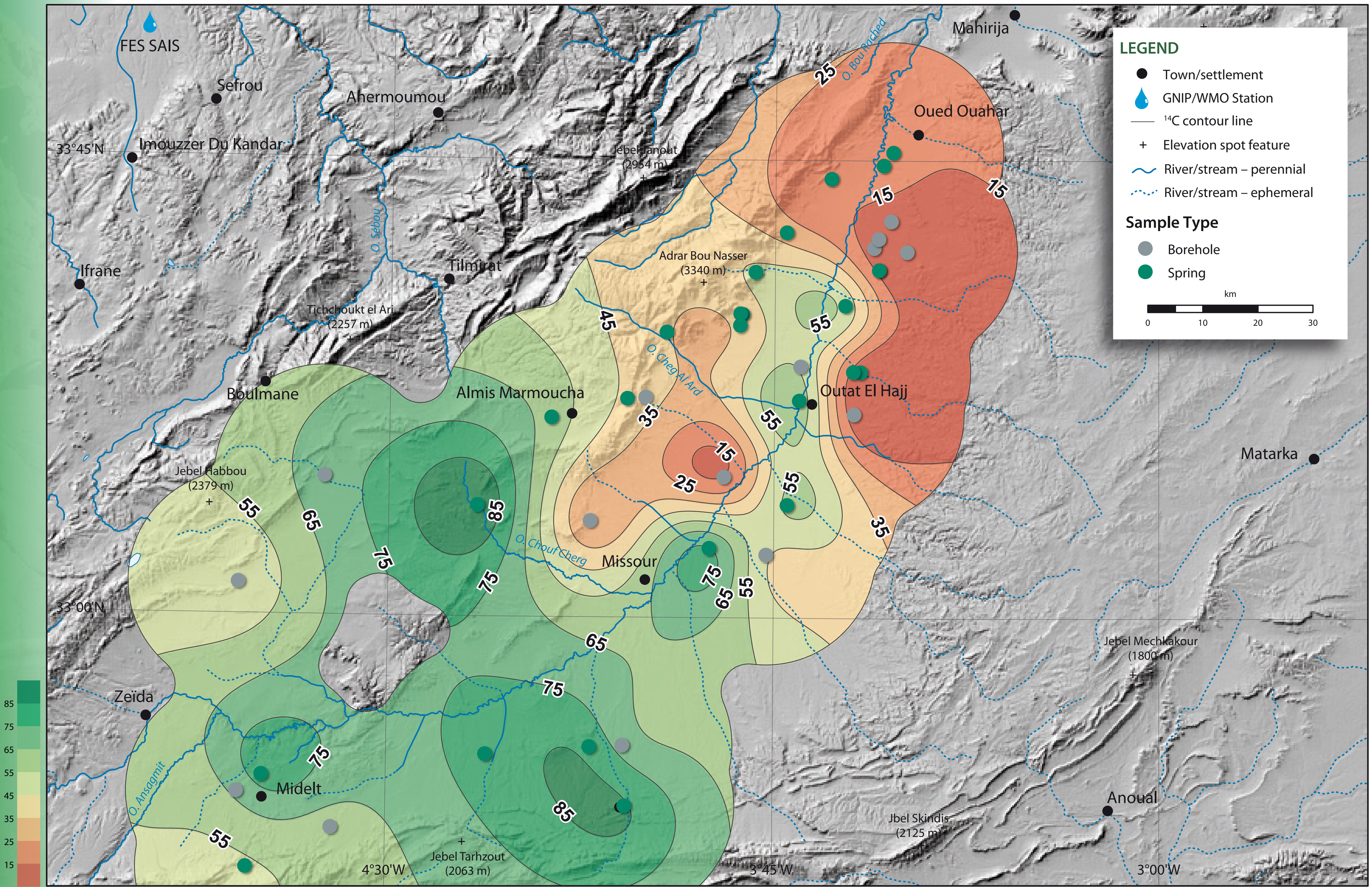






(A) Oxygen-18 interpolation

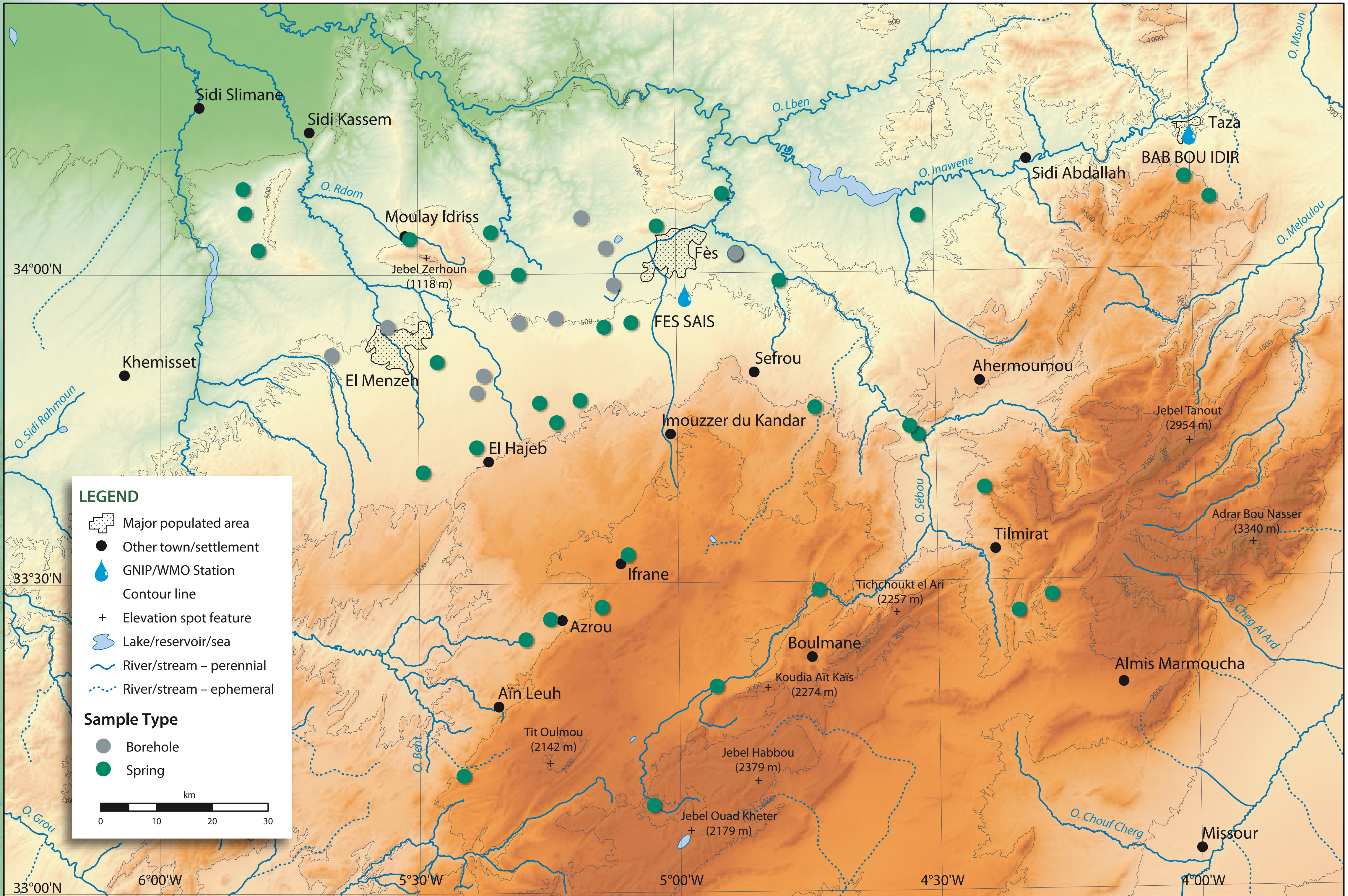
Tension: 100, Smoothing: 0.5, RMSE: 0.79 ‰



(B) Carbon-14 interpolation

Tension: 100, Smoothing: 0.5, RMSE: 6.9 pMC

Sebou basin



Sidi Slimane
Sidi Kassem
O. Rdom
Moulay Idriss
Jebel Zerhoun
(1118 m)
34°00'N
Fès
FES SAIS
O. Lben
O. Inawene
Taza
BAB BOU IDIR
Sidi Abdallah
O. Msoun
O. Meloulou
Khemisset
El Menzeh
Sefrou
Ahermoumou
Imouzzer du Kandar
El Hajeb
O. Sidi Rahmoun
Jebel Tanout
(2954 m)
O. Sebou
Adrar Bou Nasser
(3340 m)
Tilmirat
Ifrane
33°30'N
Tichchoukt el Ari
(2257 m)
Azrou
Boulmane
O. Cheg Al Ard
Almis Marmoucha
Koudia Aït Kaïs
(2274 m)
Aïn Leuh
Tit Oulmou
(2142 m)
Jebel Habbou
(2379 m)
O. Beht
Jebel Ouad Kheter
(2179 m)
O. Chouf Cherg
Missour
O. Grou
33°00'N
6°00'W
5°30'W
5°00'W
4°30'W
4°00'W
LEGEND
Major populated area
Other town/settlement
GNIP/WMO Station
Contour line
Elevation spot feature
Lake/reservoir/sea
River/stream – perennial
River/stream – ephemeral
Sample Type
Borehole
Spring
km
0
10
20
30

Study area: Sebou basin
Sampling period: 2007

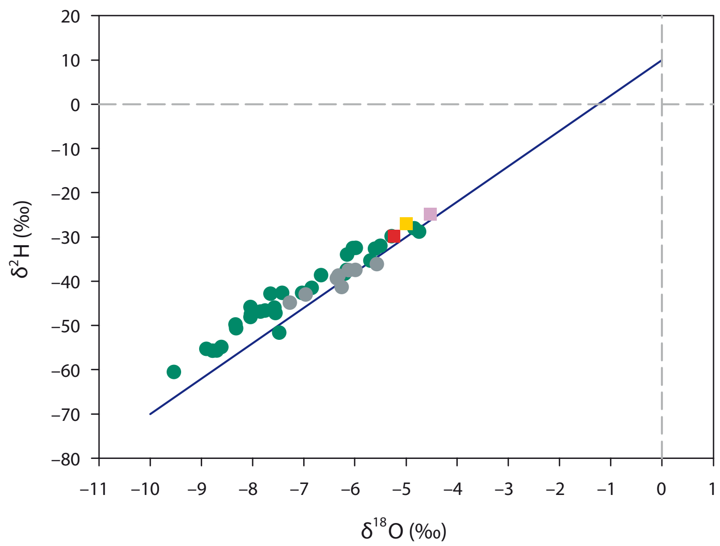
Background

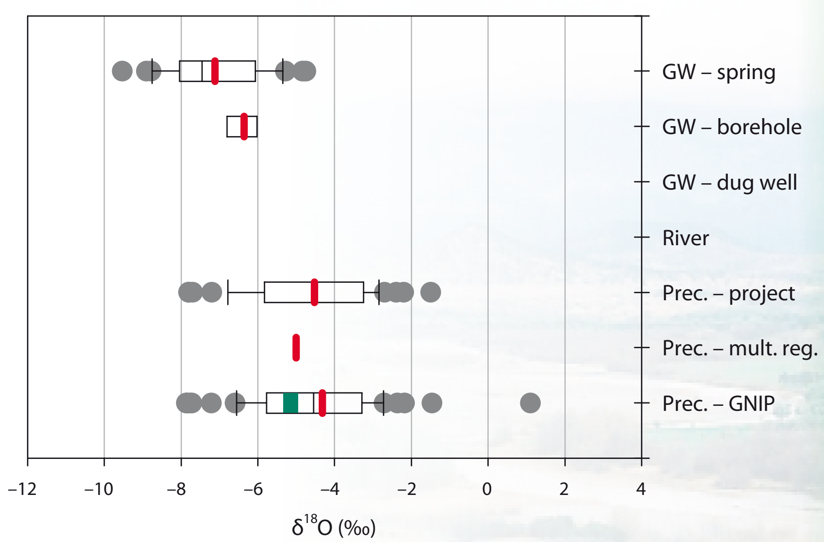
The Sebou basin lies between the Rif Mountains in the north, the middle Atlas, the Moroccan Méseta in the south and the Atlantic ocean in the west. The area of the basin is 40 000 km² and the average rainfall is about 750 mm/a. It is one of the most important basins in Morocco and contains about 10% of the national water resources. The basin springs have good quality water and are an excellent low cost water supply that is much in demand. However, these advantages make the sources very vulnerable to contamination and overuse. Thus, they require the establishment of protection zones to preserve this national heritage. The project examined four sub-basins:

- Sub-basin Fès-Meknès, composed of the Liasic limestone and Quaternary limestone aquifers. The Liasic aquifer is very deep and artesian.
- Sub-basin couloir Fès- Taza, ~~r~~epresented by low productivity Miocene sandstones and by Liassic carbonates, which are the principal water producer.
- Sub-basin Causse Moyen Atlasique, ~~c~~ontaining the tabular carbonate formations of Liassic age.
- Sub-basin Moyen Atlas Plissé, ~~a~~ multi-layer system whose principal producer resides in the lower Liassic carbonates.

All of these sub-basins contain Quaternary, Liassic and Miocene aquifers.

The main objectives of the project were to determine the recharge areas of the various springs, to calculate by isotope balance the various components of recharge, to determine the relationship between the different aquifers and between the aquifers and the wadis. Groundwater dating provided valuable information on the renewal rate of water of the springs and aquifers. The combination of the isotope results and those of the classic hydrology studies made it possible to understand the functioning of the different springs and the discharge systems of the aquifers. This information made possible to better manage groundwater resources, and also to sustain the economic development arising from the basin springs.





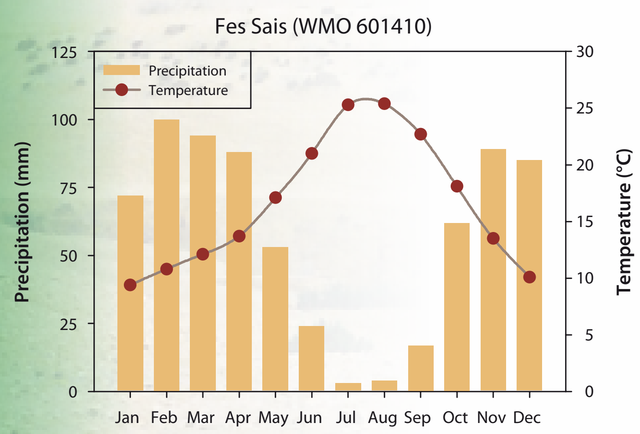
Precipitation		δ¹⁸O (‰)			δ²H (‰)			Tritium (TU)		Annual prec. (mm)	Temperature (°C)
		n	Median	Mean ± St. dev.	n	Median	Mean ± St. dev.	n	Mean ± St. dev.		
GNIP station FES SAIS	■ (red)	60	−4.55	−5.24	60	−23.3	−29.8			457	17.4
Interpolation – multiple reg.	■ (yellow)			−5.00			−27.0				
Project	■ (pink)	46	−4.45	−4.53 ± 1.5	46	−22.9	−24.8 ± 11.7	38	5.7 ± 2.9		

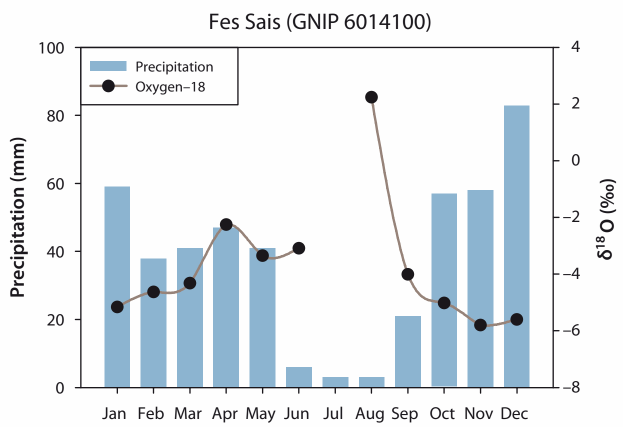
Surface waters		δ¹⁸O			δ²H			Tritium			
		n	Median	Mean ± St. dev.	n	Median	Mean ± St. dev.	n	Mean ± St. dev.		
Lake/reservoir/sea	▲										
River	▲										

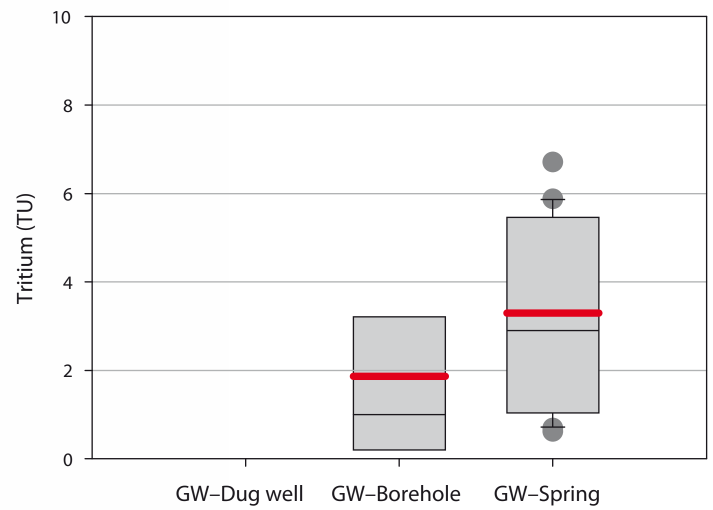
Groundwaters		δ¹⁸O			δ²H			Tritium		¹⁴C (pMC)		δ¹³C (‰)	
		n	Median	Mean ± St. dev.	n	Median	Mean ± St. dev.	n	Mean ± St. dev.	n	Mean ± St. dev.	n	Mean ± St. dev.
GW–Borehole	●	8	−6.29	−6.36 ± 0.5	8	−39.1	−39.8 ± 3.0	6	1.9 ± 2.6				
GW–Dug well	●												
GW–Spring	●	32	−7.45	−7.11 ± 1.3	32	−42.8	−42.9 ± 8.9	26	3.3 ± 2.2				

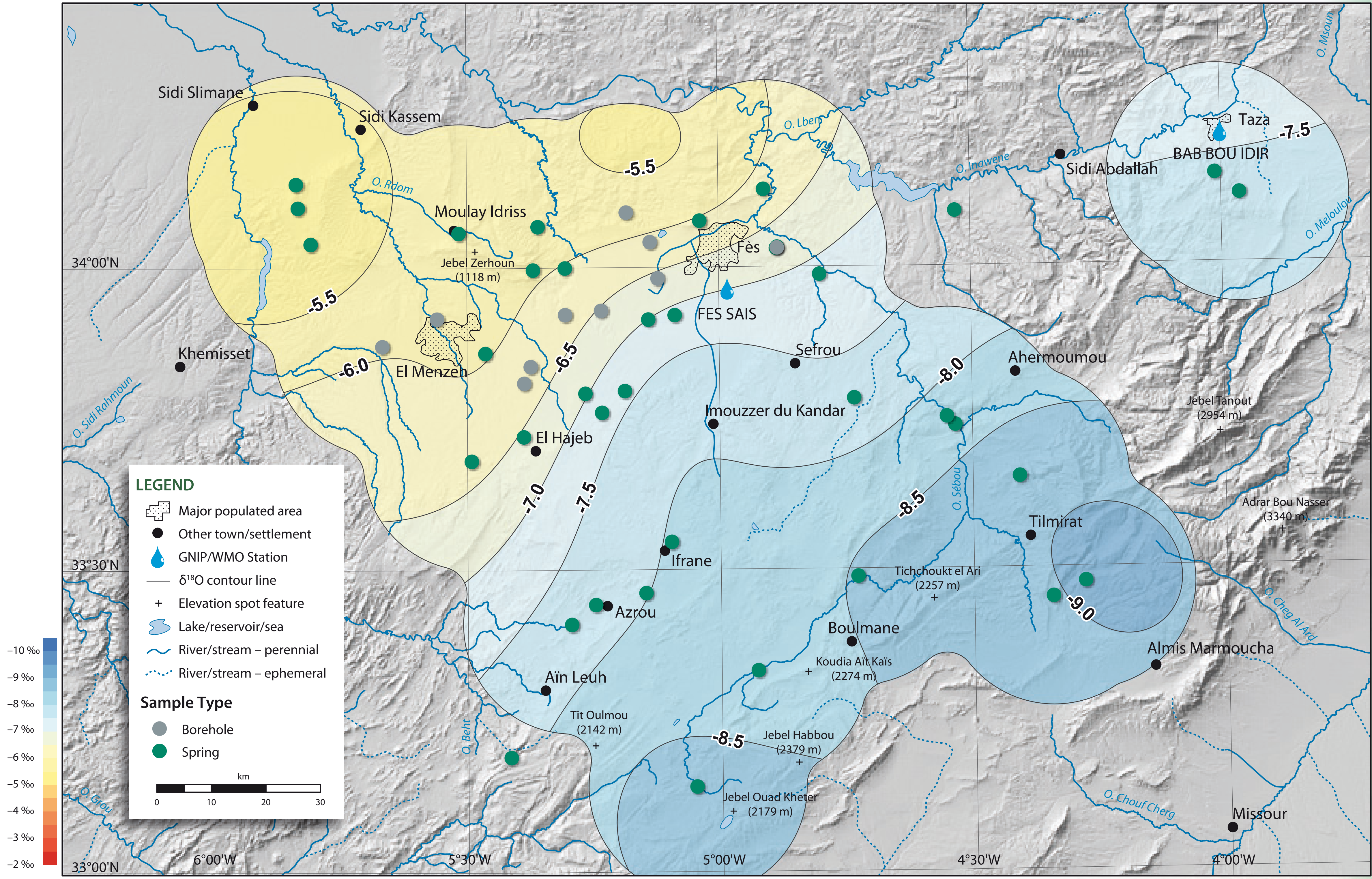
Results

Isotope techniques were used for the definition of recharge areas for 24 major springs in the Sebou basin along with some boreholes. The study focused on the use of oxygen-18 and deuterium in addition to chemical and hydrogeological characterization of these springs. Chemical characterization of these waters showed that groundwater chemistry is affected by the geology of the recharge areas and is modified as it moves along groundwater flow paths. Deuterium and oxygen-18 data plot along a line similar to local rainfall (Fes Sais GNIP station), indicating that the aquifers are recharged by rapid infiltration, without significant evaporation. The oxygen-18 data from two springs near their recharge areas were used to define an elevation gradient of −0.27 ‰ per 100 m. The application of this gradient to isotopic contents of other springs was used to estimate altitudes of recharge. By measuring oxygen stable isotopes, recharge altitudes in areas of the basin where locations of recharge areas were not originally clear could be established. The oxygen-18 interpolation map (A) shows an increasing trend from the south to the north which reflects the higher altitude recharge from the south. The tritium interpolation map (B) suggests older waters in the northern part of the study area. These results are being used to establish protection zones for the springs.



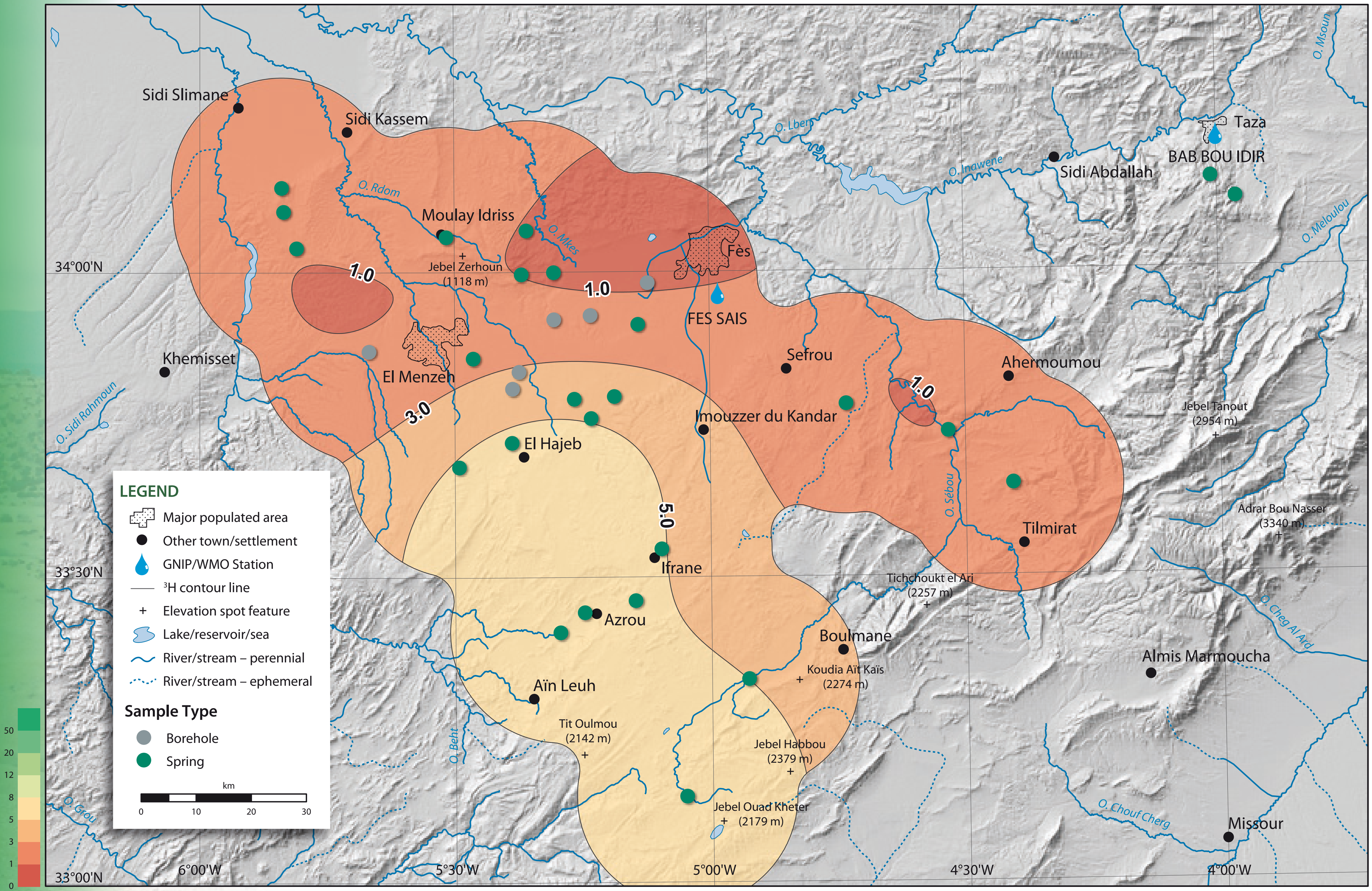






(A) Oxygen-18 interpolation

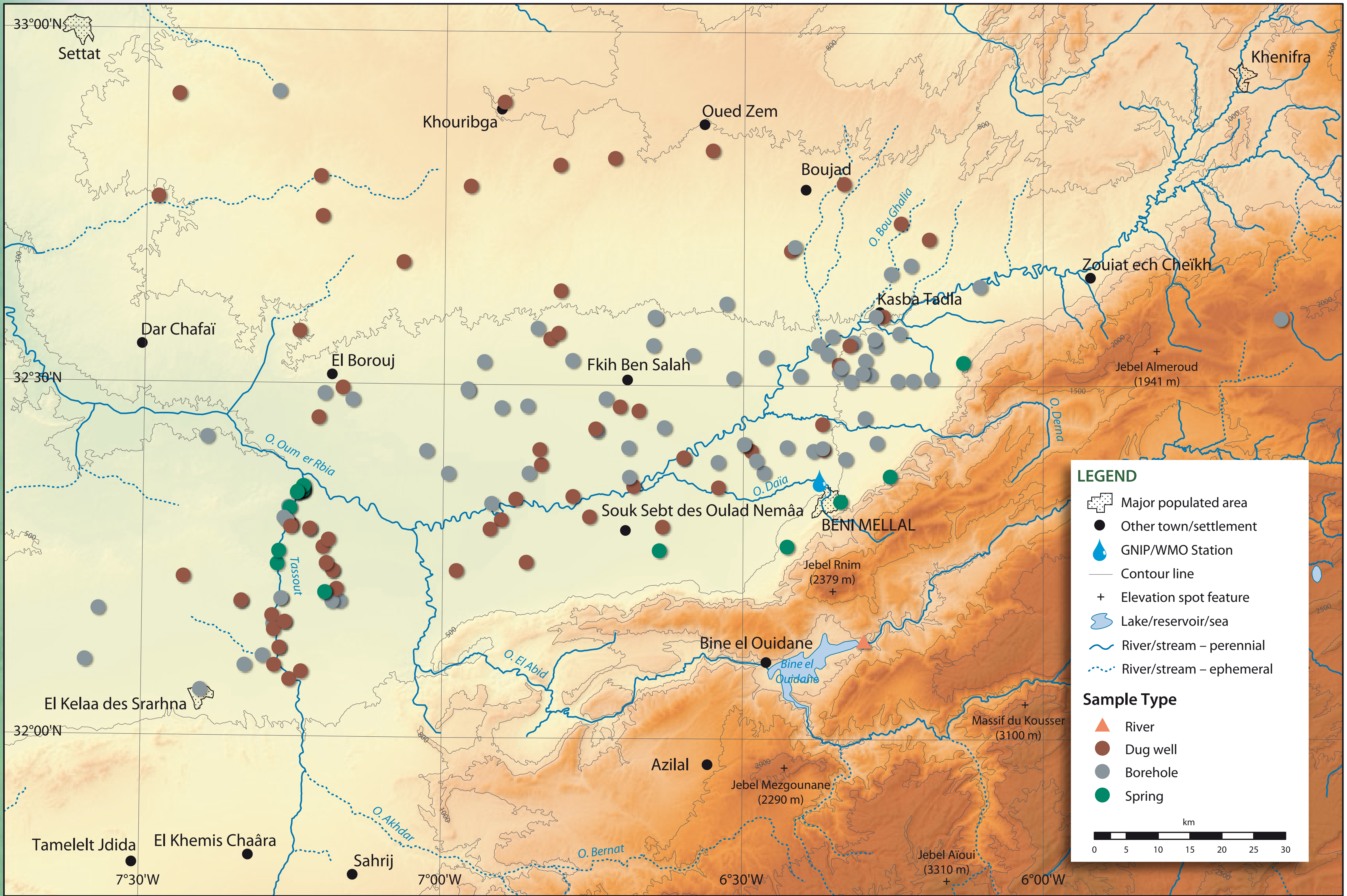
Tension: 40, Smoothing: 0.5, RMSE: 0.25 ‰



(B) Tritium interpolation

Tension: 40, Smoothing: 0.5, RMSE: 0.86 TU

Tadla basin

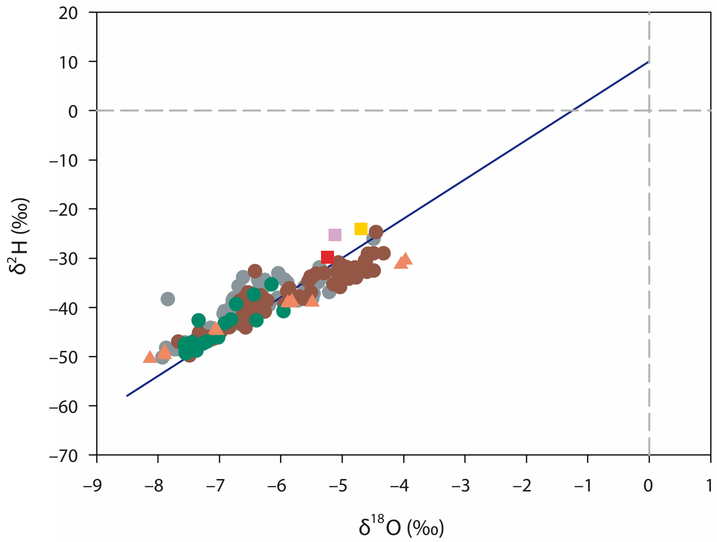

33°00'N
Settat
Khouribga
Oued Zem
Boujad
Khenifra
O. Bou Ghalia
Zouiat ech Cheïkh
Kasba Tadla
Dar Chafaï
El Borouj
Fkih Ben Salah
32°30'N
Jebel Almeroud
(1941 m)
O. Derna
O. Oum er Rbia
O. Daïa
Souk Sebt des Oulad Nemâa
BENI MELLAL
Tassout
Jebel Rnim
(2379 m)
Bine el Ouidane
Bine el Ouidane
O. El Abid
El Kelaa des Srarhna
32°00'N
Massif du Kousser
(3100 m)
Azilal
Jebel Mezgounane
(2290 m)
O. Akhdar
O. Bernat
Tamelelt Jdida
El Khemis Chaâra
Sahrij
Jebel Aïoui
(3310 m)
7°30'W
7°00'W
6°30'W
6°00'W
LEGEND
Major populated area
Other town/settlement
GNIP/WMO Station
Contour line
Elevation spot feature
Lake/reservoir/sea
River/stream – perennial
River/stream – ephemeral
Sample Type
River
Dug well
Borehole
Spring
km
0 5 10 15 20 25 30

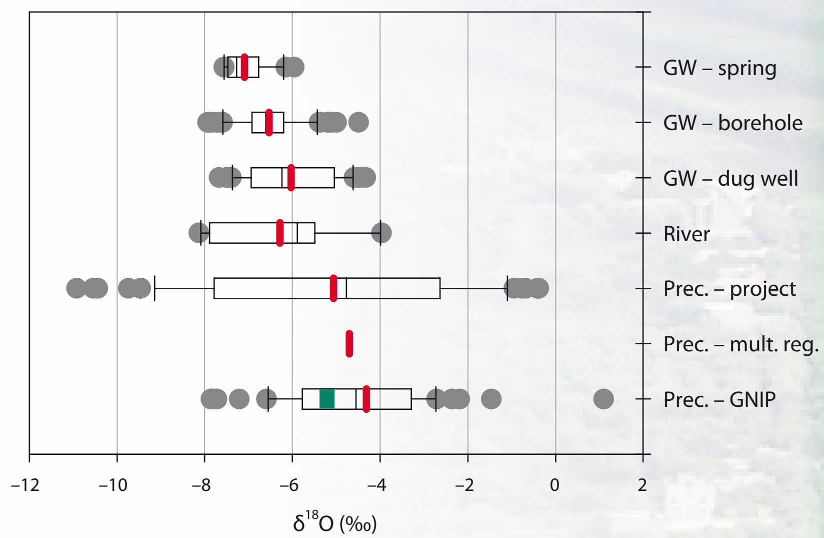
Study area: Tadla basin
Sampling period: 1999–2002

Background

The Tadla basin is situated in the centre of Morocco, north of the Atlas Mountains. It is formed by three geographical units: Plateau des phosphates, Plaine du Tadla and Tassaout Aval. The basin area is about 10 000 km^2. It is crossed by the Oum Erbia River. The average rainfall is about 550 mm/a. The Tadla plain, where most of the investigation has been carried out, contains four aquifers (Mio-Plio-Quaternary, Eocene, Senonian and Turonian) which are separated by semi-permeable horizons. These horizons have the potential to allow mixing between the aquifers.

The objectives of the isotope investigations in the Tadla basin were to provide a better understanding of the hydraulic conditions in the basin and quantify hydrological characteristics in order to provide better model simulations of groundwater dynamics and to optimize resource management for the Tadla plain. More than 150 groundwater samples were collected from the unconfined and confined aquifers of the basin and analysed for their chemical and isotopic composition.





Precipitation		δ18O (‰)			δ2H (‰)			Tritium (TU)			Annual prec. (mm)		Temperature (ºC)
		n	Median	Mean ± St. dev.	n	Median	Mean ± St. dev.	n	Mean ± St. dev.				
GNIP station FES SAIS	■	60	−4.55	−5.24	60	−23.3	−29.8				457		17.4
Interpolation – multiple reg.	■			−4.70			−24.0						
Project	■	44	−4.77	−5.12 ± 2.9	44	−20.7	−25.3 ± 20.1						
Surface waters		**δ18O**			**δ2H**			**Tritium**					
		n	Median	Mean ± St. dev.	n	Median	Mean ± St. dev.	n	Mean ± St. dev.				
Lake/reservoir/sea	▲												
River	▲	11	−5.89	−6.28 ± 1.5	11	−39.2	−41.5 ± 6.9	8	4.1 ± 1.5				
Groundwaters		**δ18O**			**δ2H**			**Tritium**		**14C (pMC)**		**δ13C (‰)**	
		n	Median	Mean ± St. dev.	n	Median	Mean ± St. dev.	n	Mean ± St. dev.	n	Mean ± St. dev.	n	Mean ± St. dev.
GW–Borehole	●	84	−6.61	−6.53 ± 0.7	84	−39.5	−40.0 ± 4.8	54	2.3 ± 2.7	39	45.0 ± 30.7	39	−9.9 ± 1.8
GW–Dug well	●	68	−6.24	−6.03 ± 1.0	68	−38.0	−38.5 ± 6.2	31	5.9 ± 2.5	36	63.6 ± 25.4	36	−10.6 ± 1.1
GW–Spring	●	21	−7.27	−7.09 ± 0.5	21	−47.1	−45.1 ± 4.1	12	5.3 ± 2.3	5	78.7 ± 12.7	5	−8.9 ± 1.2

Results

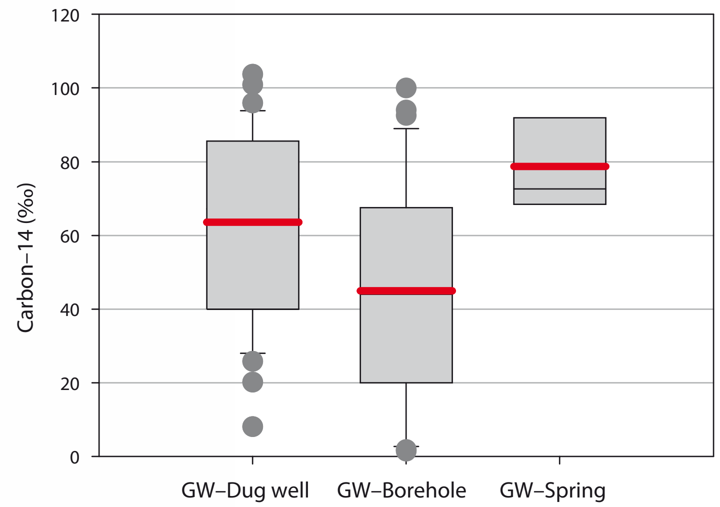
A special effort was made to generate aquifer based interpolations because sufficient data were available to make meaningful interpolations. Comparing oxygen-18 interpolations for the south parts of the basin between the Turonian (A) and Eocene (B) aquifers shows that the Turonian tends to be more negative than the Eocene. This difference likely indicates climatic differences during recharge. The Quaternary aquifer interpolation (C) shows differences between the east (Beni Mellal) and the southwest side of the basin. These differences reflect recharge and mixing from the two rivers. The southwest oxygen-18 values are more negative, reflecting the higher elevation of the recharge source compared to the Oum Erbia headwaters in the east.

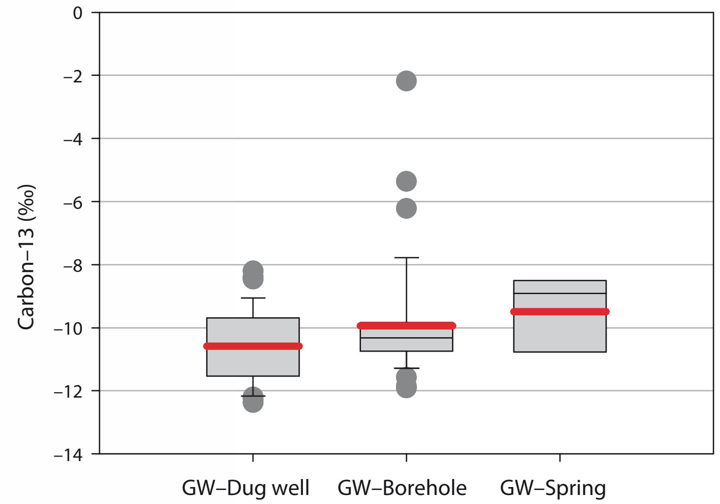
The Turonian aquifer is the most important water source in the basin, and the tritium interpolation (D) shows old water (low TU values) over much of the basin and modern water in the northeast (around Boujad). The Eocene tritium interpolation (E) is similar to the Turonian except that it does not show modern water in the northeast (because there were no data available for the Boujad area). The Quaternary tritium interpolation (F) is dominated by higher tritium values than the other two aquifers, consistent with relatively large amounts of modern water input. Based on high tritium in Béni Mellal spring in the Atlas Mountains in the southeast, there does not appear to be a relationship between modern recharge from the Atlas and the deeper aquifers. Some boreholes drilled in the southern Tadla are dry indicating a lack of connection between the mountains and the deeper aquifers.

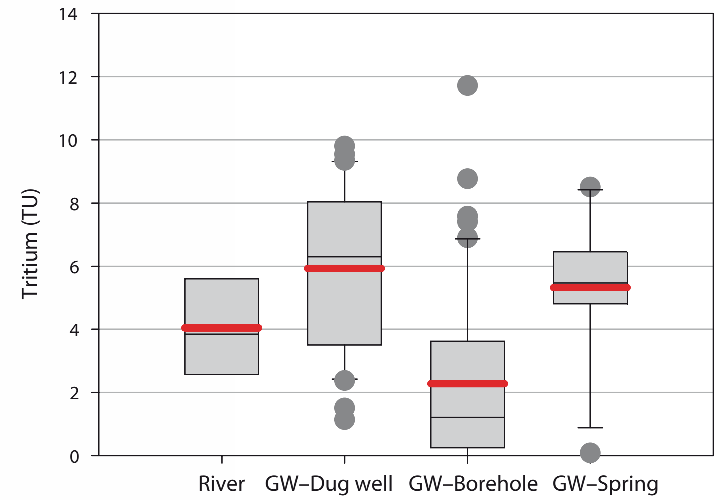
The carbon-14 interpolation (G) for the Turonian is consistent with the tritium interplation (D) in that recharge appears to occur mainly in the northeast (high carbon-14 and tritium values). Tritium and carbon-14 values decrease substantially toward the west, which indicates the groundwater flow direction. The interpolations also show that the confined aquifer zone in the center of the basin is dominated by old water (low carbon-14 and tritium values). The carbon-14 data also distinguishes two recharge periods in the deeper Turonian. The first period occurred under cold climate conditions around 18 000 years BP and the second period was about 3500 years BP. The carbon-14 interpolation for the Eocene aquifer (H) shows a dominance of older water (low carbon-14 contents) along the south. There are a few 'bullseye' areas with high carbon-14 contents. These bullseyes are centered around dug wells and may contain younger water because of leakage from the Quaternary system. The Quaternary carbon-14 interpolation (I) is similar to the tritium interpolation (F) being dominated by young (high carbon-14 values) water. Only the centre of the basin contains water that suggests an older component.

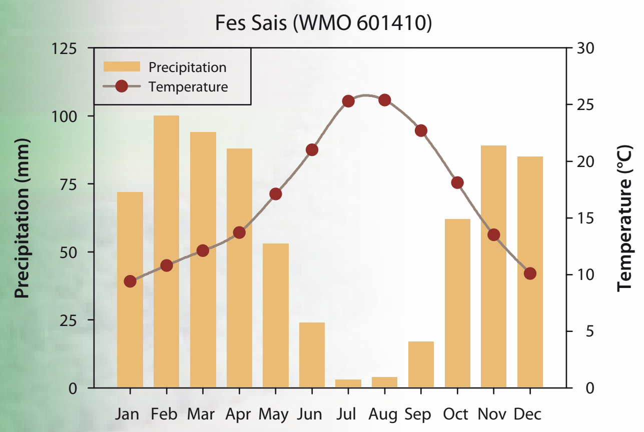
The Tassaout Springs, near the outlet of the basin, do not appear to be fed be the deep Tadla aquifers because the stable and radioisotope results are not consistent with a deep aquifer source.

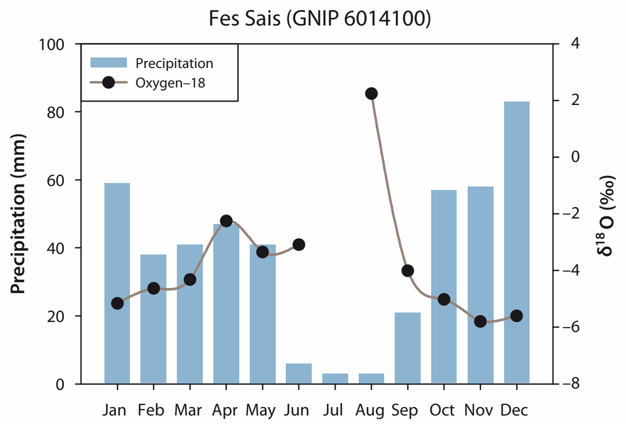
Integration of isotope results helped to develop an improved version of the Tadla hydrologic flow model for management purposes. The isotope results were used to refine permeability estimates in the basin flow model. A reduction in permeability was required for the model results to be consistent with the isotope results which yielded an improved model calibration. Thus, isotopes have been directly used to improve groundwater resource management in the Tadla basin.

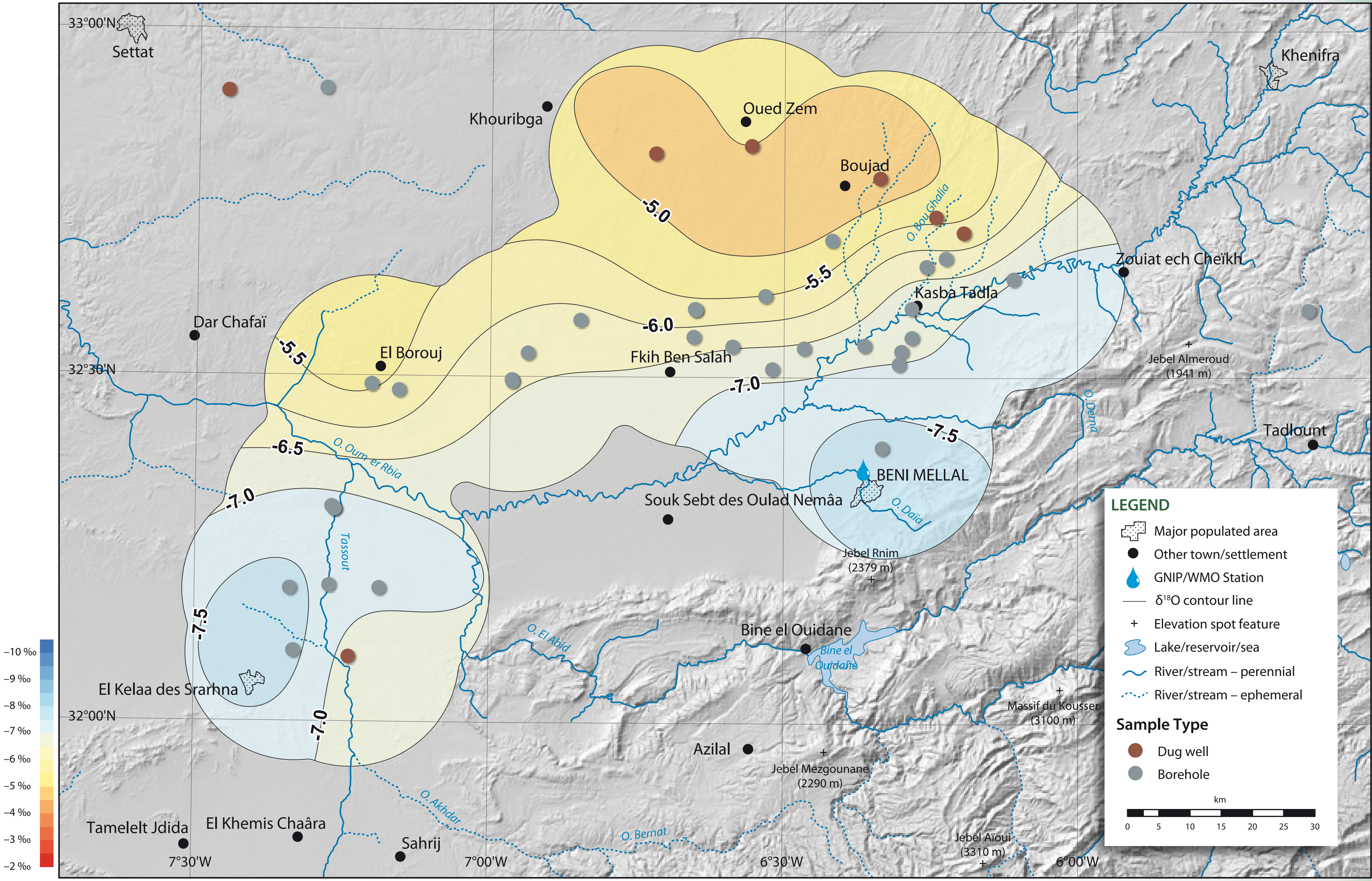






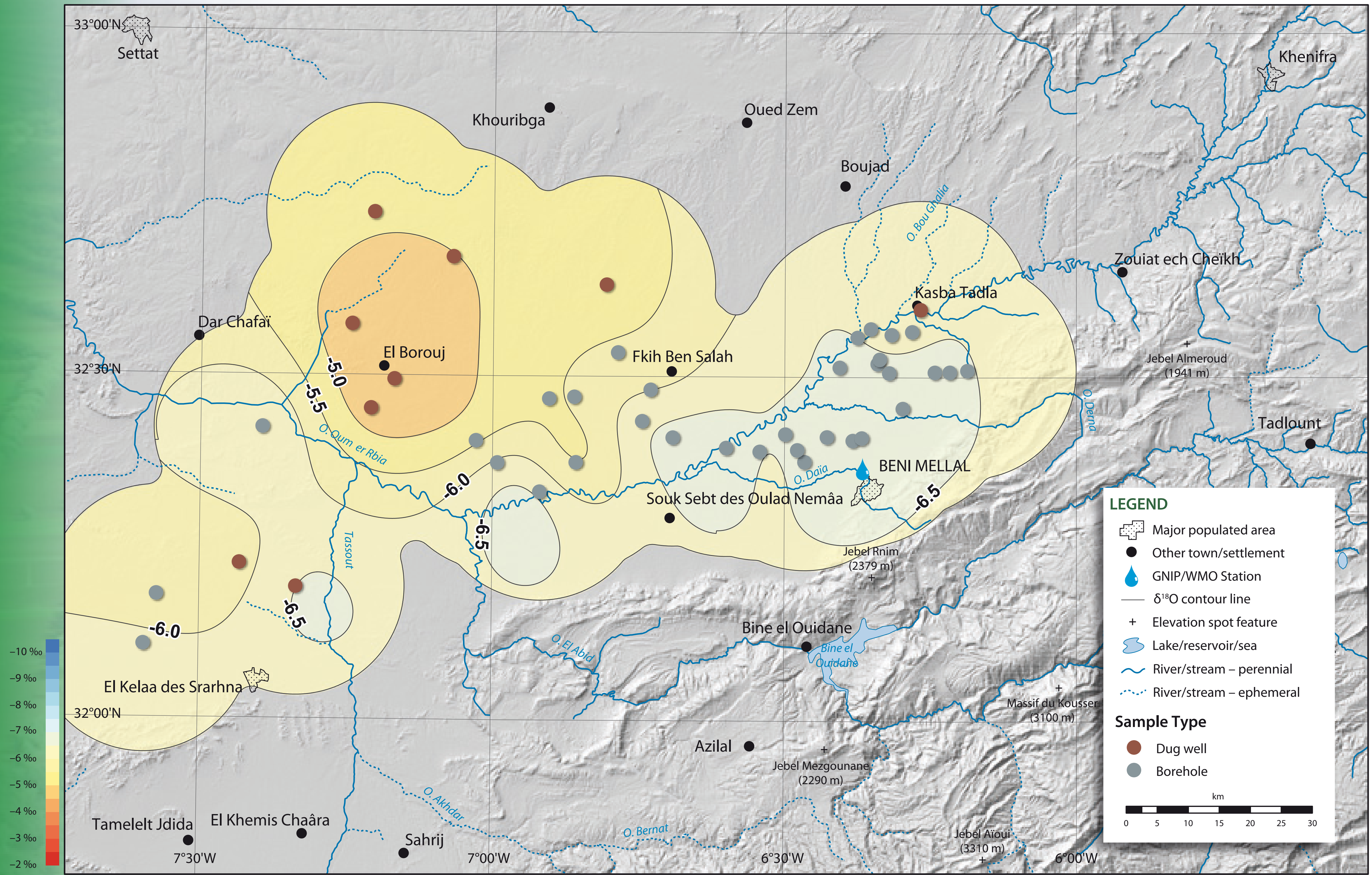






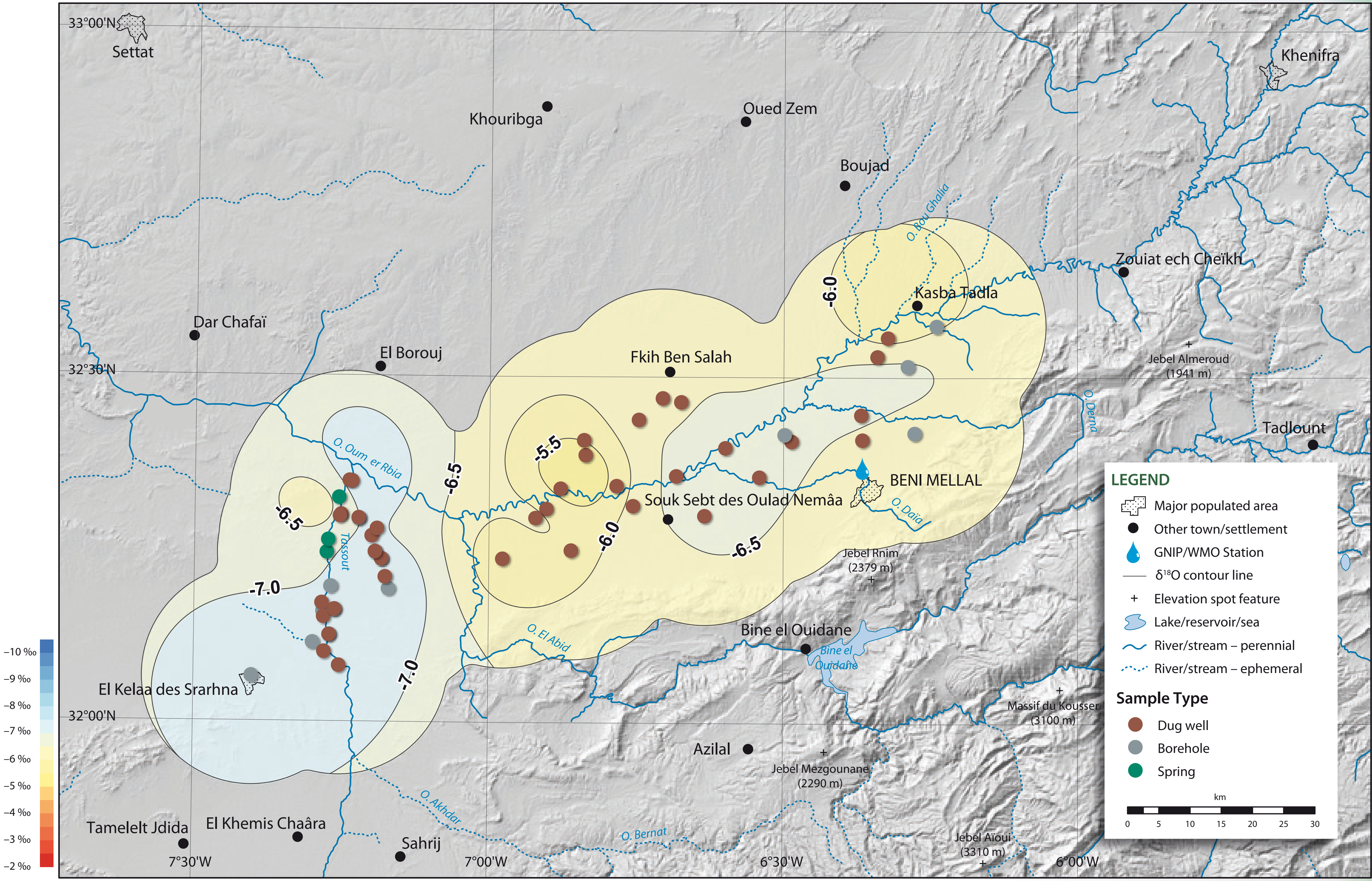
(A) Turonian aquifer oxygen-18 interpolation

Tension: 70, Smoothing: 0.5, RMSE: 0.87 ‰



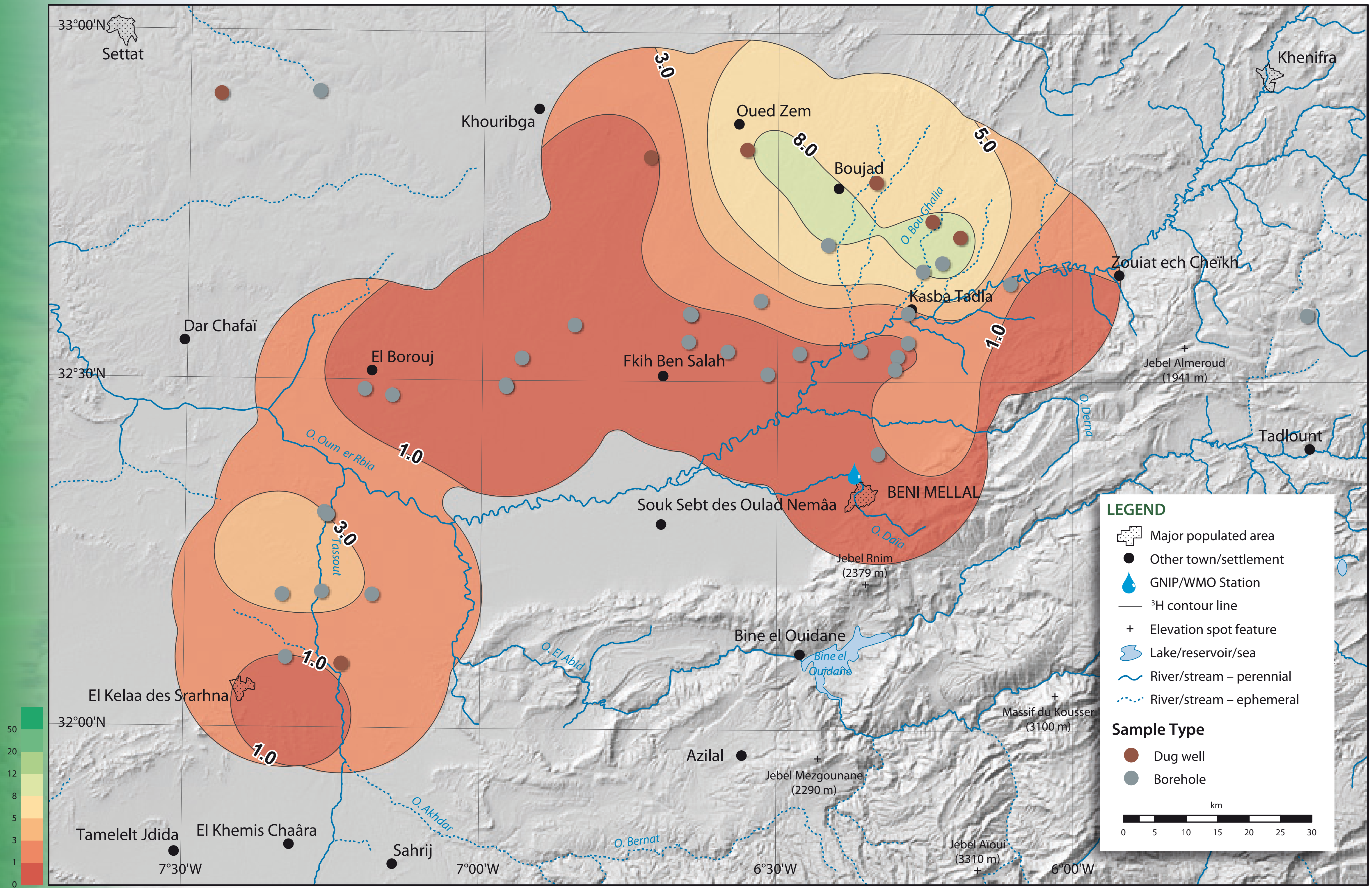
(B) Eocene aquifer oxygen-18 interpolation

Tension: 70, Smoothing: 0.5, RMSE: 0.33 ‰



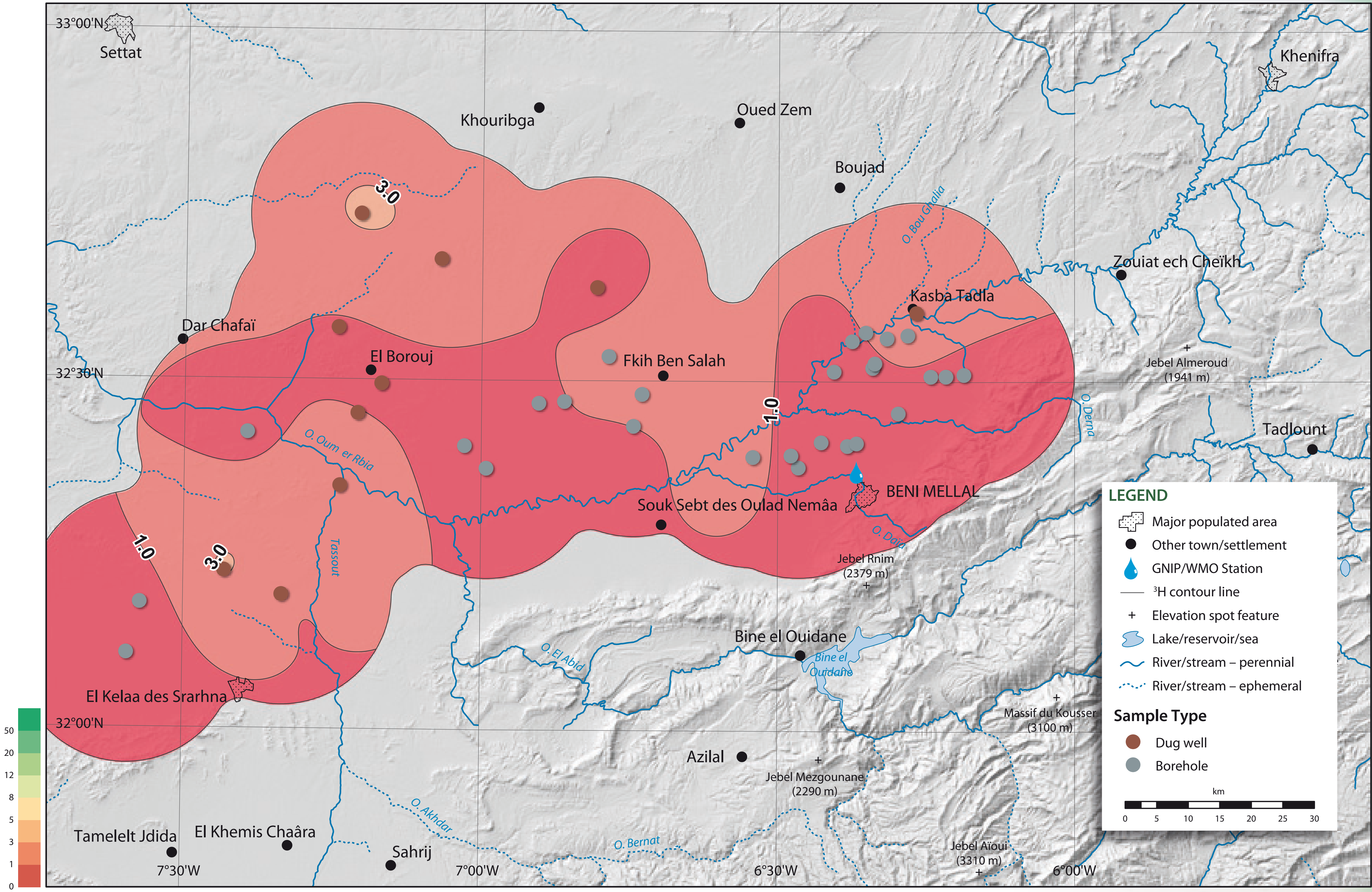
(C) Quaternary aquifer oxygen-18 interpolation

Tension: 70, Smoothing: 0.5, RMSE: 0.35 ‰



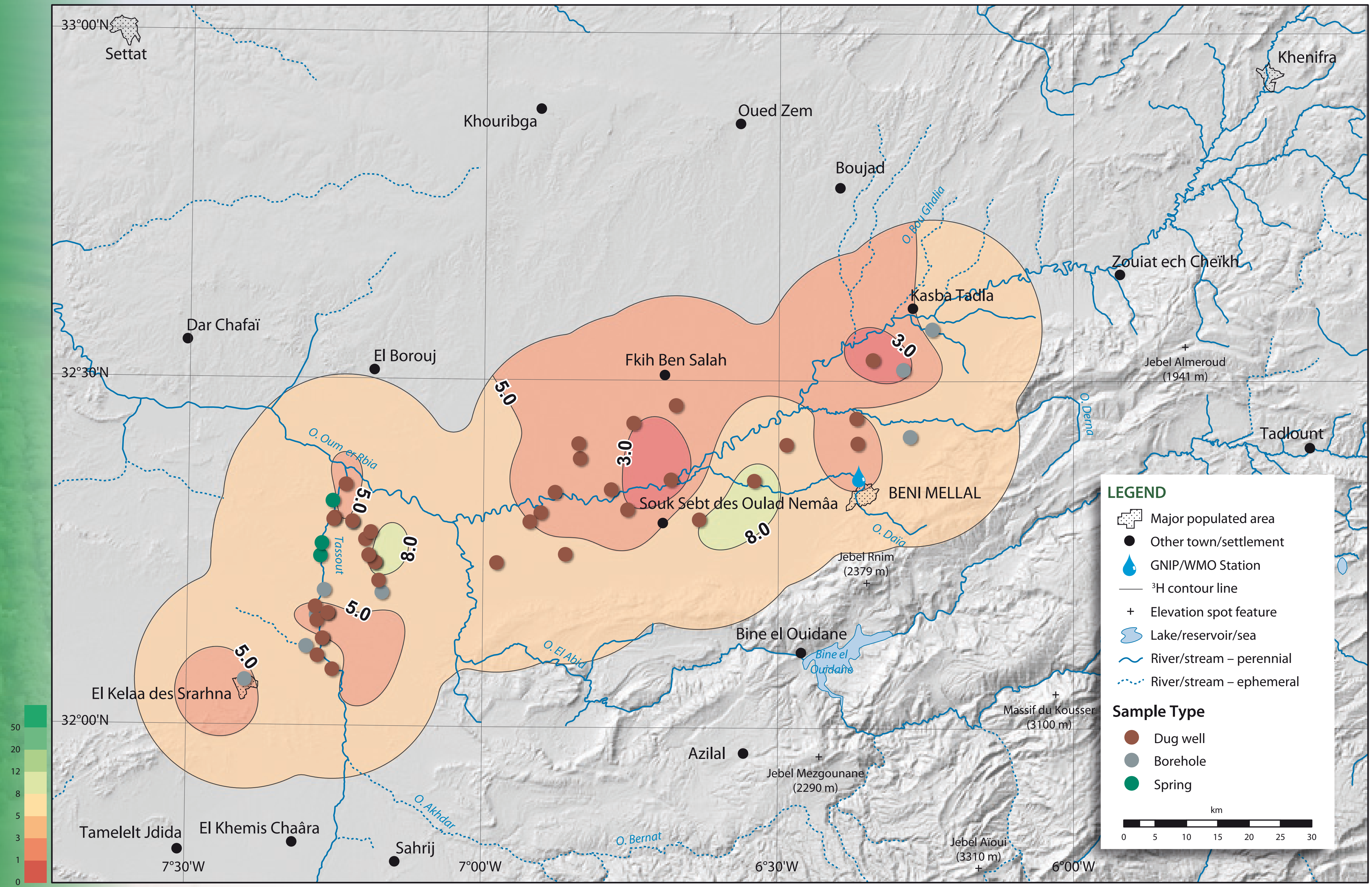
(D) Turonian aquifer tritium interpolation

Tension: 100, Smoothing: 0.5, RMSE:1.69 TU



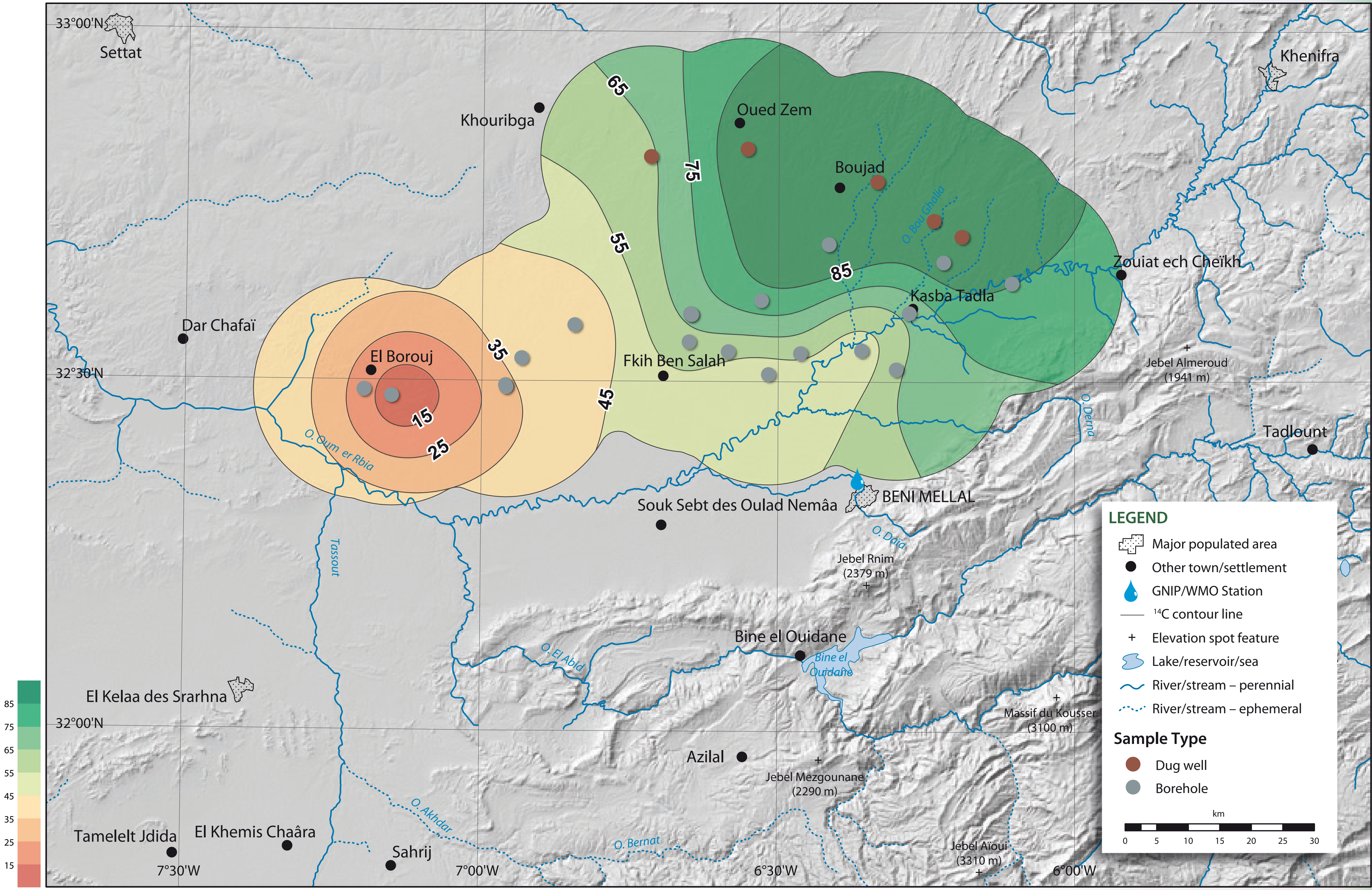
(E) Eocene aquifer tritium interpolation

Tension: 100, Smoothing: 0.5, RMSE: 0.26 TU



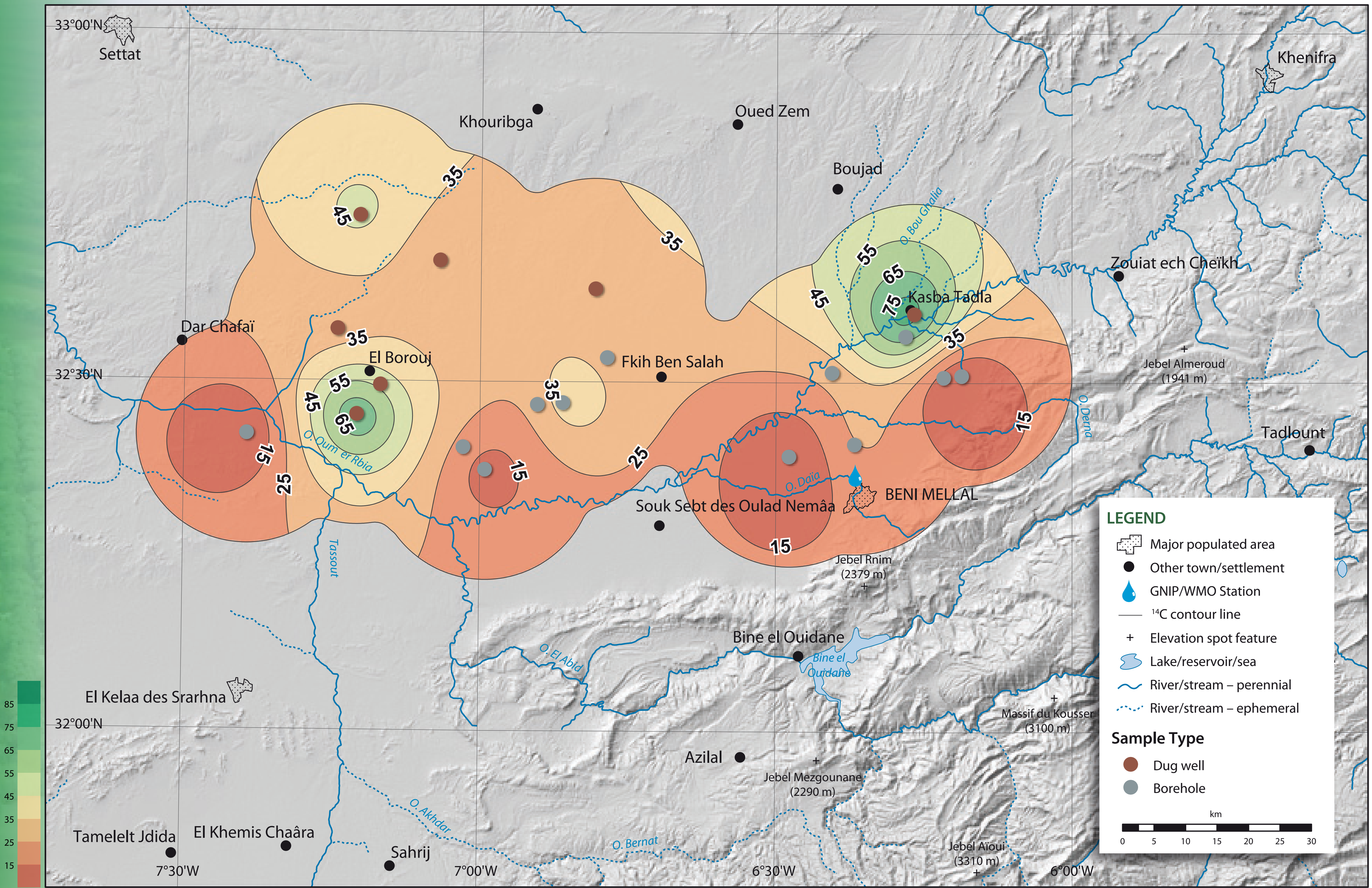
(F) Quaternary aquifer tritium interpolation

Tension: 100, Smoothing: 0.5, RMSE: 0.74 TU



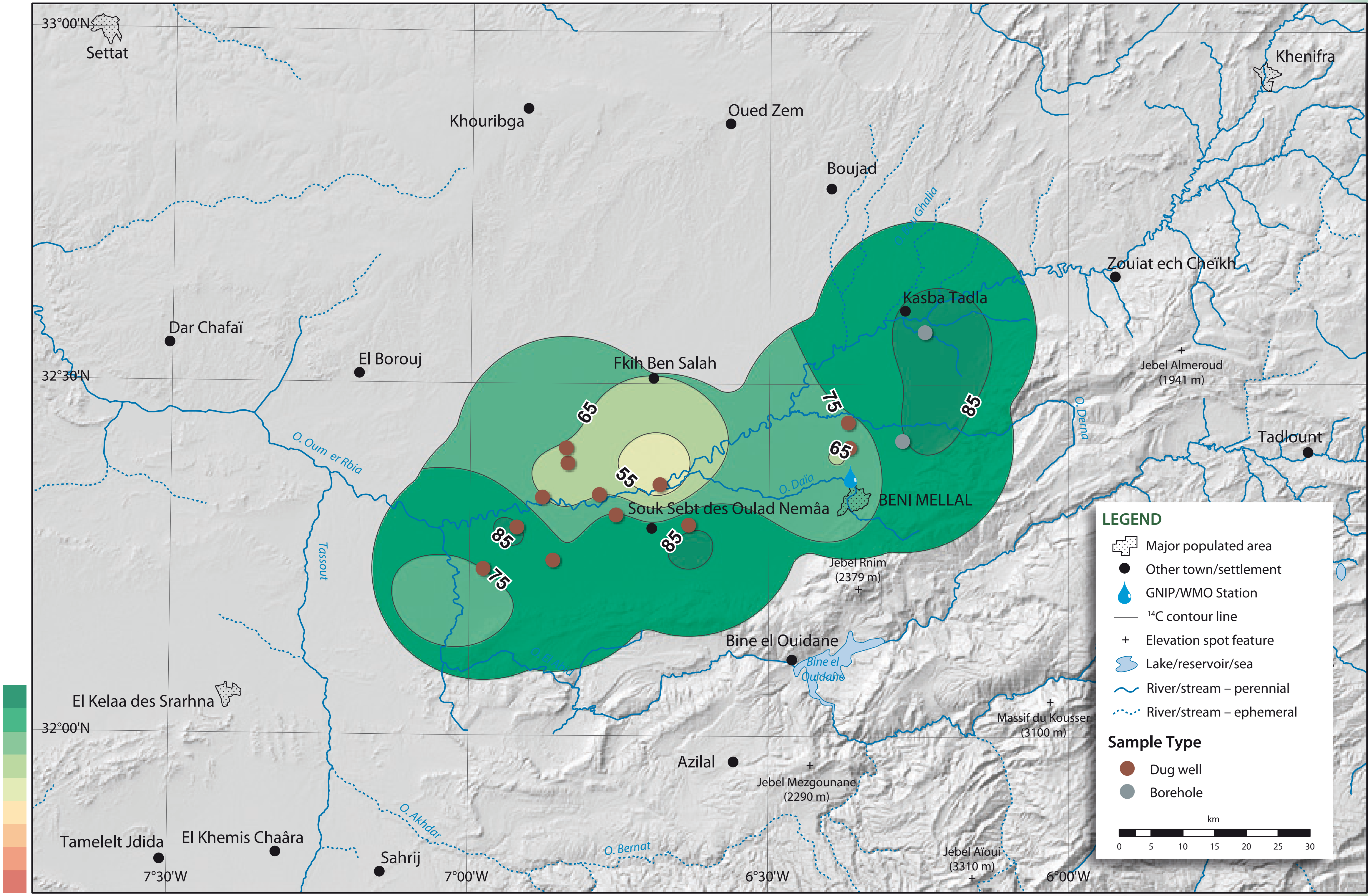
(G) Turonian aquifer ^{14}C interpolation

Tension: 100, Smoothing: 0.5, RMSE: 8.55 pMC



(H) Eocene aquifer ^{14}C interpolation

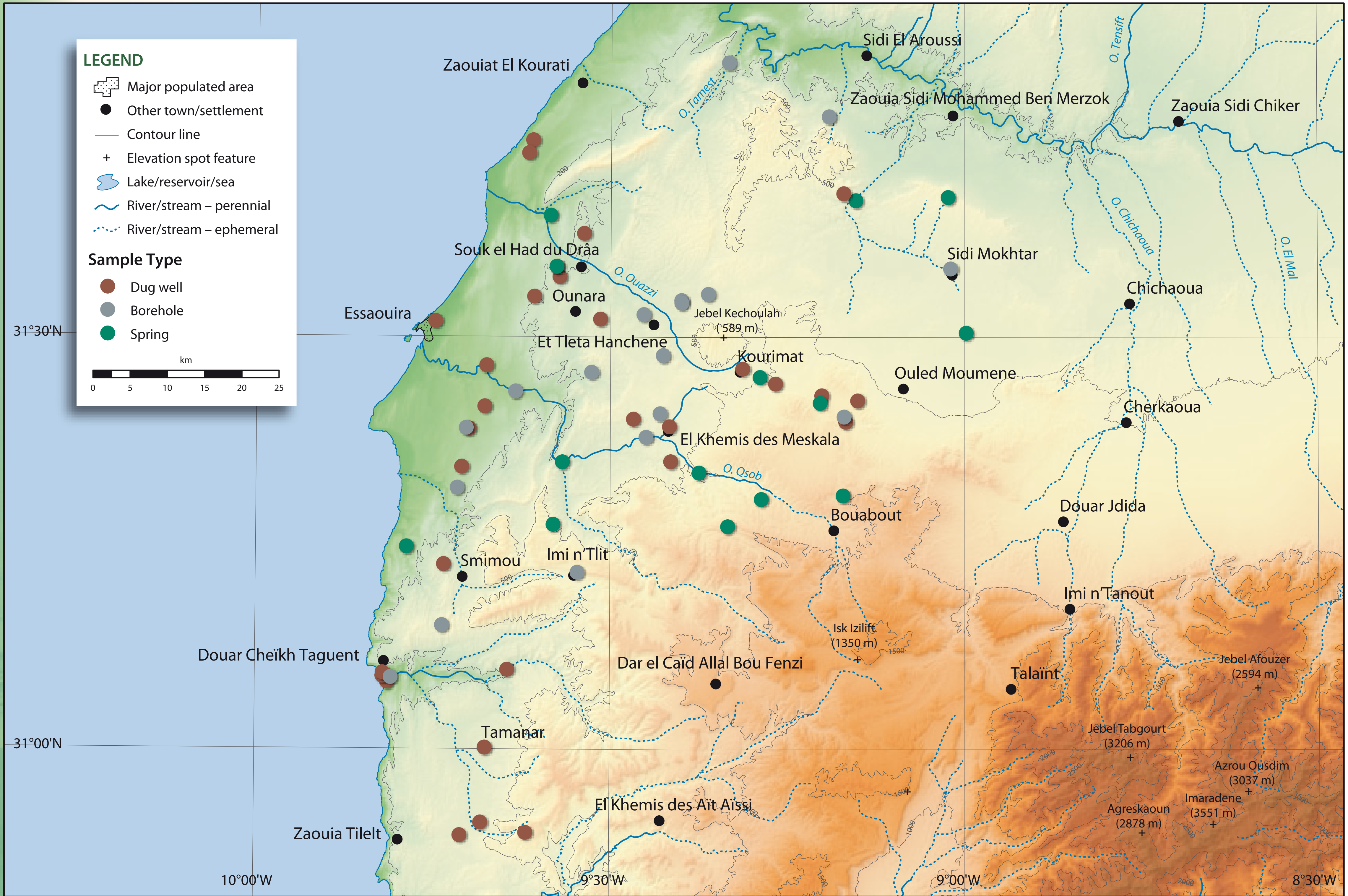
Tension: 100, Smoothing: 0.5, RMSE: 3.82 pMC



(I) Quaternary aquifer ^{14}C interpolation

Tension: 100, Smoothing: 0.5, RMSE: 3.58 pMC

Essaouira basin

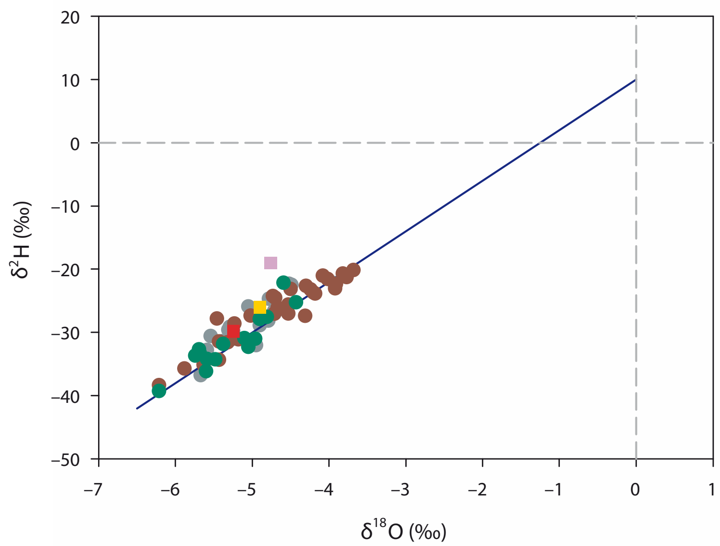

LEGEND
Major populated area
Other town/settlement
Contour line
Elevation spot feature
Lake/reservoir/sea
River/stream – perennial
River/stream – ephemeral
Sample Type
Dug well
Borehole
Spring
km
0 5 10 15 20 25
Zaouiat El Kourati
Sidi El Aroussi
Zaouia Sidi Mohammed Ben Merzok
Zaouia Sidi Chiker
O. Tamest
O. Tensift
O. Chichaoua
O. El Mal
Souk el Had du Drâa
O. Ouazzi
Sidi Mokhtar
Chichaoua
Ounara
Essaouira
Jebel Kechoulah
(589 m)
Et Tleta Hanchene
Kourimat
Ouled Moumene
Cherkaoua
El Khemis des Meskala
O. Qsob
Bouabout
Douar Jdida
Smimou
Imi n'Tlit
Imi n'Tanout
Isk Izilift
(1350 m)
Douar Cheïkh Taguent
Dar el Caïd Allal Bou Fenzi
Talaïnt
Jebel Afouzer
(2594 m)
Tamanar
Jebel Tabgourt
(3206 m)
Azrou Ousdim
(3037 m)
Imaradene
(3551 m)
Agreskaoun
(2878 m)
El Khemis des Aït Aïssi
Zaouia Tilelt
31°30'N
31°00'N
10°00'W
9°30'W
9°00'W
8°30'W

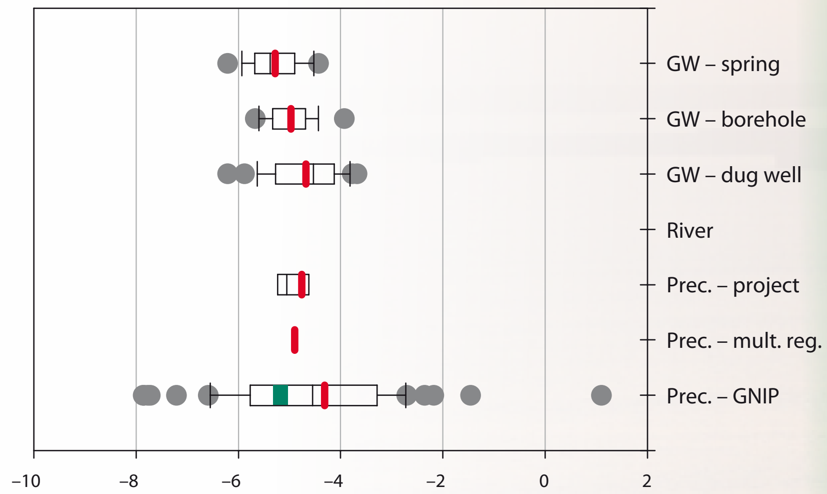
Study area: Essaouira basin
Sampling period: 2003

Background

The Essaouira basin is located between Jbel Amsittène in the south and Jbel Hadid in the north. The basin is a vast syncline open to the Atlantic Ocean. The Essaouira basin has a population of 400 000 inhabitants and is predominantly rural. The basin area is about 6000 km². The basin is characterized by limited and discontinuous water resources. It is necessary, therefore, to locate potential new areas for groundwater production in order to build integrated water supply projects.

Two main aquifers constitute the system. The Mio-Plio-Quaternary aquifer provides the bulk of the water supply and is mainly composed of sand, sandstone and conglomerates. The Cenomanian-Turonian aquifer is mainly calco-dolomitic. The Cenomanian was recently drilled for supply for the city of Essaouira. The objective of this study was the application of isotopic techniques to: determine the possible interconnections between aquifers in the coastal zone of Essaouira (Mio-Plio-Quaternary aquifer) and the aquifers in the Meskala region (Turonian aquifer); quantify mixing between the different aquifers within the Meskala region; and date groundwaters in the coastal zone and Meskala region aquifers.





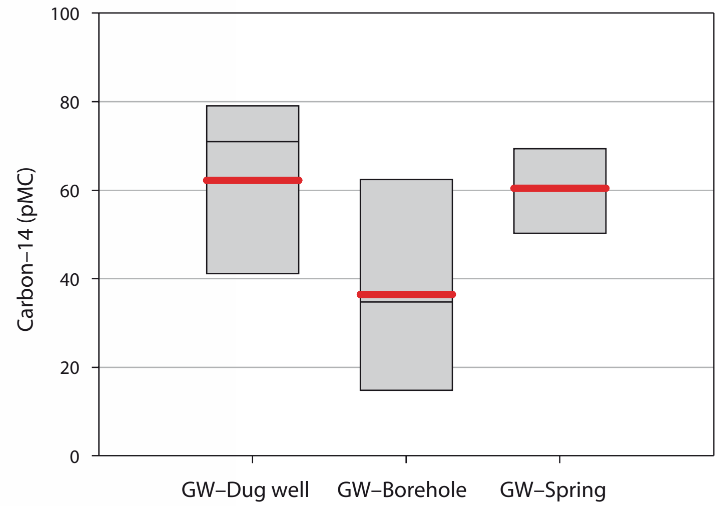
Precipitation		$\delta^{18}O$ (‰) n	Median	Mean ± St. dev.	δ^2H (‰) n	Median	Mean ± St. dev.	Tritium (TU) n	Mean ± St. dev.	Annual prec. (mm)	Temperature (°C)
GNIP station FES SAIS	■ (red)	60	−4.55	−5.24	60	−23.3	−29.8			457	17.4
Interpolation – multiple reg.	■ (yellow)			−4.90			−26.0				
Project	■ (pink)	7	−5.06	−4.76 ± 0.8	7	−20.6	−19.0 ± 7.1				

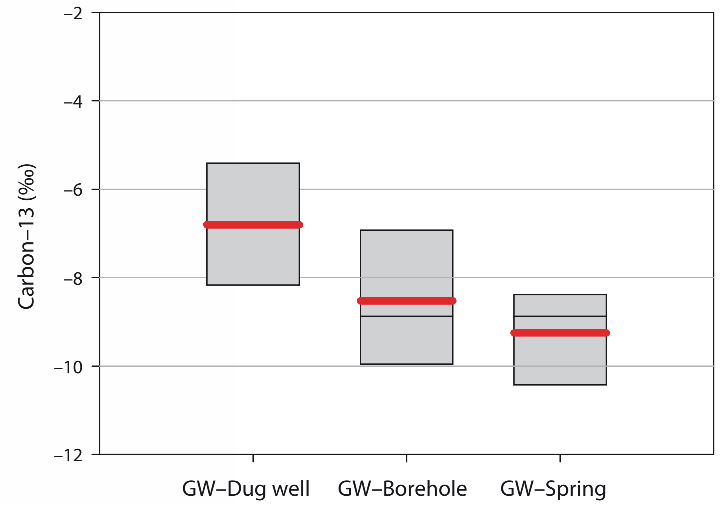
Surface waters		$\delta^{18}O$ n	Median	Mean ± St. dev.	δ^2H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.
Lake/reservoir/sea	▲ (orange)								
River	▲ (salmon)								

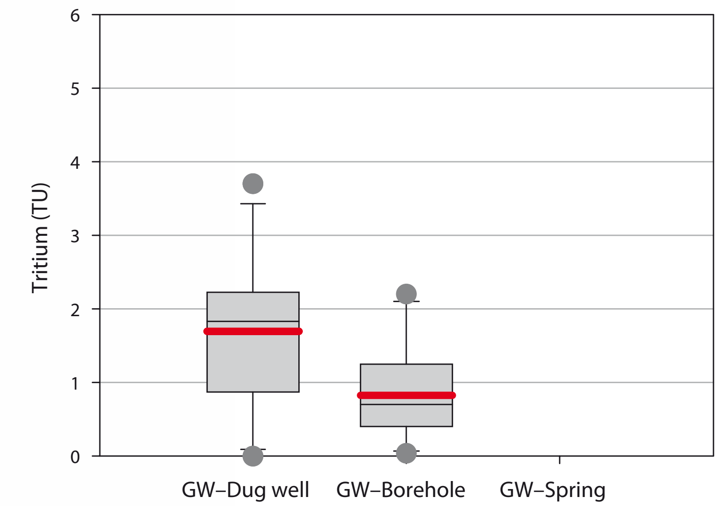
Groundwaters		$\delta^{18}O$ n	Median	Mean ± St. dev.	δ^2H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.	^{14}C (pMC) n	Mean ± St. dev.	$\delta^{13}C$ (‰) n	Mean ± St. dev.
GW–Borehole	● (grey)	18	−4.93	−4.97 ± 0.5	18	−28.5	−28.1 ± 3.9	11	0.8 ± 0.7	6	36.5 ± 25.1	5	−8.5 ± 1.7
GW–Dug well	● (brown)	29	−4.53	−4.68 ± 0.7	29	−25.6	−26.5 ± 5.0	18	1.7 ± 1.1	5	62.2 ± 24.2	4	−6.8 ± 1.4
GW–Spring	● (green)	15	−5.38	−5.28 ± 0.5	15	−32.3	−31.5 ± 4.3			6	60.4 ± 9.9	6	−8.9 ± 1.1

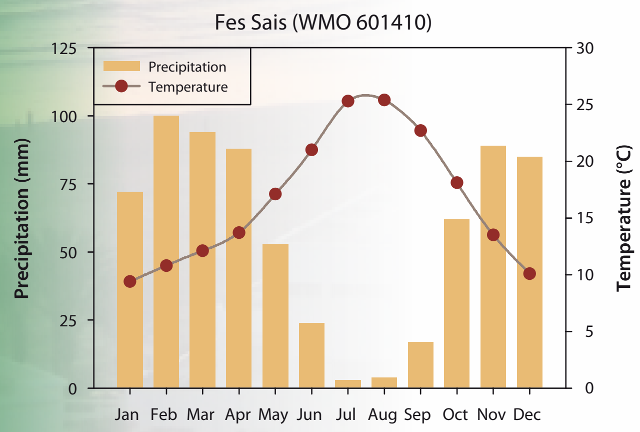
Results

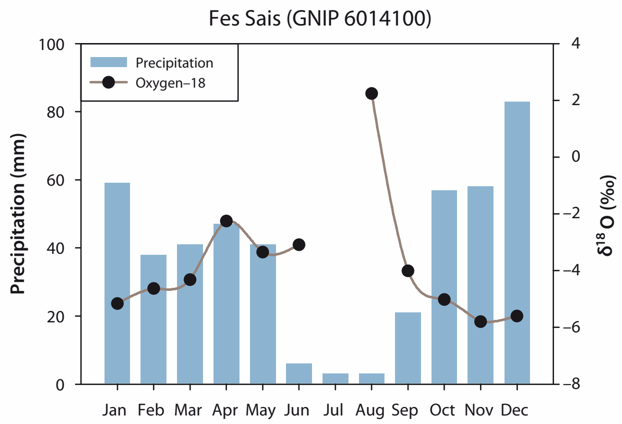
The stable isotope data show that most groundwater in the basin is not significantly affected by evaporation. Rainwater infiltrates quickly. This rapid infiltration may be related to the nature of the karst terrain (dolomitic limestone of Turonian age). There appears to be little connection or mixing between coastal zone aquifers and those of Meskala, based on the distinct stable isotope signature of the two aquifers. This difference can also be seen in the $\delta^{18}O$ interpolation plot (A) where more negative values occur in the west as opposed to the coastal areas to the east. The isotope signatures of the Turonian, Plio-Quaternary and Eocene aquifers in the Meskala region are not distinct, suggesting that there may be substantial vertical mixing between the aquifers. The recharge altitude estimated using stable isotopes suggests that maximum altitudes for coastal zone aquifers of Essaouira are about 600 m, which is reasonable for this region. In Meskala, the maximum recharge altitude is estimated to be 840 m, as indicated by the stable isotope values compared with typical isotope contents in the coastal area around Essaouira. The tritium results show that most shallow waters in the Essaouira basin are similar to modern precipitation in the coastal region. However in the deep aquifer the groundwater age is older than 60 years. The tritium interpolation map (B) of the deeper waters shows generally low TU values across the study area.

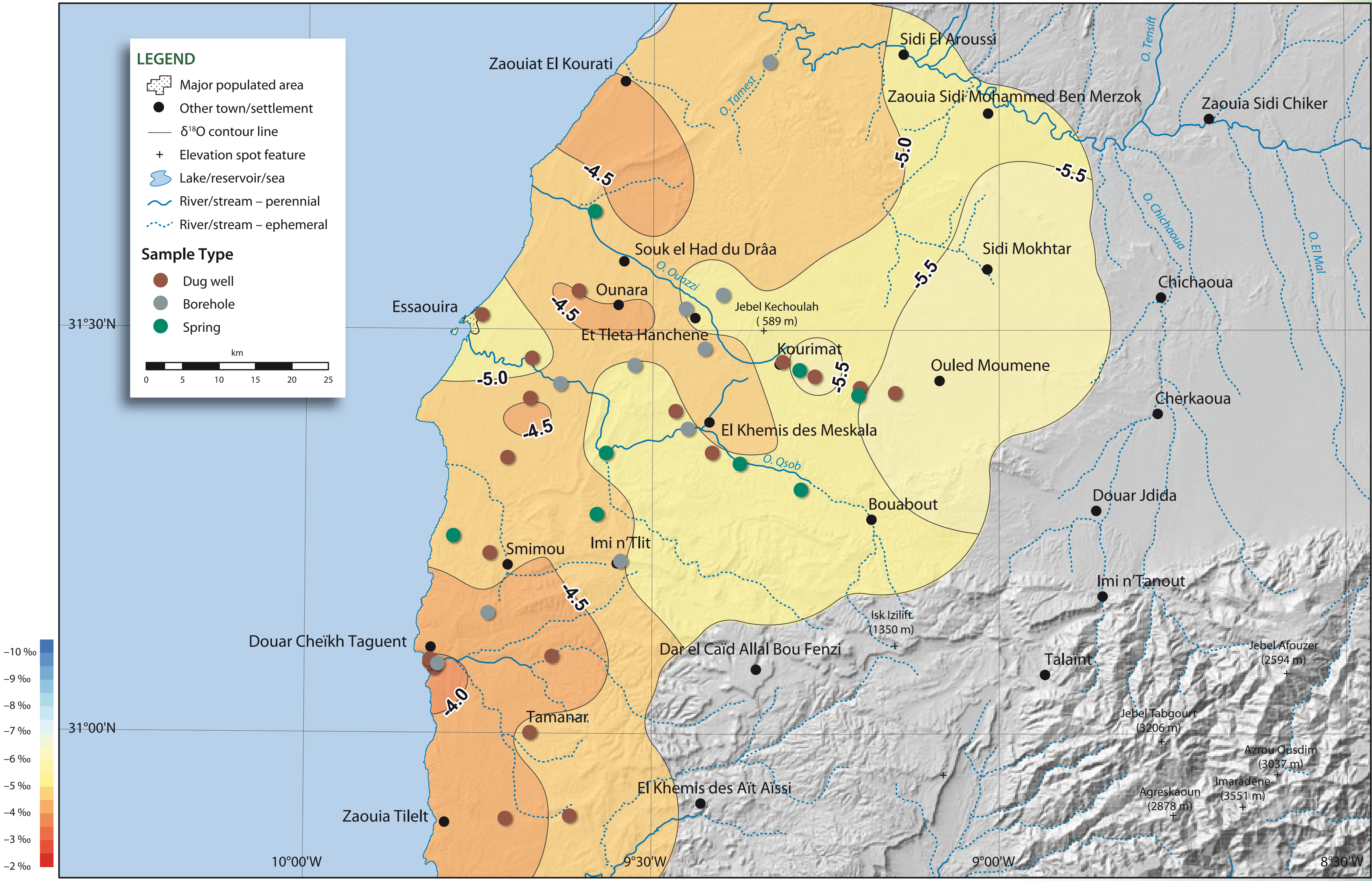






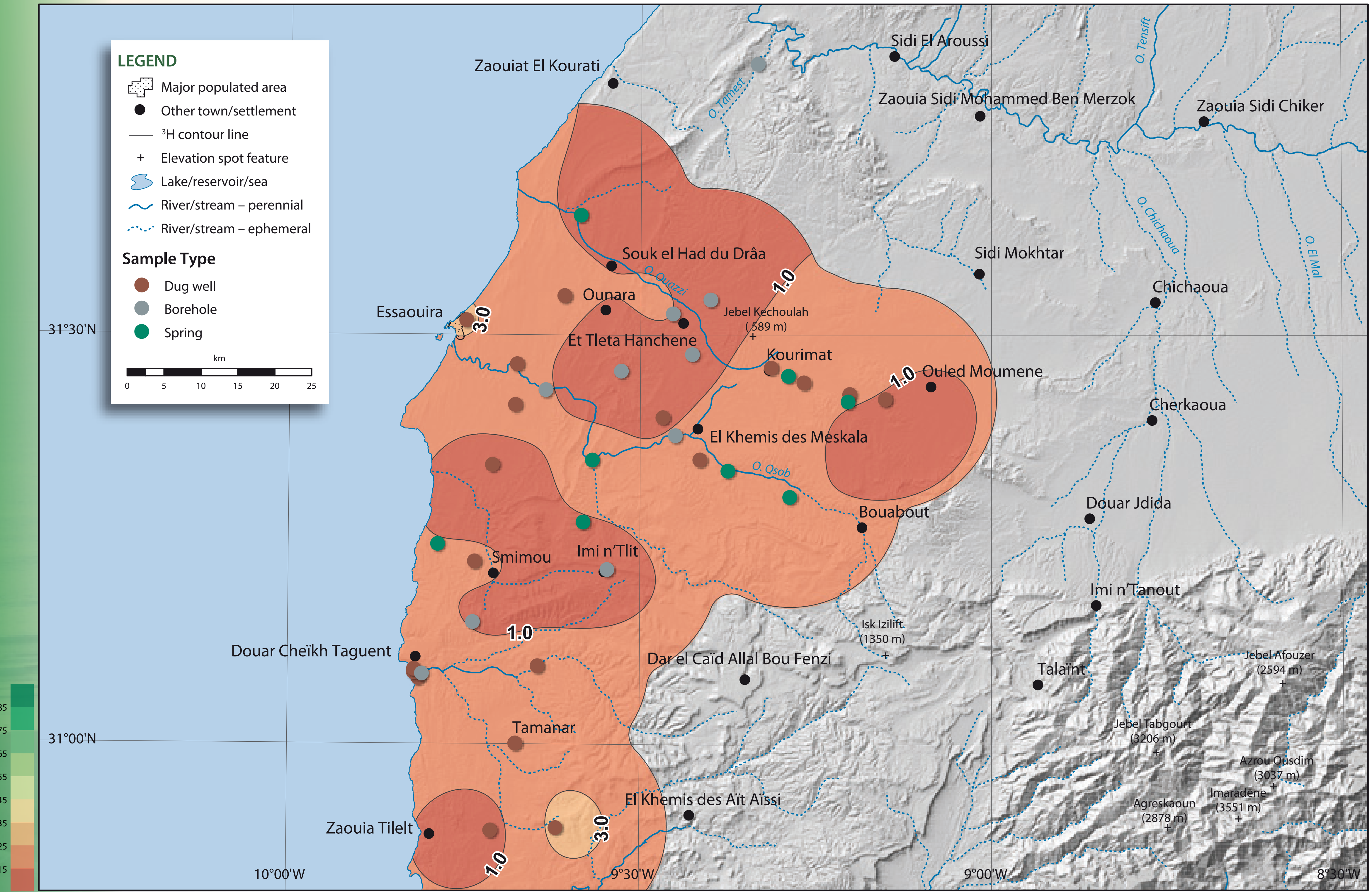






(A) Oxygen-18 interpolation

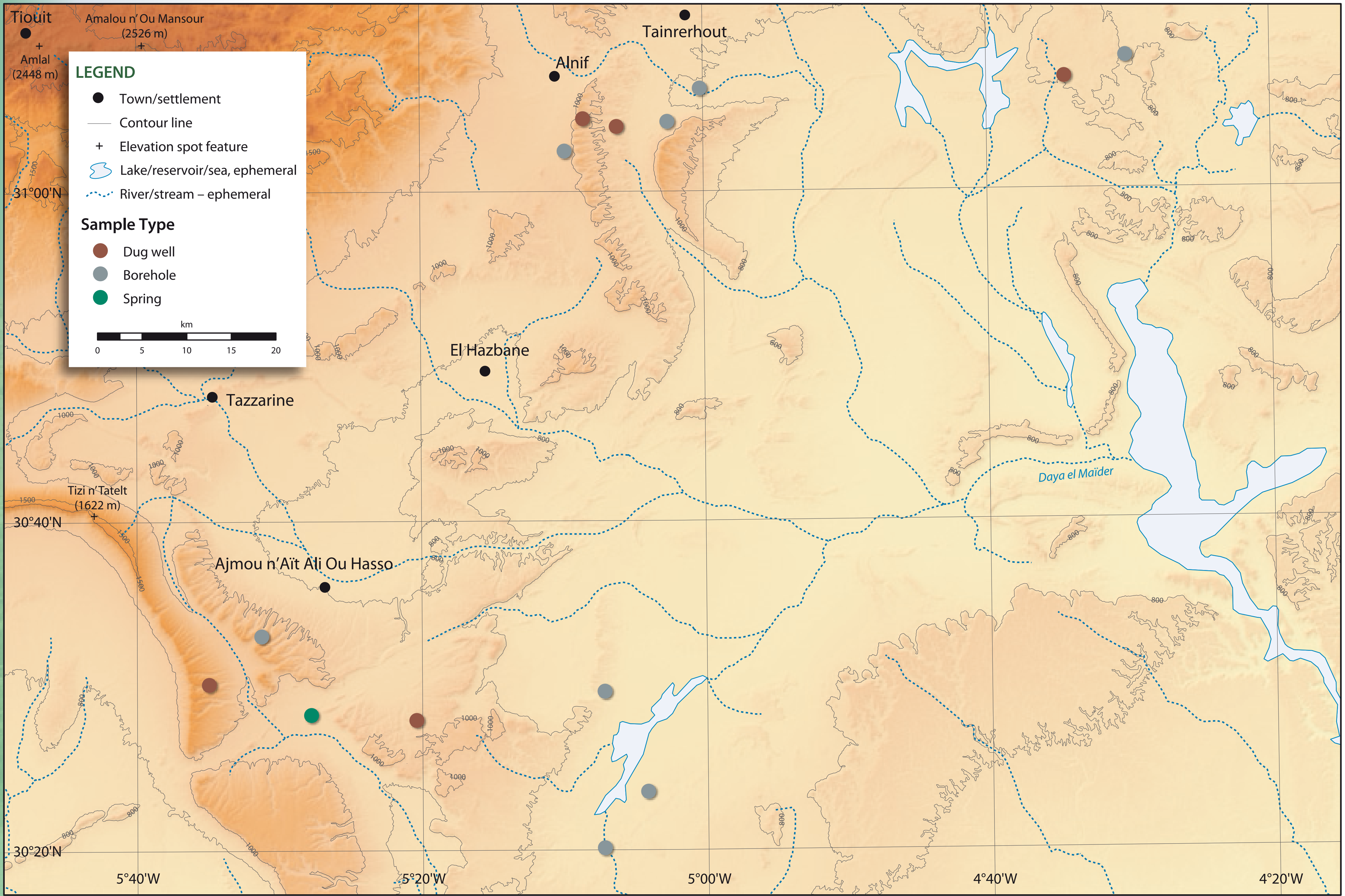
Tension: 70, Smoothing: 0.5, RMSE: 0.52 ‰



(B) Tritium interpolation

Tension: 100, Smoothing: 0.5, RMSE: 1.53 TU

Maïdere area



Tiouit
Amalou n'Ou Mansour (2526 m)
Amlal (2448 m)
LEGEND
Town/settlement
Contour line
Elevation spot feature
Lake/reservoir/sea, ephemeral
River/stream – ephemeral
Sample Type
Dug well
Borehole
Spring
km
0 5 10 15 20
Alnif
Tainrerhout
El Hazbane
Tazzarine
Tizi n'Tatelt (1622 m)
Ajmou n'Aït Ali Ou Hasso
Daya el Maïder
31°00'N
30°40'N
30°20'N
5°40'W
5°20'W
5°00'W
4°40'W
4°20'W

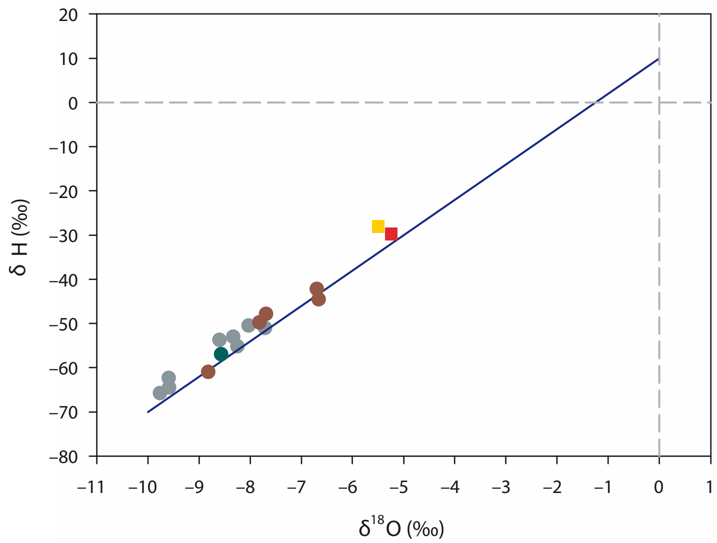
Study area: Maïdere area
Sampling period: 1995–2001

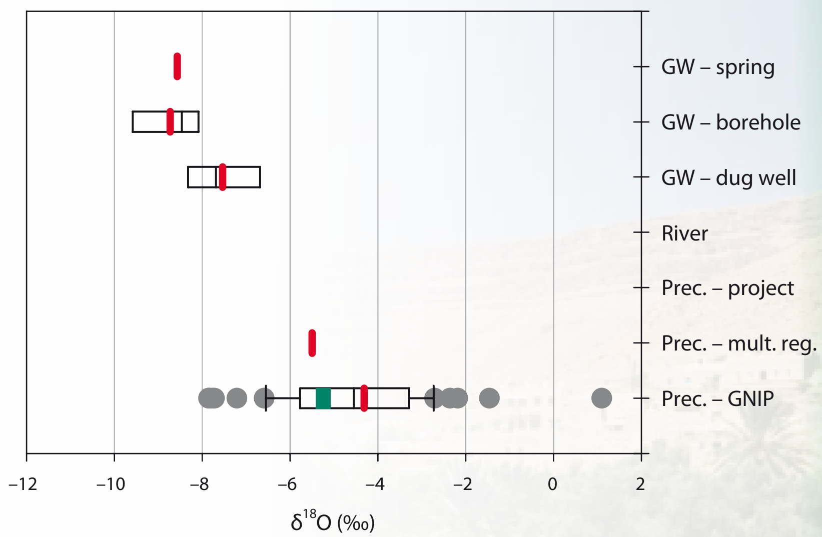
Background

The Maïdere area of the Errachidia basin, located in the south of Morocco, extends over 13 000 km². It is bounded by the Jebels Sarhro-Ougnate in the north, by the plain of Tafilalt in the east, by Jebel Bani in the west and in the south and south-east by the Hamada Cretaceous rocks of Kem-Kem. The Maïdere basin is characterized by an arid and semi-arid climate with a mean rainfall of about 80 mm/a, a mean monthly air temperature in the range 15–40°C, and very high evapotranspiration.

Lithological formations cropping out in the basin are divided into compartments by major faults of NE-SW direction. This fault network creates aquifers that are laterally discontinuous. Five aquifers constitute the multilayer system: Precambrian, Lower Cambrian, Middle Cambrian, Ordovician and Quaternary. Ordovician outcrops cover a large area and constitute the most important aquifer in the basin. Furthermore, gases like carbon dioxide are observed to bubble out in some wells.

The compartmentalized situation makes it very difficult to apply methods based on piezometric measurements. Thus, a geochemical and isotopic study was undertaken to better understand the hydrodynamic functioning of the aquifer units and to determinate the origin of the CO_2 gas. Fourteen samples were collected for geochemical and isotopic analysis.





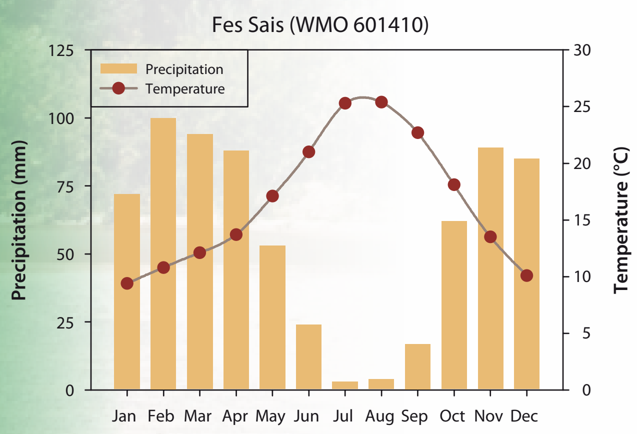
Precipitation		δ18O (‰) n	Median	Mean ± St. dev.	δ2H (‰) n	Median	Mean ± St. dev.	Tritium (TU) n	Mean ± St. dev.	Annual prec. (mm)	Temperature (ºC)
GNIP station FES SAIS		60	−4.55	−5.24	60	−23.3	−29.8			457	17.4
Interpolation – multiple reg.				−5.50			−28.0				
Project											

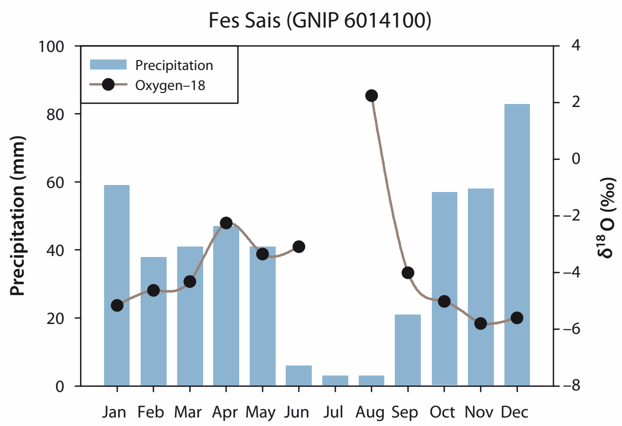
Surface waters		δ18O n	Median	Mean ± St. dev.	δ2H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.
Lake/reservoir/sea									
River									

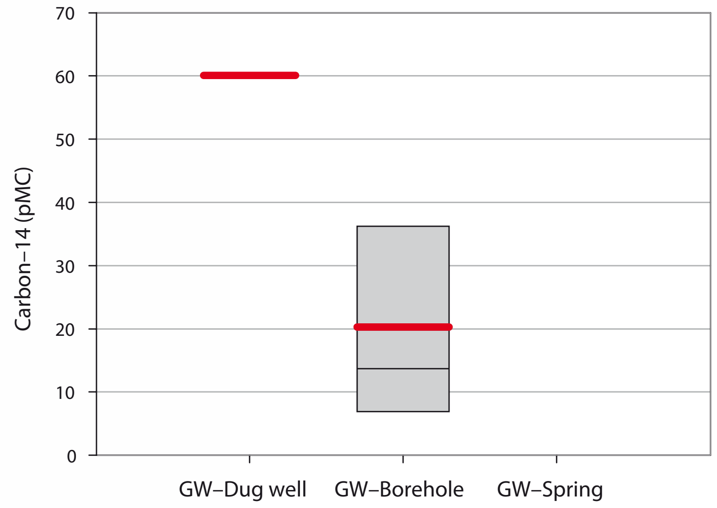
Groundwaters		δ18O n	Median	Mean ± St. dev.	δ2H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.	14C (pMC) n	Mean ± St. dev.	δ13C (‰) n	Mean ± St. dev.
GW–Borehole		8	−8.47	−8.73 ± 0.8	8	−54.5	−57.0 ± 6.2	8	1.9 ± 2.3	8	20.1 ± 17.3	8	−6.5 ± 2.0
GW–Dug well		5	−7.69	−7.54 ± 0.9	5	−47.9	−49.1 ± 7.3	5	3.0 ± 2.9	1	60.0	1	−8.7
GW–Spring		1		−8.57	1		−57.0	1	0.1				

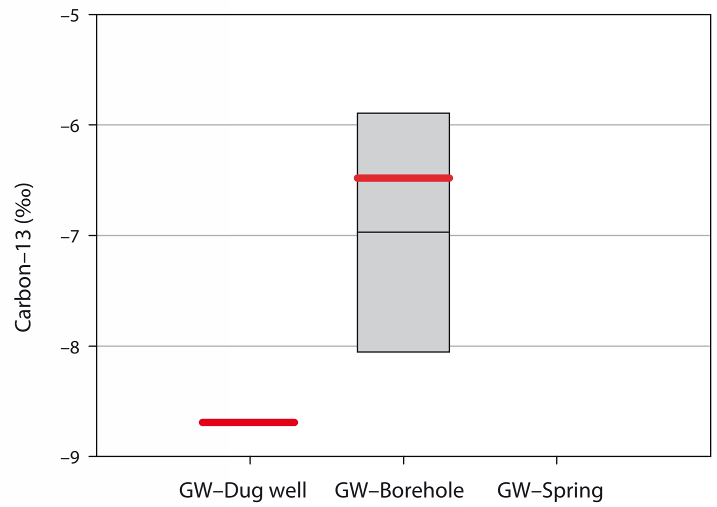
Results

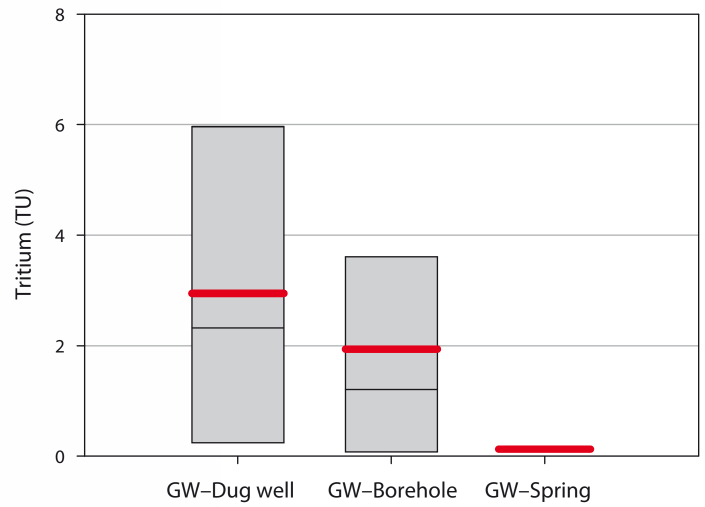
The geochemical study of groundwater investigated in the Maïdere area shows that mineralization is mainly governed by dissolution of carbonates, and halite and cation exchange with clay minerals. Some samples show contributions of deep CO_2. The isotopic study revealed fossil groundwaters in the Ordovician and Upper Cambrian aquifers (ages between 12 000 and 18 000 year BP). However, recent recharge was detected using tritium at M'cissi, Tiguirna, Mejrane, N'kob, Timerzite, Imikerne and Tazarine. The deuterium excess values for most water samples are between +10 and +14‰, indicating that the origin of precipitation is from the Atlantic Ocean and the Mediterranean sea. Because of the limited number of samples no interpolations were made for this project.



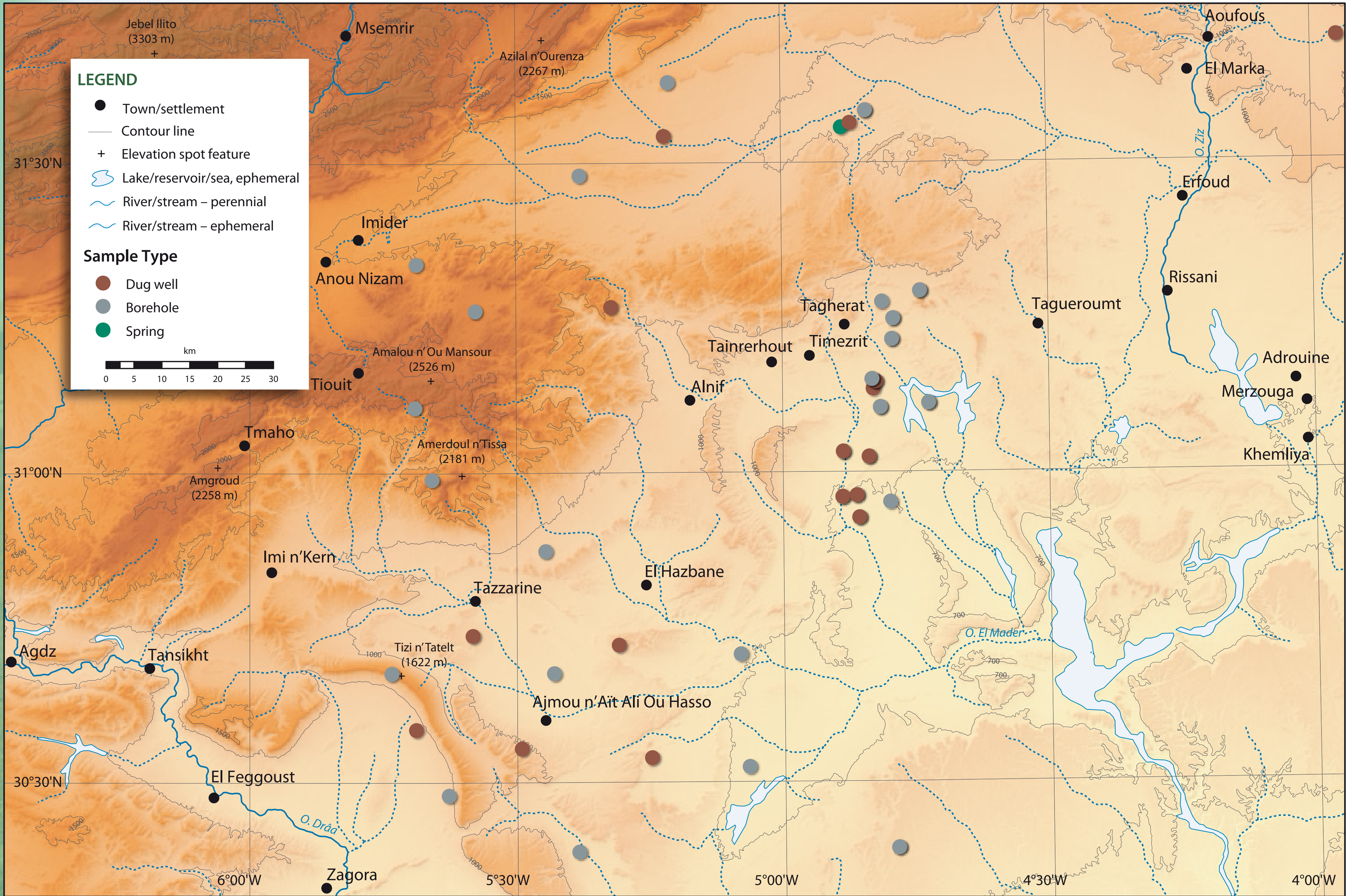








Tafilalet area

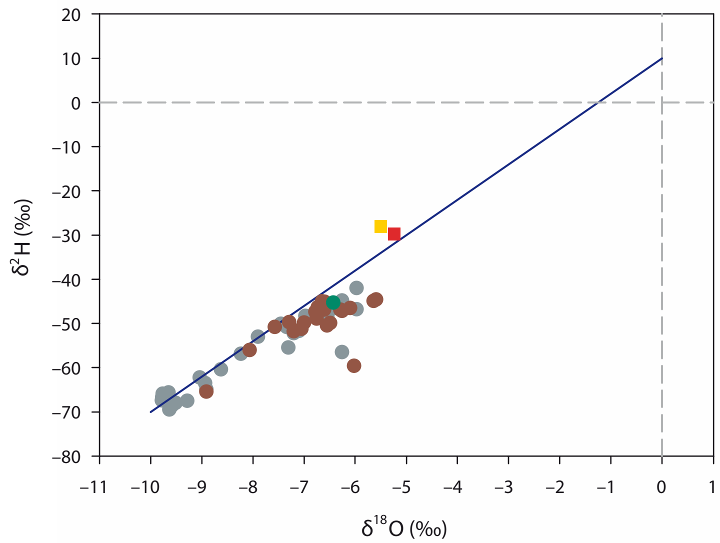

LEGEND
Town/settlement
Contour line
Elevation spot feature
Lake/reservoir/sea, ephemeral
River/stream – perennial
River/stream – ephemeral
Sample Type
Dug well
Borehole
Spring
km
0 5 10 15 20 25 30
Jebel Ilito (3303 m)
Msemrir
Azilal n'Ourenza (2267 m)
Aoufous
El Marka
O. Ziz
Erfoud
Rissani
Imider
Anou Nizam
Tagherat
Tagueroumt
Tainrerhout
Timezrit
Alnif
Adrouine
Merzouga
Khemliya
Amalou n'Ou Mansour (2526 m)
Tiouit
Tmaho
Amerdoul n'Tissa (2181 m)
Amgroud (2258 m)
Imi n'Kern
Tazzarine
El Hazbane
O. El Mader
Agdz
Tansikht
Tizi n'Tatelt (1622 m)
Ajmou n'Aït Ali Ou Hasso
El Feggoust
O. Drâa
Zagora
31°30'N
31°00'N
30°30'N
6°00'W
5°30'W
5°00'W
4°30'W
4°00'W

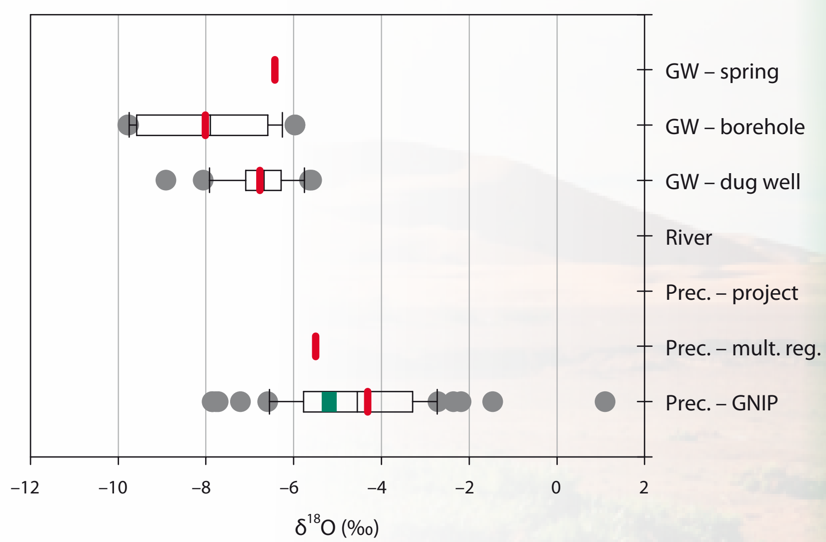
Study area: Tafilalet area
Sampling period: 1999

Background

The Tafilalet area of the Errachidia basin is located in the southwest of Morocco in the pre-Saharan zone, between latitudes 31°10′ N and 31°30′ N and longitudes 4°10′ W and 4°20′ W. The average rainfall is about 80 mm/a in the low altitude region and 129 mm/a in the higher altitude region. The rivers Ziz and Rheris are the principal perennial water courses of this region.

Although groundwater potential is good in this region, the salinity of groundwater can be high. The threat of groundwater salinity to the supply of drinking water and the impacts of the agricultural economy in this region are a serious problem. Therefore, it is important to understand the mechanisms of groundwater salinization, the interconnection between surface water and groundwater, and the sources of recharge in order to optimally manage the water resources in this region. Groundwater occurs in a multi-aquifer system that contains both confined and unconfined conditions (Infracenomanian, Cenomanian-Turonian, Senonian and Quaternary aquifers).





Precipitation		$\delta^{18}O$ (‰) n	Median	Mean ± St. dev.	δ^2H (‰) n	Median	Mean ± St. dev.	Tritium (TU) n	Mean ± St. dev.	Annual prec. (mm)		Temperature (ºC)	
GNIP station FES SAIS	■ (red)	60	−4.55	−5.24 ± 0.9	0		−29.8 ± 5.5			457		17.4	
Interpolation – multiple reg.	■ (yellow)			−5.50			−28.0						
Project	■ (pink)												
Surface waters		$\delta^{18}O$ n	Median	Mean ± St. dev.	δ^2H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.				
Lake/reservoir/sea	▲												
River	▲												
Groundwaters		$\delta^{18}O$ n	Median	Mean ± St. dev.	δ^2H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.	^{14}C (pMC) n	Mean ± St. dev.	$\delta^{13}C$ (‰) n	Mean ± St. dev.
GW–Borehole	● (grey)	31	−7.90	−8.01 ± 1.4	31	−56.5	−57.1 ± 9.0	20	5.8 ± 6.5	14	17.5 ± 27.4	14	−3.3 ± 6.1
GW–Dug well	● (brown)	22	−6.68	−6.77 ± 08	22	−48.2	−49.6 ± 5.1	21	12.1± 5.3	1	26.9	1	−4.1
GW–Spring	● (green)	1		−6.43	1		−45.3	1	11.0	1	86.9	1	−11.6

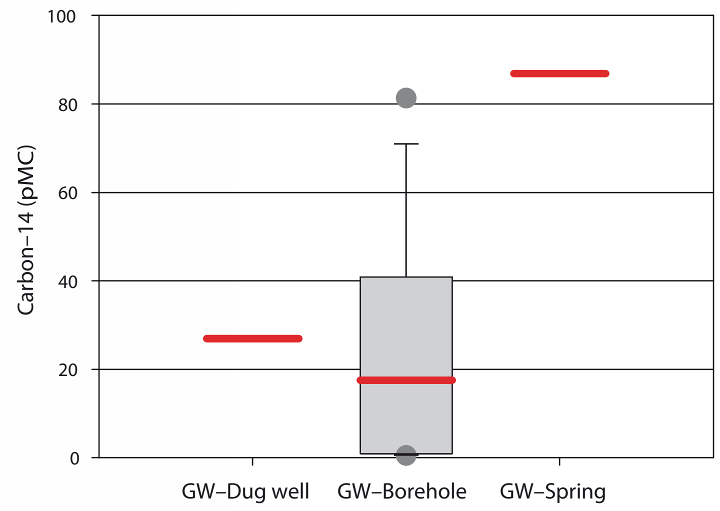
Results

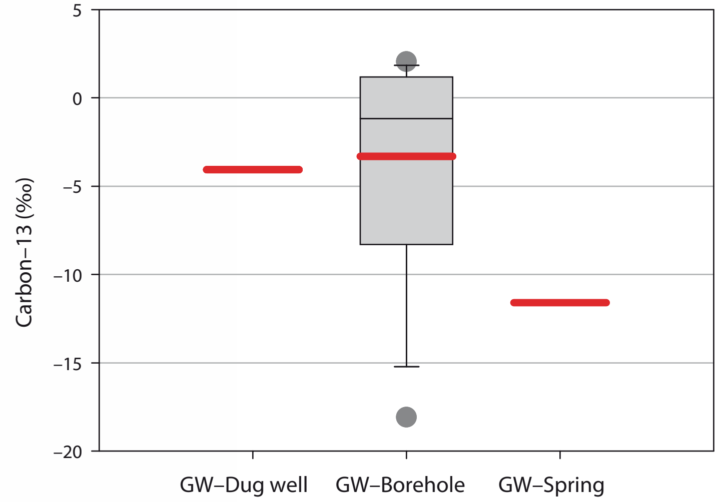
The Infracenomanian aquifer of the Errachidia basin is unconfined. Groundwater in this aquifer has significantly more negative stable isotope values than present-day precipitation, has almost no tritium (<0.5 TU), and the carbon-14 groundwater ages are old (25 000 to 40 000 BP), indicating little to no recent recharge. The very negative stable isotope values and old groundwater ages suggest that this aquifer was probably recharged during the Pleistocene period. Groundwater salinity in this aquifer is mainly derived from dissolution of the aquifer matrix.

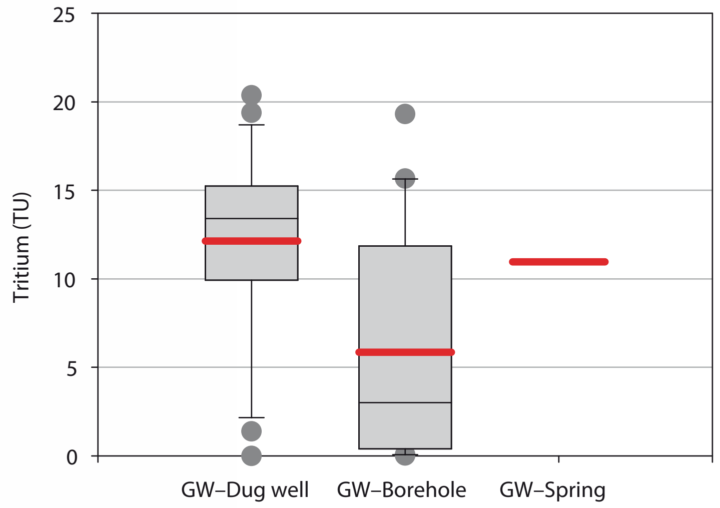
The Turonian aquifer is mostly drained by springs along the river flowing through the main valley. The high salinity of this water is mainly derived from the dissolution of anhydrite, gypsum and evaporitic minerals.

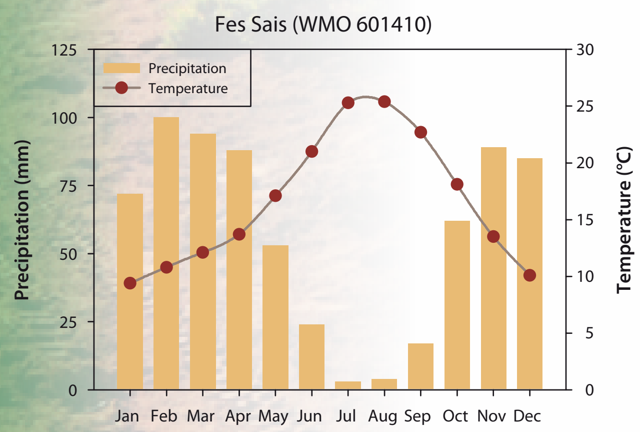
Groundwater of the Quaternary aquifer in the Tafilalet area also has negative stable isotope values compared with local precipitation, although it has high tritium levels. These results suggest that this aquifer is receiving modern recharge from a higher altitude. The recharge zone is probably located in the northwest part of the Errachidia basin. Additional recharge may derive from a reservoir which is also located in the northern part of the study area.

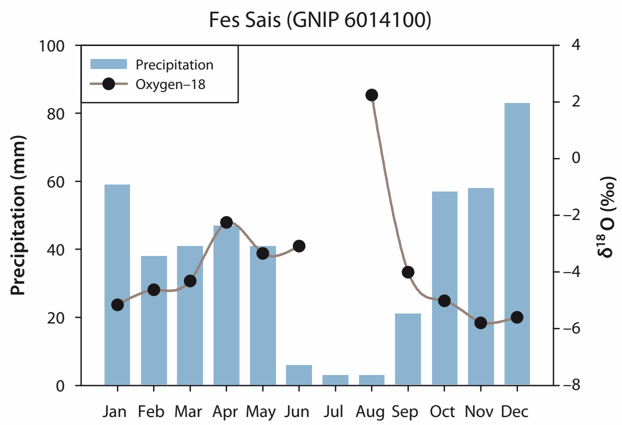
The $\delta^{18}O$ and tritium interpolation maps (A, B) are based on a combination of isotope data from the three aquifers because the data distribution was not adequate to make aquifer specific maps. The $\delta^{18}O$ interpolation (A) is consistent with both palaeoclimatic and altitude effects because a large part of the basin shows values that are more negative than those of modern precipitation over the basin (e.g. approximately −6‰). The tritium interpolation map (B) shows low values along the northern end of the study area, which is likely controlled by the Infracenomanian aquifer results. Much of the rest of the interpolation shows high tritium values reflecting groundwater in the Quaternary aquifer.

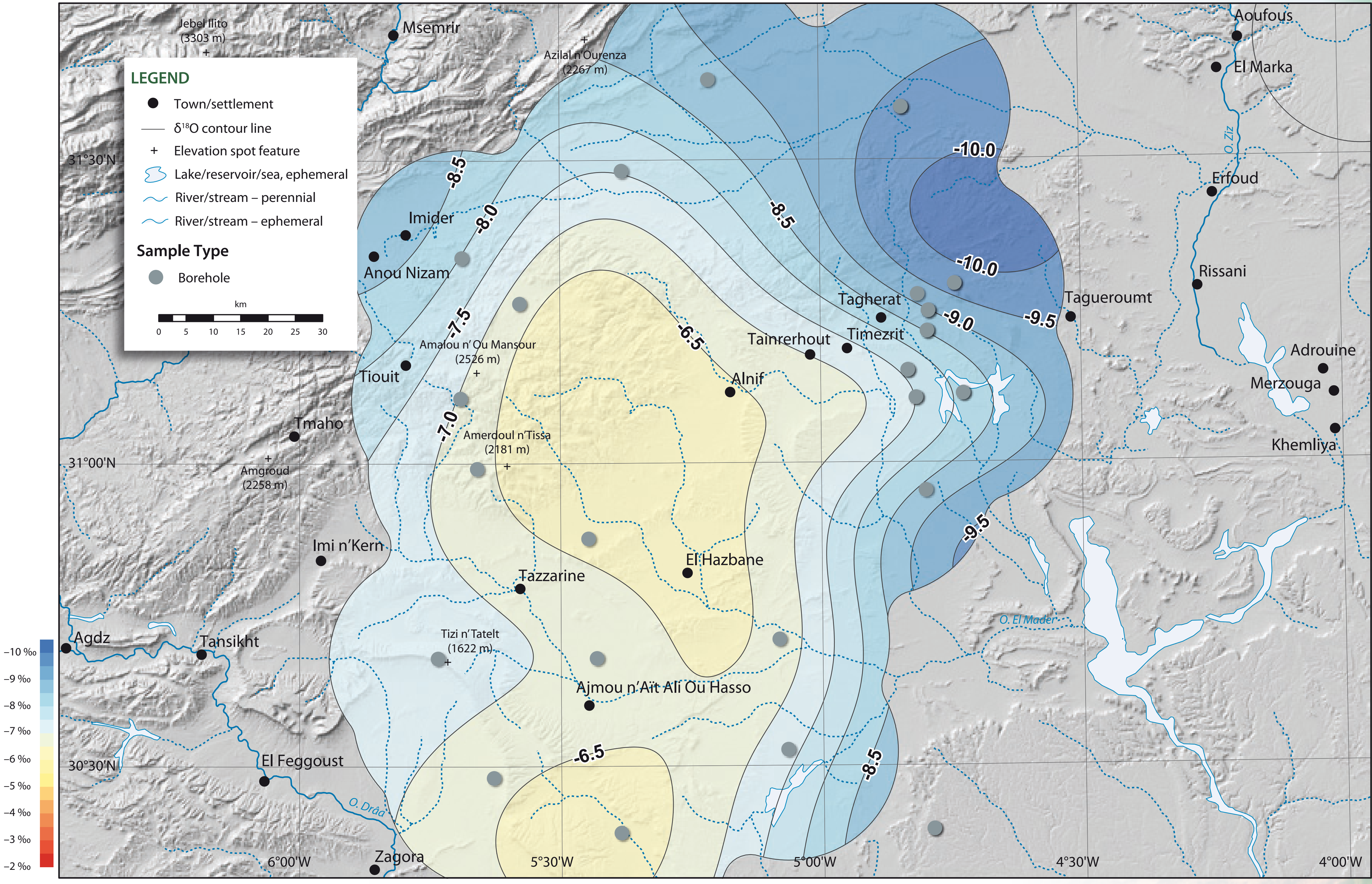




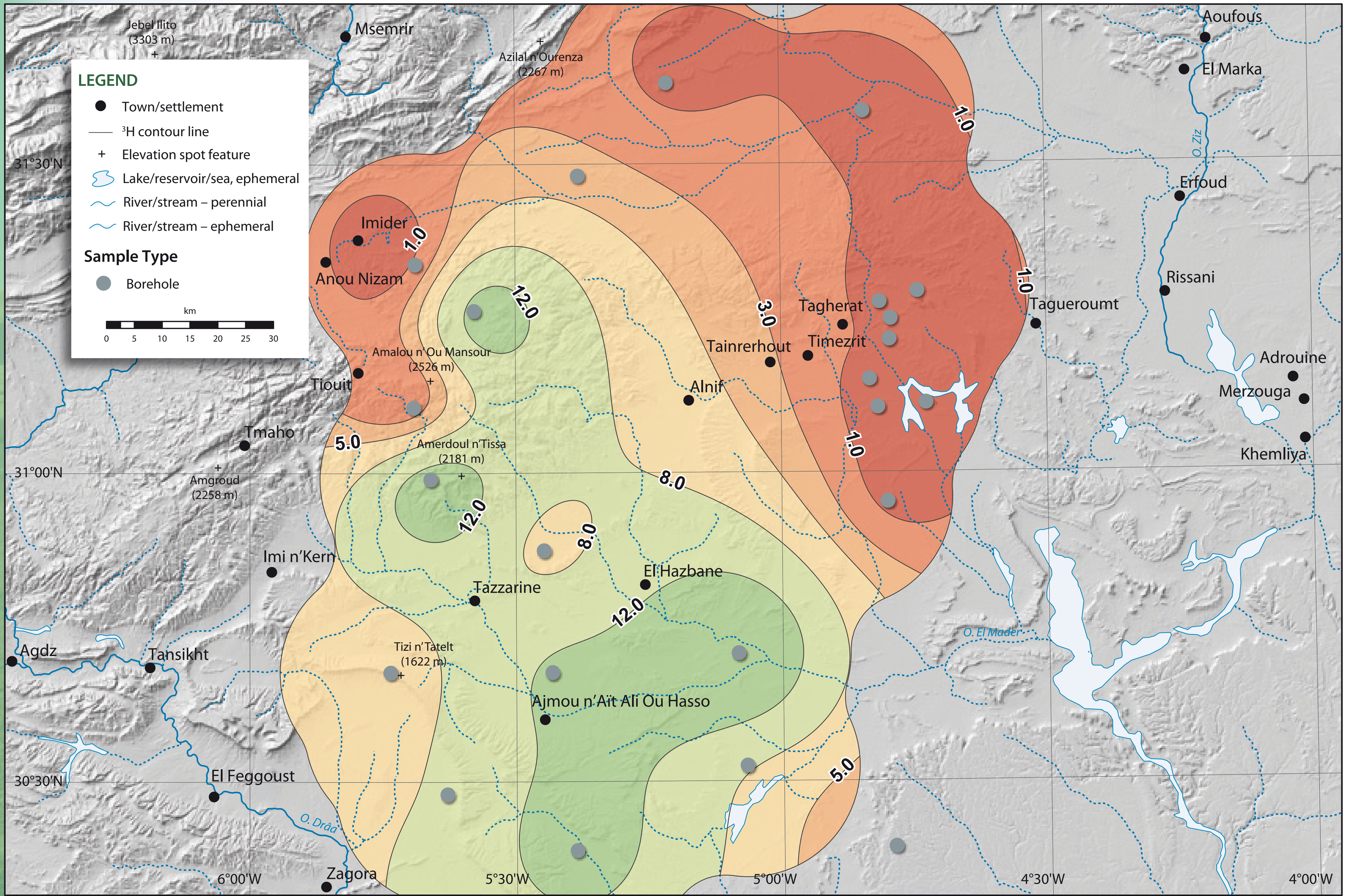








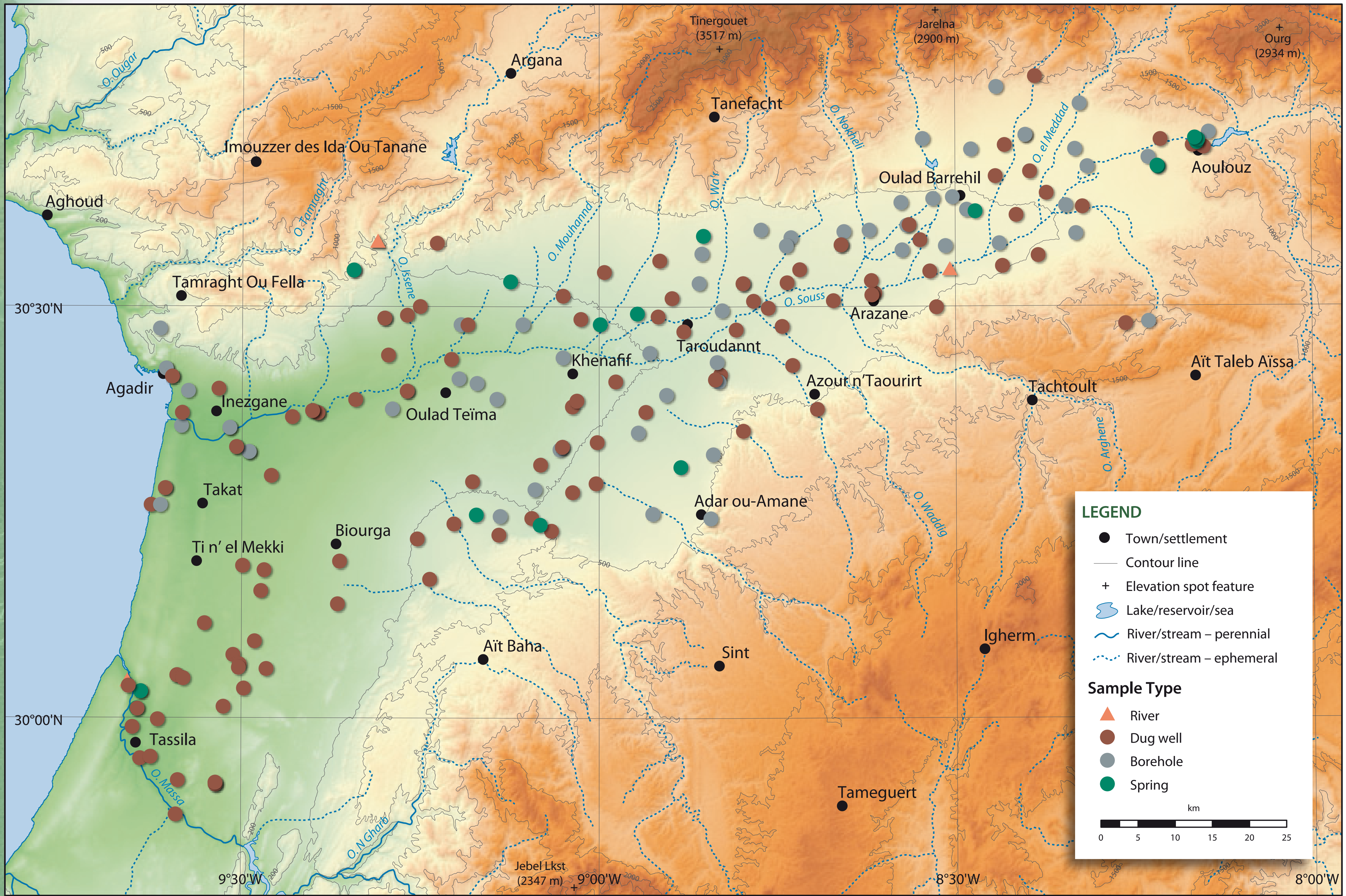
(A) Oxygen-18 interpolation



(B) Tritium interpolation

Tension: 100, Smoothing: 0.5, RMSE: 1.53 TU

Souss-Massa River basin



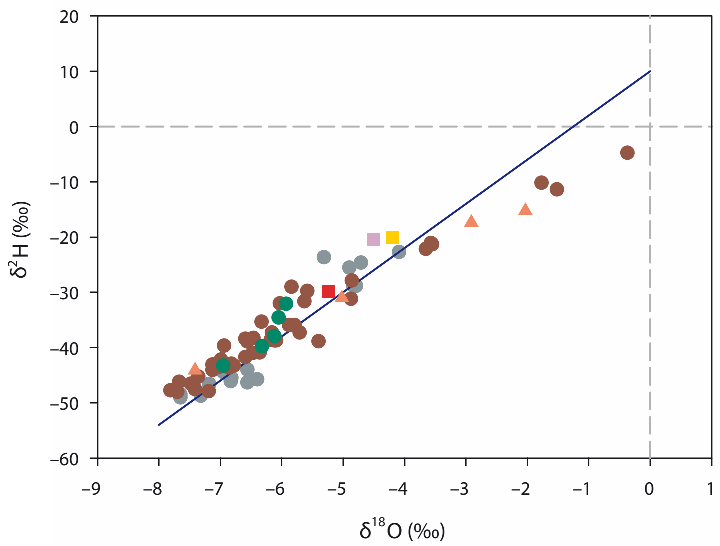
Tinergouet (3517 m)
Jarelna (2900 m)
Ourg (2934 m)
Argana
Tanefacht
Imouzzer des Ida Ou Tanane
Oulad Barrehil
Aoulouz
Aghoud
O. Ougar
O. Tamraght
O. Issene
O. Mouhannd
O. War
O. Nokheil
O. el Meddad
O. Souss
Tamraght Ou Fella
30°30'N
Arazane
Taroudannt
Khenafif
Aït Taleb Aïssa
Agadir
Inezgane
Oulad Teïma
Azour n'Taourirt
Tachtoult
O. Arghene
Takat
Adar ou-Amane
O. Waddig
Biourga
Ti n' el Mekki
Aït Baha
Sint
Igherm
30°00'N
Tassila
O. Massa
Tameguert
O. N Ghalo
Jebel Lkst (2347 m)
9°30'W
9°00'W
8°30'W
8°00'W
LEGEND
Town/settlement
Contour line
Elevation spot feature
Lake/reservoir/sea
River/stream – perennial
River/stream – ephemeral
Sample Type
River
Dug well
Borehole
Spring
km
0
5
10
15
20
25

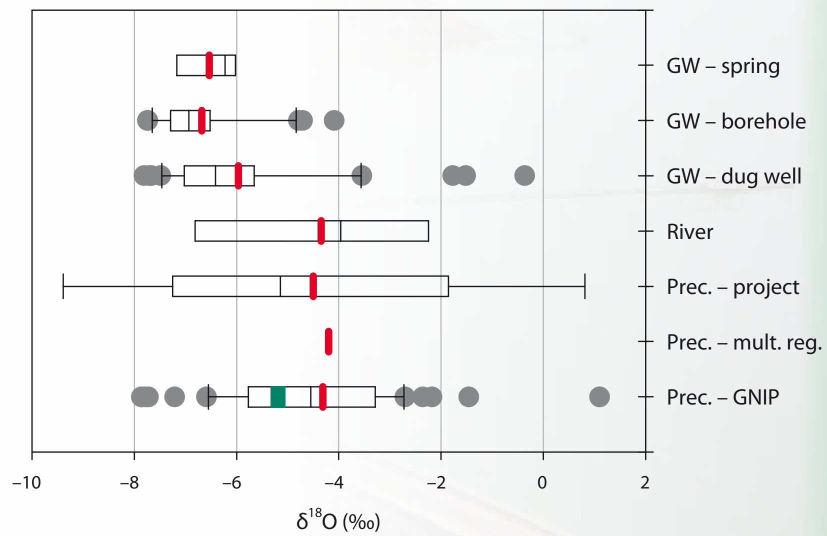
Study area: Souss-Massa River basin
Sampling period: 1969, 1999–2001

Background

The Souss-Massa River basin covers approximately 27,000 km². The area is characterized by a semi-arid climate and by a marked seasonal contrast. The rainfall average amounts to 250 mm/a in the plain area and 500 mm/a in the mountains. The principal water resource is provided by the Souss-Massa Plio-Quaternary plain aquifer and by surface reservoirs. The water quality is variable and in some areas salinity is high and can exceed 4 g/L.

Seawater intrusion and other processes that contribute dissolved solids to groundwater are a major threat to water quality in the heavily exploited Souss-Massa basin nestled between the High Atlas and Anti-Atlas Mountains of Morocco. A hydrogeologic investigation using isotopes such as ^{2}H, ^{3}H, ^{14}C, ^{18}O, ^{4}He, ^{36}Cl and ^{129}I has been carried out with the goal of determining the source of the water, the source of salinity and the age of the groundwater samples from the Souss-Massa area. Information regarding the relative importance of various salinity and water sources is being used to make informed decisions about water resource allocation and possible remediation strategies. An earlier study in 1969 has been supplemented with a new data from 1999–2001.





1969 Results

Precipitation		δ¹⁸O (‰) n	Median	Mean ± St. dev.	δ²H (‰) n	Median	Mean ± St. dev.	Tritium (TU) n	Mean ± St. dev.	Annual prec. (mm)	Temperature (ºC)
GNIP station FES SAIS	■	60	−4.55	−5.24 ± 0.9	60	−23.3	−29.8 ± 5.5			457	17.4
Interpolation – multiple reg.	■			−4.20			−20.0				
Project	■										

Surface waters		δ¹⁸O n	Median	Mean ± St. dev.	δ²H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.
Lake/reservoir/sea	▲								
River	▲								

Groundwaters		δ¹⁸O n	Median	Mean ± St. dev.	δ²H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.	¹⁴C (pMC) n	Mean ± St. dev.	δ¹³C (‰) n	Mean ± St. dev.
GW–Borehole 1969	●	13	−6.76	−6.85 ± 0.7	9	−45.4	−44.0 ± 5.9	7	3.9 ± 2.0				
GW–Dug well 1969	●	39	−6.73	−6.64 ± 0.6	10	−43.9	−43.9 ± 4.5	31	23.0 ± 26.9				
GW–Spring 1969	●	6	−6.87	−7.04 ± 0.7	4	−43.8	−43.5 ± 2.1	3	69.2 ±11.6				

Study area: Souss-Massa River basin
Sampling period: 1969, 1999–2001

Background

Continued

1999–2001 Results

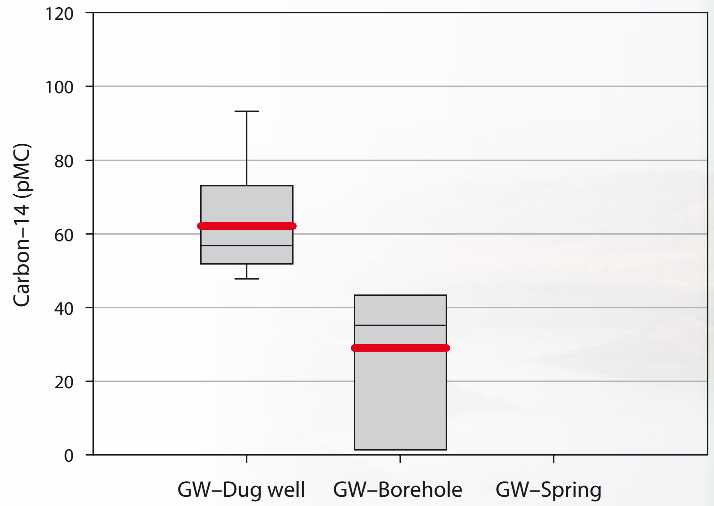
Precipitation	δ18O (‰) n	δ18O (‰) Median	δ18O (‰) Mean ± St. dev.	δ2H (‰) n	δ2H (‰) Median	δ2H (‰) Mean ± St. dev.	Tritium (TU) n	Tritium (TU) Mean ± St. dev.	Annual prec. (mm)	Temperature (ºC)
GNIP station FES SAIS	60	−4.55	−5.24 ± 0.9	60	−23.3	−29.8 ± 5.5			457	17.4
Interpolation – multiple reg.			−4.20			−20.0				
Project										

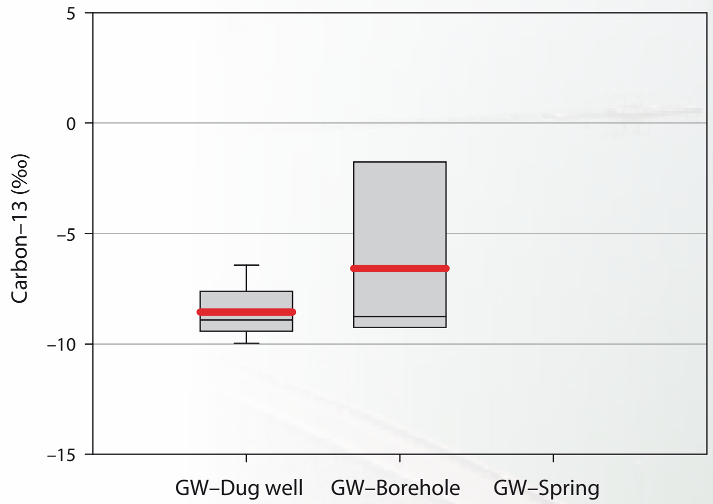
Surface waters	δ18O n	δ18O Median	δ18O Mean ± St. dev.	δ2H n	δ2H Median	δ2H Mean ± St. dev.	Tritium n	Tritium Mean ± St. dev.
Lake/reservoir/sea 1999	4	−3.10	−3.09 ± 2.8	4	−25.4	−23.6 ± 16.1	1	2.7
River	6	−3.97	−4.41 ± 2.4	6	−24.2	−27.5 ± 14.1	2	3.7 ± 2.5

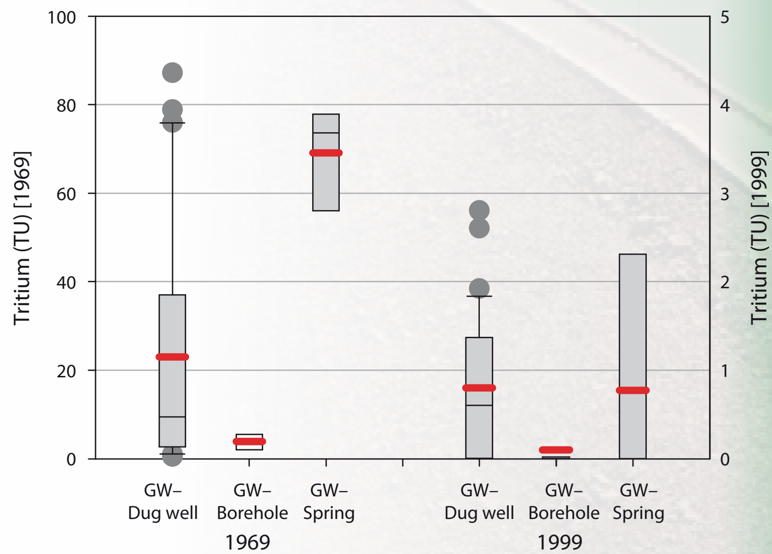
Groundwaters	δ18O n	δ18O Median	δ18O Mean ± St. dev.	δ2H n	δ2H Median	δ2H Mean ± St. dev.	Tritium n	Tritium Mean ± St. dev.	14C (pMC) n	14C (pMC) Mean ± St. dev.	δ13C (‰) n	δ13C (‰) Mean ± St. dev.
GW–Borehole 1999	13	−6.40	−5.89 ± 1.1	13	−42.5	−35.8 ± 10.0	8	0.1 ± 0.3	5	42.6 ± 26.2	5	−7.6 ± 3.3
GW–Dug well 1999	63	−6.12	−5.76 ± 1.6	63	−38.4	−35.5 ± 10.2	37	0.8 ± 0.8	8	63.4 ± 15.5	8	−8.6 ± 1.3
GW–Spring 1999	8	−6.22	−6.26 ± 0.5	8	−38.7	−38.6 ± 3.9	4	0.8 ± 1.5				−3.3 ± 0.0

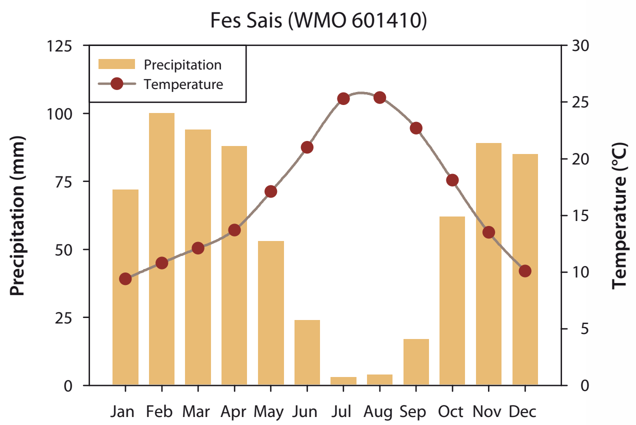
Results

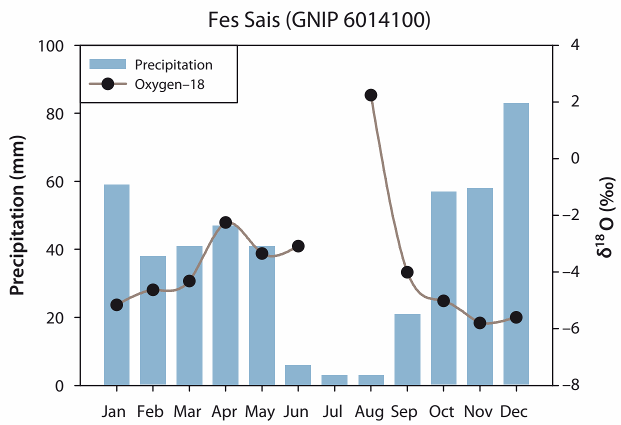
Results from stable isotope analysis of 18 groundwater samples from the central and south Souss-Massa basin suggest that relatively old water is being mined and that seawater intrusion is just one component of the dissolved solids present in these waters. The $\delta^{18}O$ interpolation map (A) shows enriched waters (−2 to −3 ‰) in the coastal areas. The enriched waters are probably related to seawater intrusion. Tritium data from the 1969 and 1999–2001 sampling campaigns (interpolation maps B and C) suggest that some of the deeper water in the basin was recharged before the 1950s. Radiogenic ^4He excess from U and Th decay ranges up to 2×10^{-7} cm^3 STP/g, indicating ages as great as several tens of thousands of years. The 1969 data (interpolation map C) show much higher tritium values, which reflect modern water present in the shallow aquifer systems. The geochemistry, including bromide, indicates that seawater intrusion from east to west is taking place. Water–rock interaction appears to be another significant source of salinity in the basin.

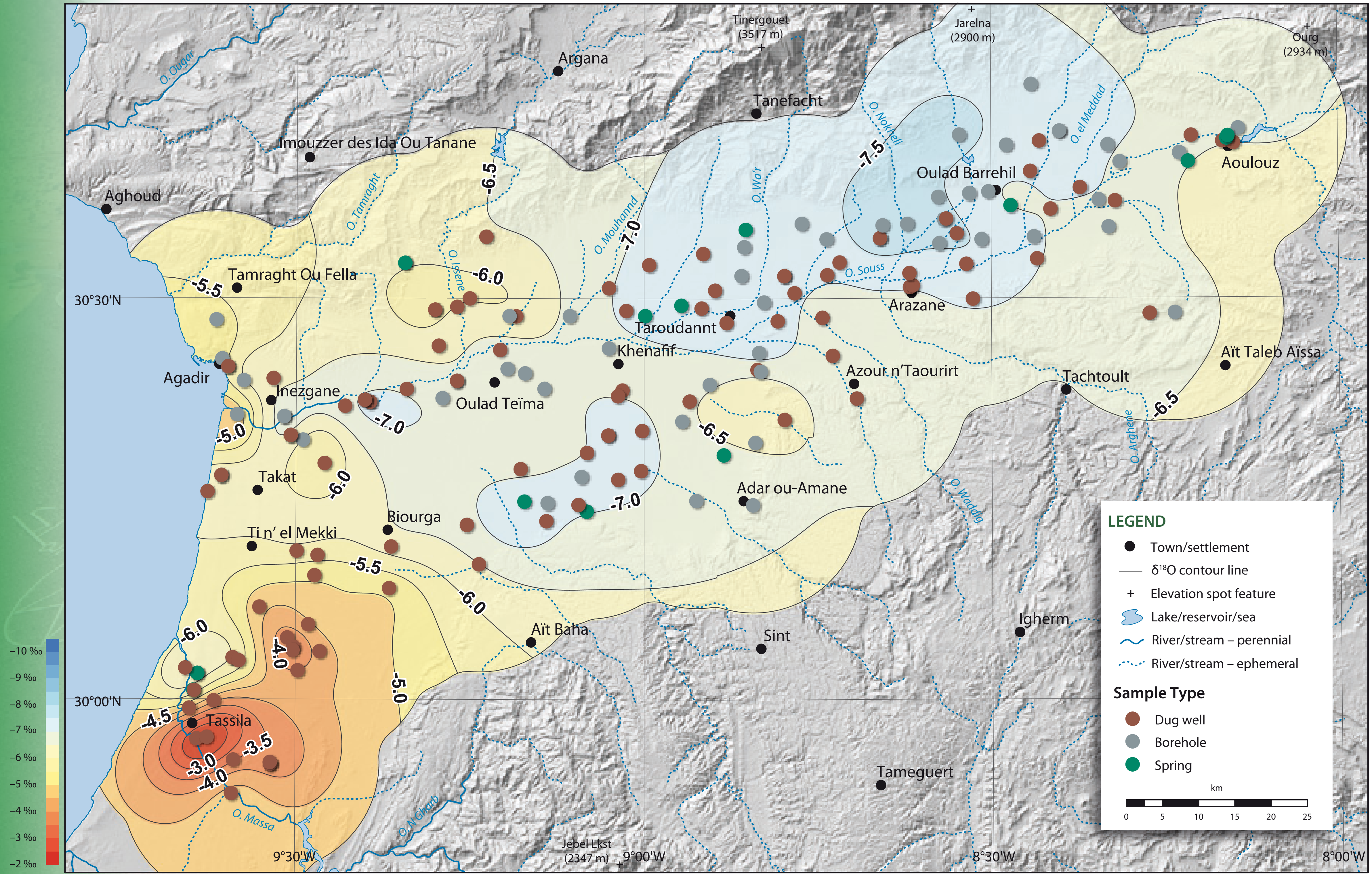






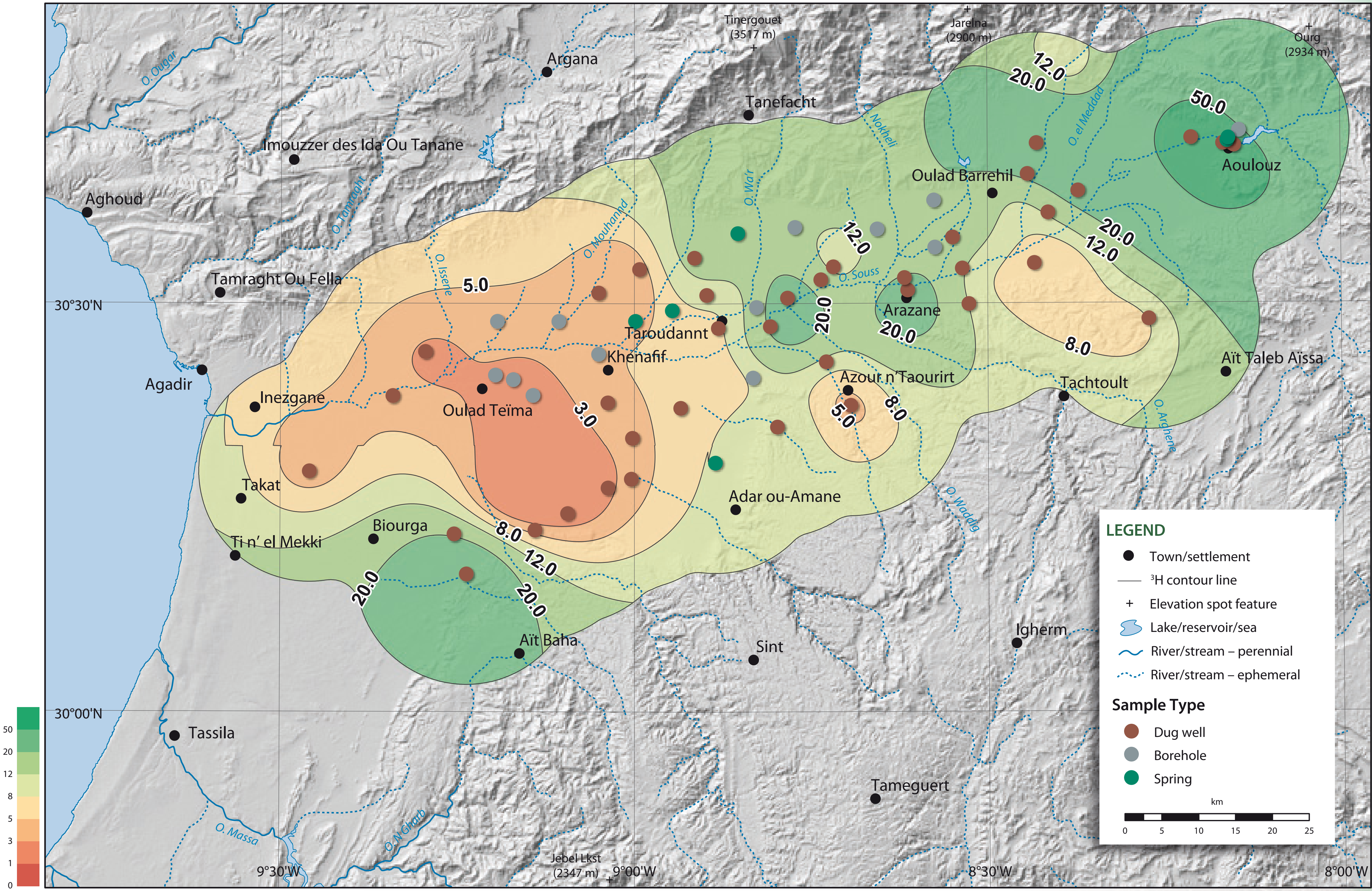






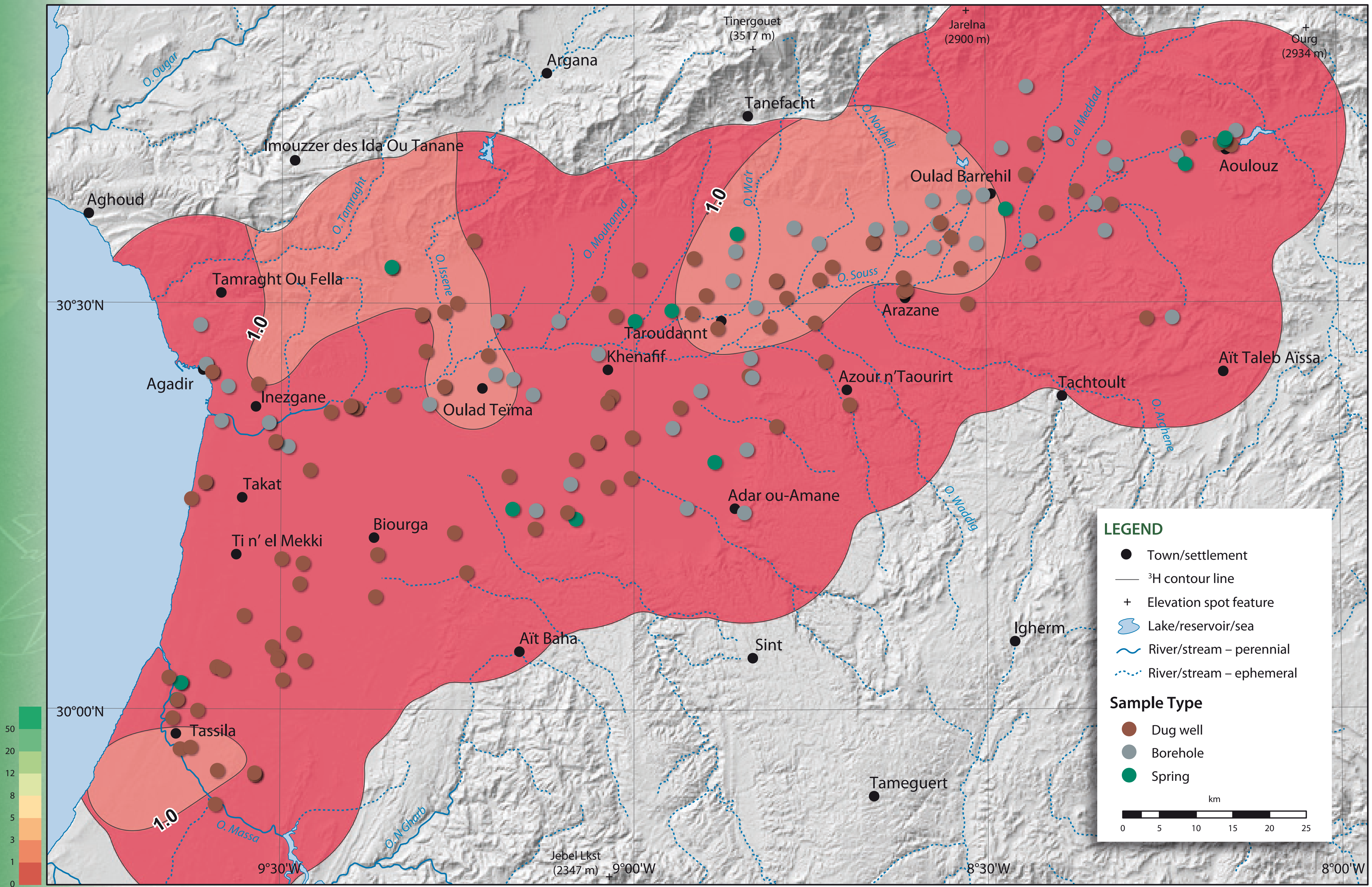
(A) Oxygen-18 interpolation

Tension: 100, Smoothing: 0.5, RMSE: 0.56 ‰



(C) Tritium interpolation from 1969 sampling

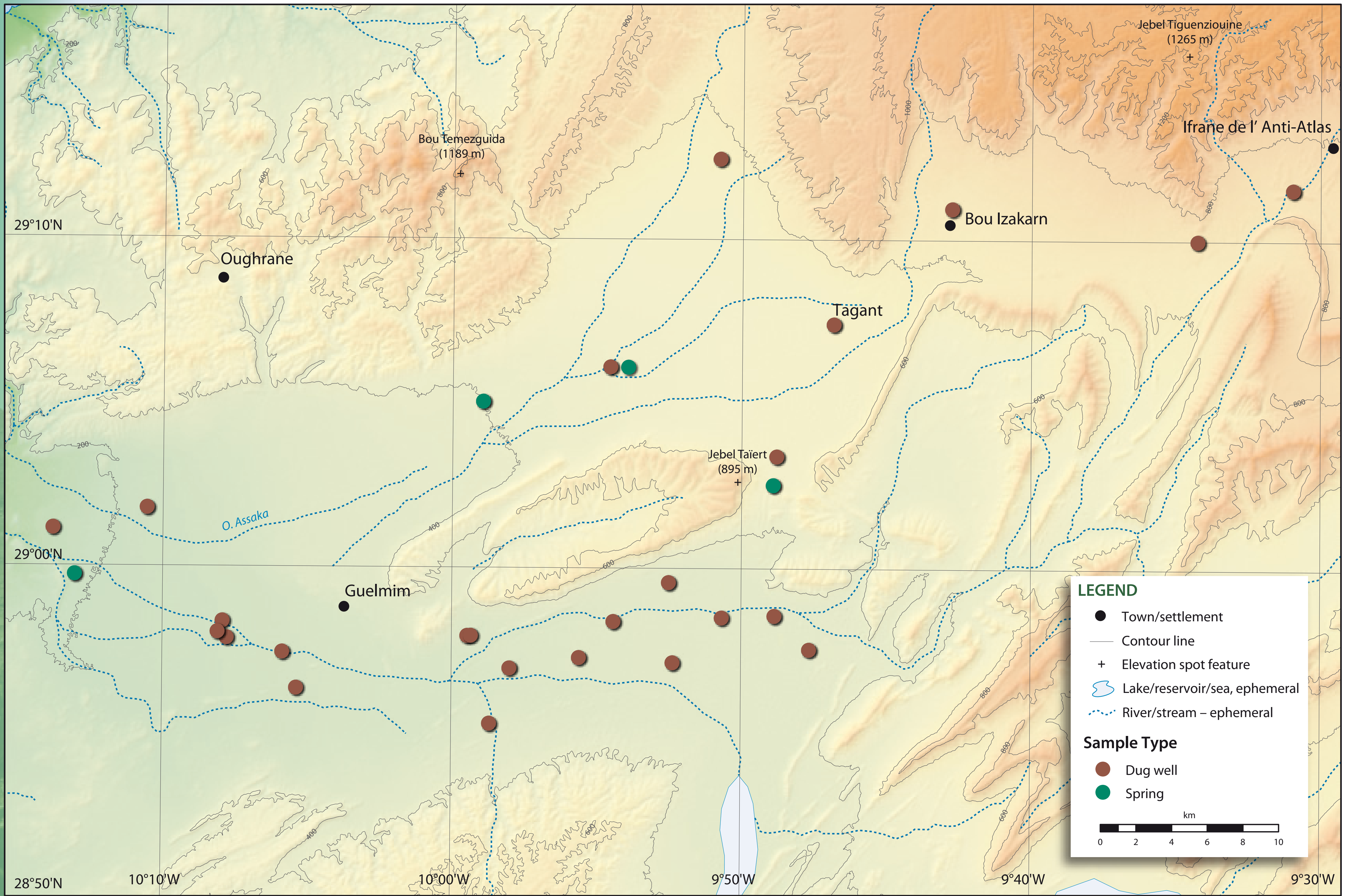
Tension: 100, Smoothing: 0.5, RMSE: 18.6 TU



(B) Tritium interpolation from 1999–2001 sampling

Tension: 100, Smoothing: 0.5, RMSE: 0.72 TU

Guelmim plain



Bou Temezguida
(1189 m)
Jebel Tiguenziouine
(1265 m)
Ifrane de l' Anti-Atlas
Bou Izakarn
Oughrane
Tagant
Jebel Taïert
(895 m)
O. Assaka
Guelmim
29°10'N
29°00'N
28°50'N
10°10'W
10°00'W
9°50'W
9°40'W
9°30'W
LEGEND
Town/settlement
Contour line
Elevation spot feature
Lake/reservoir/sea, ephemeral
River/stream – ephemeral
Sample Type
Dug well
Spring
km
0
2
4
6
8
10

Study area: Guelmim plain
Sampling period: 1995–1996

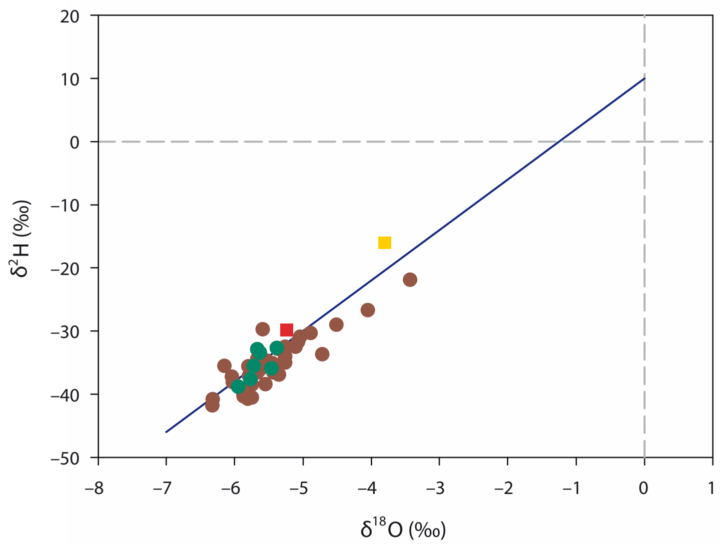
Background

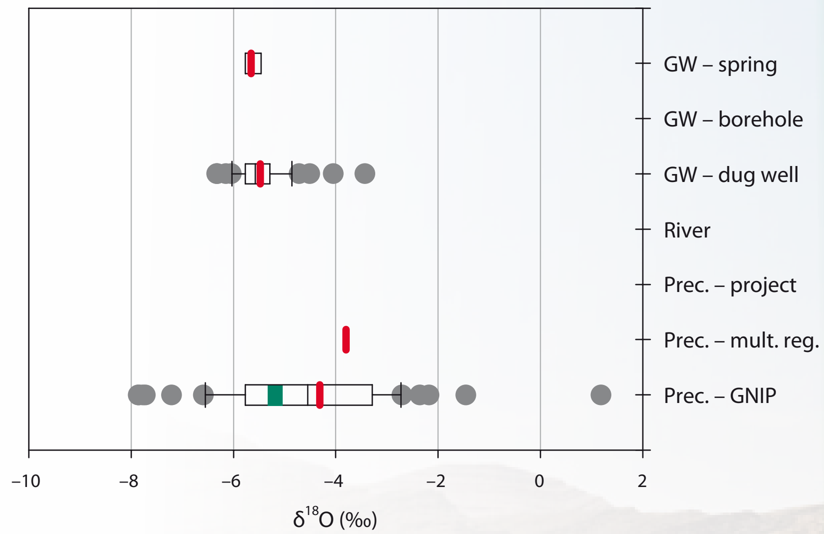
The Guelmim plain is situated in the southwest of Morocco. The area of the basin is about 1000 km². It is arid and the average annual rainfall is about 122 mm/a. The Achar, Seyyad and Noun Rivers and their tributaries form the main surface drainage in the basin and join the Assaka River in the south part of the basin.

In the Guelmim plain, groundwater is unconfined in the Quaternary aquifer. The quality of groundwater is brackish to saline and the salinity gradually increases from the eastern part of the basin to the western side. Isotope and geochemical techniques have been applied to investigate the source of salinity, the residence time of groundwater, the effect of evaporation on water quality and groundwater recharge processes.

The Guelmim plain constitutes the northern part of Guelmim basin and is covered by Cambrian and Quaternary formations (limestone, sandstone, sand, silt, lacustrine formations). The eastern and southern parts are mostly covered by schists and limestones of Cambrian age.

The objective of this study was to conduct a reconnaissance sampling to characterize the age of groundwater and evaluate potential effects of evaporation.





Precipitation		δ¹⁸O (‰) n	Median	Mean ± St. dev.	δ²H (‰) n	Median	Mean ± St. dev.	Tritium (TU) n	Mean ± St. dev.	Annual prec. (mm)	Temperature (ºC)
GNIP station FES SAIS		60	−4.55	−5.24	60	−23.3	−29.8			457	17.4
Interpolation – multiple reg.				−3.80			−16.0				
Project											

Surface waters		δ¹⁸O n	Median	Mean ± St. dev.	δ²H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.
Lake/reservoir/sea									
River									

Groundwaters		δ¹⁸O n	Median	Mean ± St. dev.	δ²H n	Median	Mean ± St. dev.	Tritium n	Mean ± St. dev.	¹⁴C (pMC) n	Mean ± St. dev.	δ¹³C (‰) n	Mean ± St. dev.
GW–Borehole													
GW–Dug well		47	−5.57	−5.48 ± 0.5	47	−35.4	−35.0 ± 3.8	14	1.3 ± 0.5	5	74.9 ± 4.7	5	−9.9 ± 2.3
GW–Spring		7	−5.67	−5.65 ± 0.2	7	−35.5	−35.3 ± 2.4	5	1.3 ± 0.8	4	69.6 ± 7.4	4	−9.6 ± 3.6

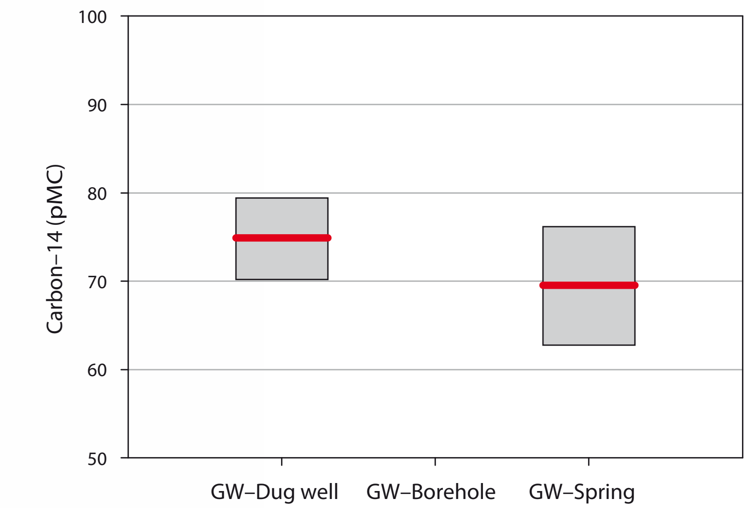
Results

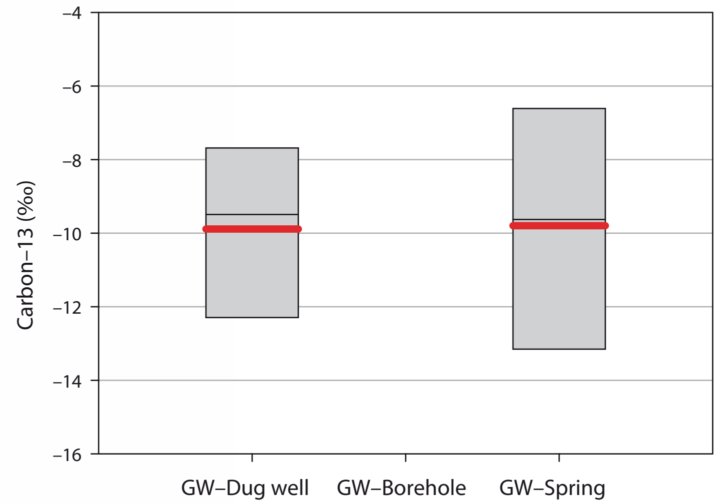
In the Guelmim basin, the salinity of groundwater gradually increases along the north to south west flow direction. In the south and south-western parts the aquifer is very shallow.

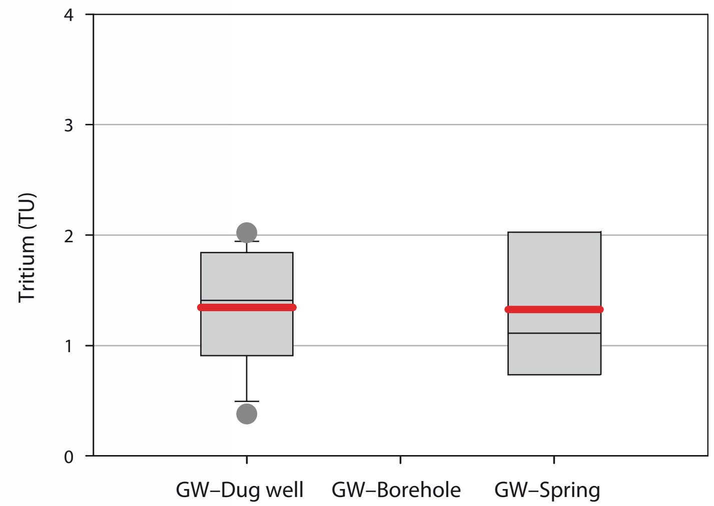
The basin is recharged from all sides based on isotopes and water levels. The extreme north-western part of the basin is the groundwater discharge point.

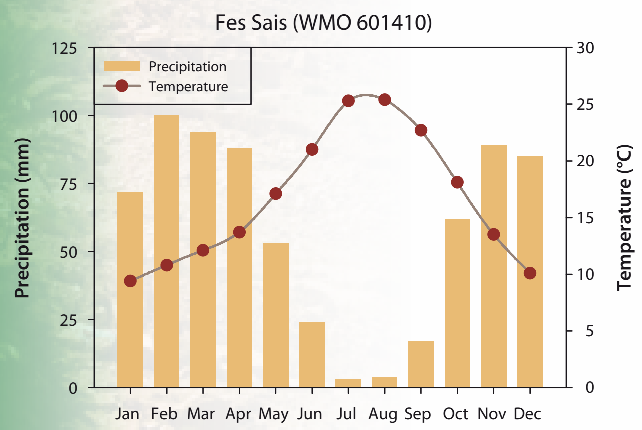
The Quaternary aquifer in the Guelmim plain is recharged from higher altitude based on the stable isotope values and the altitude implies a distant source. The carbon-14 ages are in the range of 2000 to 4000 a BP. Tritium values are also low, which indicates that there is only a limited amount of modern recharge in the basin.

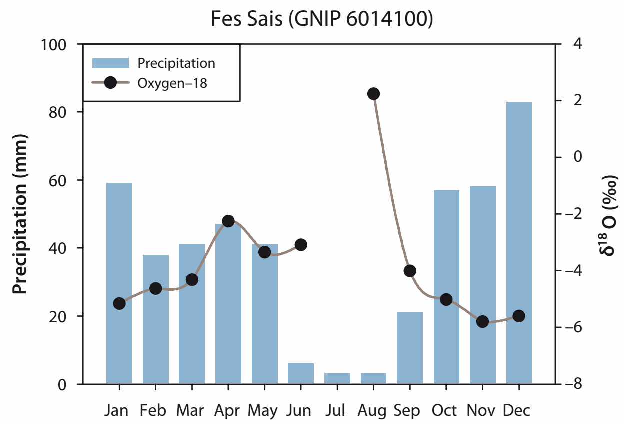
Recharge is highest in the central part of the plain, where important drinking water supply wells are situated.











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INDEX OF GEOGRAPHICAL NAMES

This index contains place names of geographical features, towns, and cities that are shown in the indicated project maps.