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SPECIAL ISSUE

Anthropogenic contamination of groundwater with nitrate in arid region: case study of southern Hodna (Algeria)

Salah Abdesselam · Amor Halitim ·
Anthony Jan · Fabienne Trolard · Guilhem Bourrié

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Abstract In southern Hodna, an arid region of Algeria, the extension of irrigated agriculture and overexploitation of groundwaters have led to a rupture with traditional land use by pastoralism. Due to the arid conditions, groundwaters are the only water resources for man and irrigation. This study focuses on nitrate contamination of groundwaters and its increase since the last 40 years, on the basis of two archives and recent analyses. The chemical facies of waters is sulphate-chloride, the risk of salinity is moderate to large. The sodicity risk, as estimated by the SAR, is low due to the large salinity and the sandy soil texture. Nitrate contamination of deep groundwater is a clear evidence when recent data are compared to the historical data. From 1996 to 2008, the proportion of samples with NO_3^- concentrations larger than 50 mg/L increases from 24 to 61 %, the proportion of samples with NO_3^- concentrations larger than 100 mg/L increases from 12 to 27 %. The study points at a general contamination of aquifers from anthropic origin: phreatic water was already contaminated when pastoralism was dominant (1967); as population increased and irrigation agriculture developed with large use of N-fertilizers and organic amendments, contamination extended spatially and vertically to deep aquifer. To remediate this contamination, fertilizers should be fractionated and limited to plant requirements on the basis of soil and plant analyses. Excess of irrigation should be avoided. Soil surface should be continuously covered to prevent nitrate leaching. Secondly, more efficient irrigation techniques, such as localized irrigation, should be implemented, with adaptation of crop systems and fertilizer inputs to arid conditions. Farmers should then be trained; simultaneously, local agronomic references that are presently lacking should be acquired.

Keywords Water quality · Groundwater · Contamination · Nitrate · Hodna · Algeria

Introduction

In rural areas, water management is largely influenced by agriculture, and intensification of agriculture requires a better control of water resources and especially in arid or semi-arid regions of irrigation when possible. However, bad irrigation management and excess of fertilizers result in degradation of water quality, mostly by contamination by nitrate. Moreover, in arid or semi-arid conditions, small pluviometry and large evapotranspiration favour this degradation. Consequently, irrigation often results in raise of the water table when drainage is poor and an increase of soil salinity (Daoud and Halitim 1994; Djili et al. 2003) and contamination of groundwater (Rouabhia et al. 2004; Baali et al. 2007).

In Southern Hodna, where irrigated agriculture has developed since some 40 years, two aquifers are present, the phreatic aquifer and the deep aquifer. The first one shows a large salt content. It has strongly decreased due to regional lowering by pumping (ANRH 2006), so it is presently limited to the immediate proximity of Chott El Hodna. The deeper one shows a small salt content. At

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S. Abdesselam · A. Halitim
Batna University, Batna, Algeria
e-mail: aksalah2001@yahoo.fr

A. Jan · F. Trolard · G. Bourrié (✉)
INRA, UMR 1114 Emmah, Avignon, France
e-mail: bourrie@paca.inra.fr

A. Jan · F. Trolard · G. Bourrié
UAPV, UMR 1114 Emmah, Avignon, France

present it is the only resource to meet man and crops needs. Its renewal is easy due to the large extension of the watershed. It has progressively lowered due to overexploitation by pumping from an increasing number of boreholes (ANRH 2007). The largest lowering of the deep aquifer is observed in the cultivated area, where intensive agriculture has developed to benefit from this water resource and from the increase of the population. Concomitantly, contamination of water by nitrate is increasingly observed (Abdesselam et al. 2008). This study aims at a better diagnosis of this contamination and of its causes.

Study area

Physiography

Hodna region, in the arid zone of Algeria, is a marked depression of *ca*. 8,500 km^2 surrounded by mountains. In its centre is situated the Chott El Hodna, of *ca*. 1,100 km^2. It is the outlet of many temporary rivers ("Oueds"), the largest of which come from the North. The main districts of Southern Hodna are Mâarif, Khoubana, M'cif, Houamed and Boussâada (Fig. 1).

The region South of Hodna, called R'Mel ("sand") region, consists of sand dunes, recent alluvial deposits and isolated rocky hills (e.g. Djbel Meharga, 900 m). To the south, at ca. 550–850 m, the landscape consists of rocky hills and large glacis (or pediment) (Grandin and Joly 2008) made of sand, gravels, pebbles locally cemented. This area is permanently submitted to wind erosion, due to the sandy texture, the absence of vegetation and soil tillage, and to sedimentation (sheet wash and wind). It is drained by numerous oueds that leach salts at depth and bring silts to soils.

Climate

The climate of Southern Hodna is subdesertic arid. Its main characteristic is the extreme variability of rainfall both in space and time (Sebhi 1987). Average pluviometry is *ca*. 172 mm, average annual temperature 19.4 °C and average potential evapotranspiration 1,330 mm/year (Abdesselam et al. 2007).

Soils

Soil texture is dominated by sand. Apart from quartz, soil components are dominated by carbonates (calcite), gypsum and salts. Due to the sandy texture and the small organic matter content, soil fertility is low with small CEC and water holding capacity; inputs of fertilizers and organic amendments are thus necessary to obtain correct yields, but fertilization is empirical.

According to soil study of Hodna (Boyadgiev 1975), and to WRB (2006), the main soil types present in the irrigated area are:

- Haplic Arenosols (Aridic):
- Haplic Fluvisols (Aridic, Gypsic);
- Haplic Gypsisols (Aridic);
- Gypsic Gleysols (Aridic);
- Gypsic Solonchaks (Aridic);
- Haplic Solonchaks (Aridic).

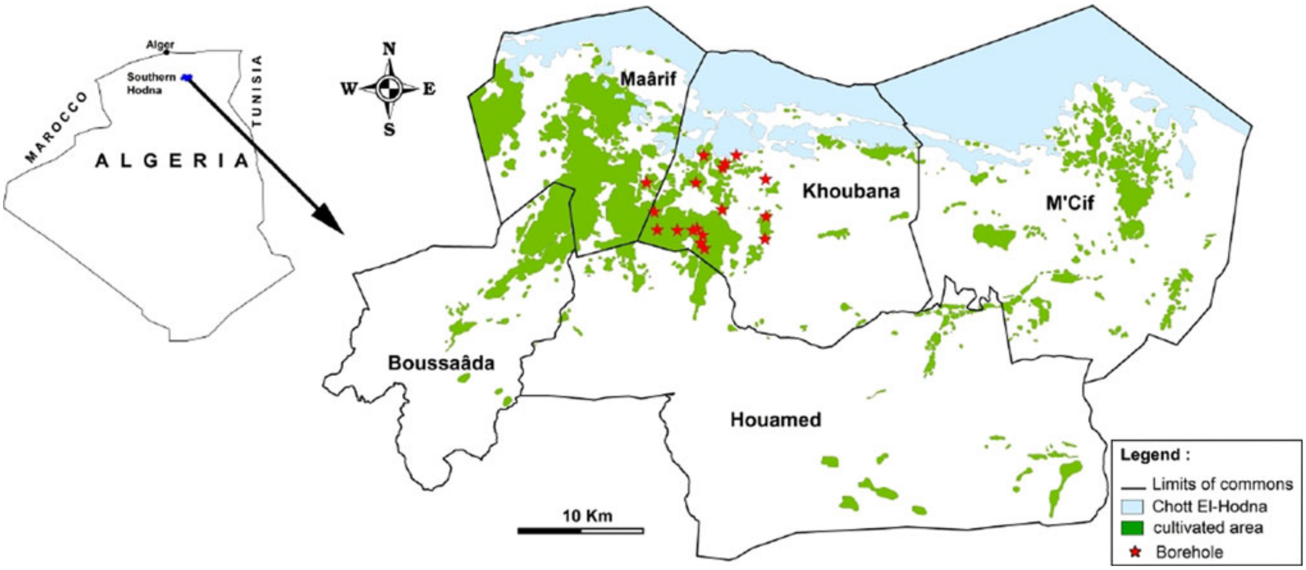


Fig. 1 Situation of the study area, south of Chott El Hodna. Boreholes sampled in 2008 are indicated by *red stars*

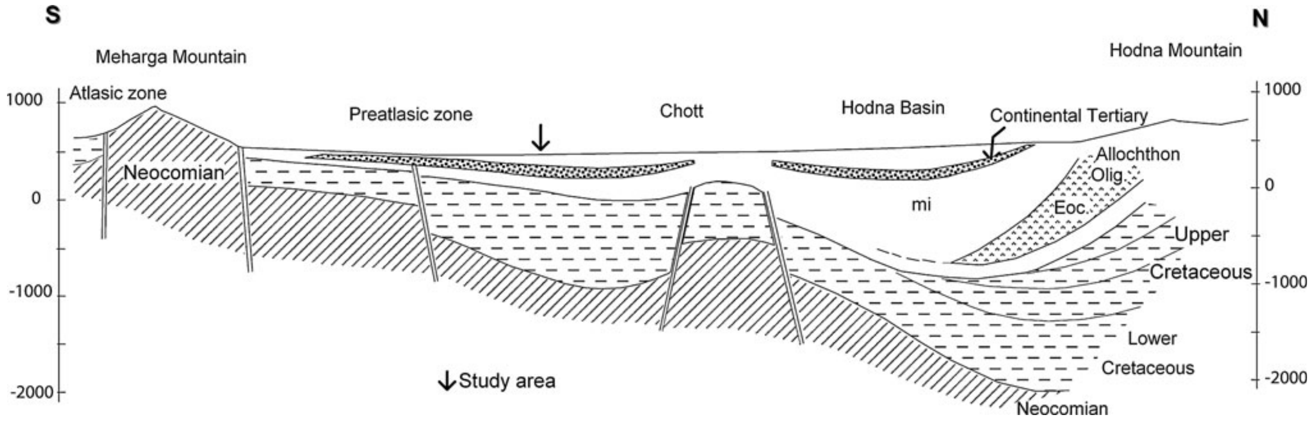


Fig. 2 Schematic cross section of the Chott El Hodna Basin. Elevation and depth, /metre

Water resources

The first evaluation of water resources (FAO 1972, 1973) aimed at serving as a basis for the agricultural development of the region. In the South Hodna, the aquifer consists of Quaternary sands and sandy clays of small thickness. The phreatic groundwater is very shallow with a high salinity: TDS ranges from 0.5 to 250 g/L. The deep aquifer consists of intercalated marls and conglomerates (Continental Tertiary) (Fig. 2). This formation, *ca*. 100–400 m thick, lies upon nearly all older formations. It collects water from them and constitutes the major aquifer. Water is in charge between the southern reliefs and the Chott El Hodna (FAO 1968). It is a renewable aquifer (FAO 1972; ANRH 2006). Its recharge implies three contributions:

- direct infiltration of rainfall;
- infiltration of water from oueds;
- deep recharge by surrounding formations.

Groundwater exploitation led to the extension of irrigated areas and land use change at the expense of pastoralism. Borehole water salinity is between 0.5 and 5 g/L. Isopiezometric lines of the two groundwaters converge in the Chott (FAO 1973). The Chott is the natural outlet of water evaporation for the phreatic groundwater and for the groundwater in charge. Presently, lowering of the groundwater level larger than 15 m since the 1970s was registered (ANRH 2006). Simulation of scenarios of water pumping (ANRH 2007) show that lowering of the groundwater level below the level of the Chott could result in a reversal of the flow direction with saline water from the Chott flowing to the aquifer, and serious damage to economic development of the region.

Indeed, the limits between phreatic aquifer and deep aquifer are always unclear (FAO 1970), as they are not separated by a continuous formation of small permeability, but by discontinuous lenses of variable permeability. Consequently, the two groundwaters may communicate and contamination of the deep aquifer from the surface is possible.

Land use change and agricultural development

This region is subject to heavy pressures, both natural such as aridity of climate, eolian erosion, and anthropic such as overgrazing, overexploitation of water resources, and intensive agriculture (Abdesselam et al. 2007). Since several decades, important changes in land use and exploitation of water resources have occurred, driven by successive agricultural policies in Algeria, the agricultural revolution, access to private land property, and the national program of agricultural development.

It is since *ca*. 1976 that irrigation was initiated, in the framework of agricultural revolution, with the purpose to irrigate 300 ha by exploitation of the underlying artesian groundwater (Sebhi 1987). During the last 30 years, agricultural lands extended at the expense of land used for pastoralism. Sandy formations extended too (Abdesselam et al. 2009). The reduction of pastoral devoted areas is mainly due to the extension of cultivated areas. Moreover soil tillage resulted in increasing eolian erosion (Mimoune 1995) and the formation of sand dunes. The degradation of pastoral areas is not only due to climatic conditions, but mainly to overgrazing.

Agriculture has developed where water resources are accessible, *i.e*. in the sandy area, south of the Chott El Hodna. From the statistics of the Direction des Services Agricoles (DSA), the arable land area (ALA) is *ca*. 42,000 ha, of which 50 % is irrigated.

Materials and methods

Archive data both from wells and boreholes were collected and recently boreholes were sampled. Wells sample mainly

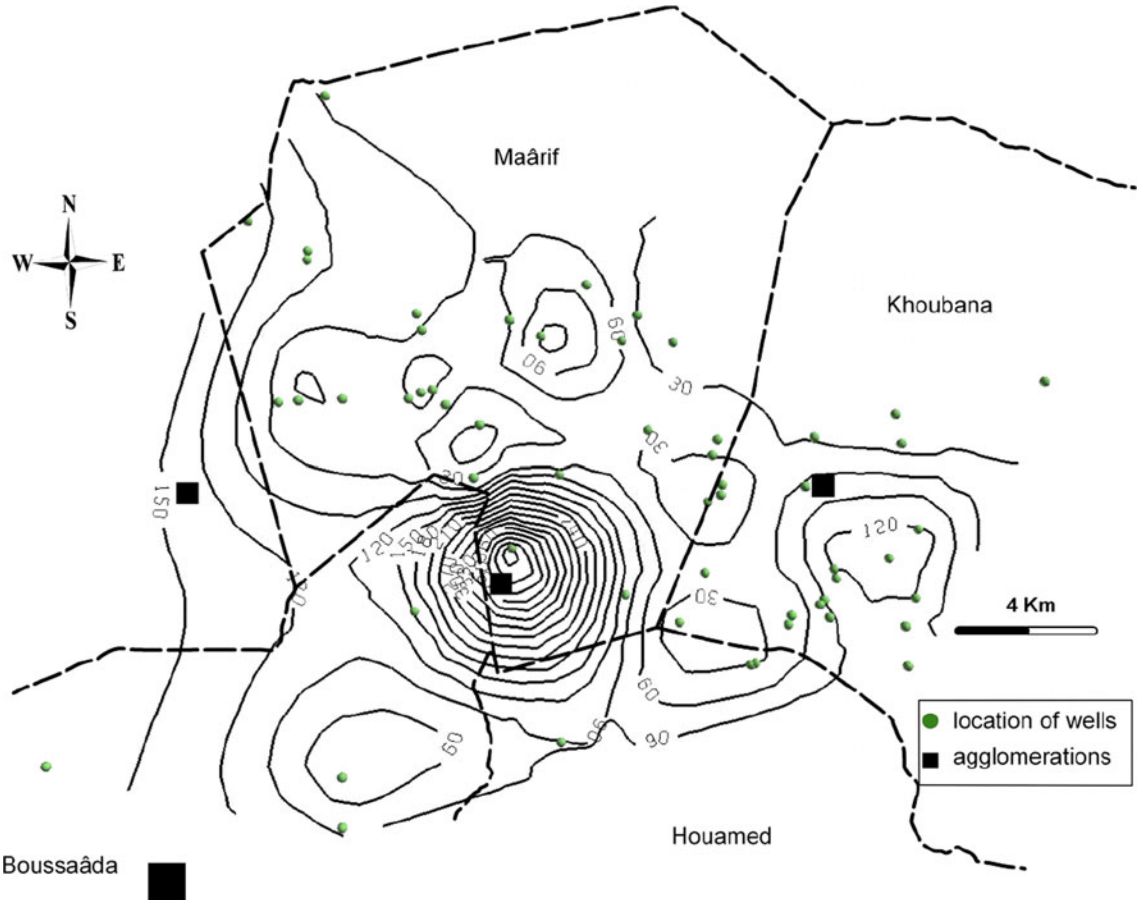


Fig. 3 Situation of wells and spatial variability of nitrate in phreatic groundwater in 1967. Data from FAO (1973), NO_3^- concentrations /mg L^{-1}

the phreatic, shallow aquifer, and boreholes sample mainly the deep aquifer, but those aquifers are not separated by an impervious formation. Contamination of the deep aquifer by the phreatic one is thus possible. The risk of contamination is enhanced by the unavoidable imperfections in the boring techniques or errors.

Archive data

The archive data consist of (1) analyses of 63 wells (FAO 1973) sampled in the whole western part of the agricultural area (Maârif-Khoubana, Boussaâda and Houamed) (Fig. 3); (2) analyses of 50 boreholes (ANRH 1996), sampled in the extreme west (Maârif) (Fig. 4).

Present data

Samples were taken in 18 boreholes in the deep groundwater after 1 h pumping, in polyethylene bottles, in May 2008, near Khoubana, south of Hodna (Fig. 1), from the Chott to Mergueb, Guebouhia and Memdouda. Temperature, pH and electrical conductivity were measured in the field, with a portable pH-meter/conductimeter HANNA. Samples were immediately transferred to the laboratory of ANRH (Agence Nationale des Ressources Hydrauliques) for analysis of major ions. Ca and Mg were analyzed by complexation and spectrophotometry with a SKALAR SAN continuous flux analyzer; Na and K were analyzed by flame photometry, sulphate by turbidimetry, chloride by colorimetry, nitrate by continuous flux analysis at 540 nm and alkalinity by volumetry. Total dissolved salts (TDS) were measured by gravimetry after evaporation.

Spatial interpolation

Spatial interpolation of data was achieved with geomodel gOcad (Mallet 2002) in order to compare data obtained at different dates and locations.

Results and discussion

Chemical facies of groundwater

Complete analyses are given in Tables 1, 2 and 3. Synthetic statistical parameters are given in Table 4. The

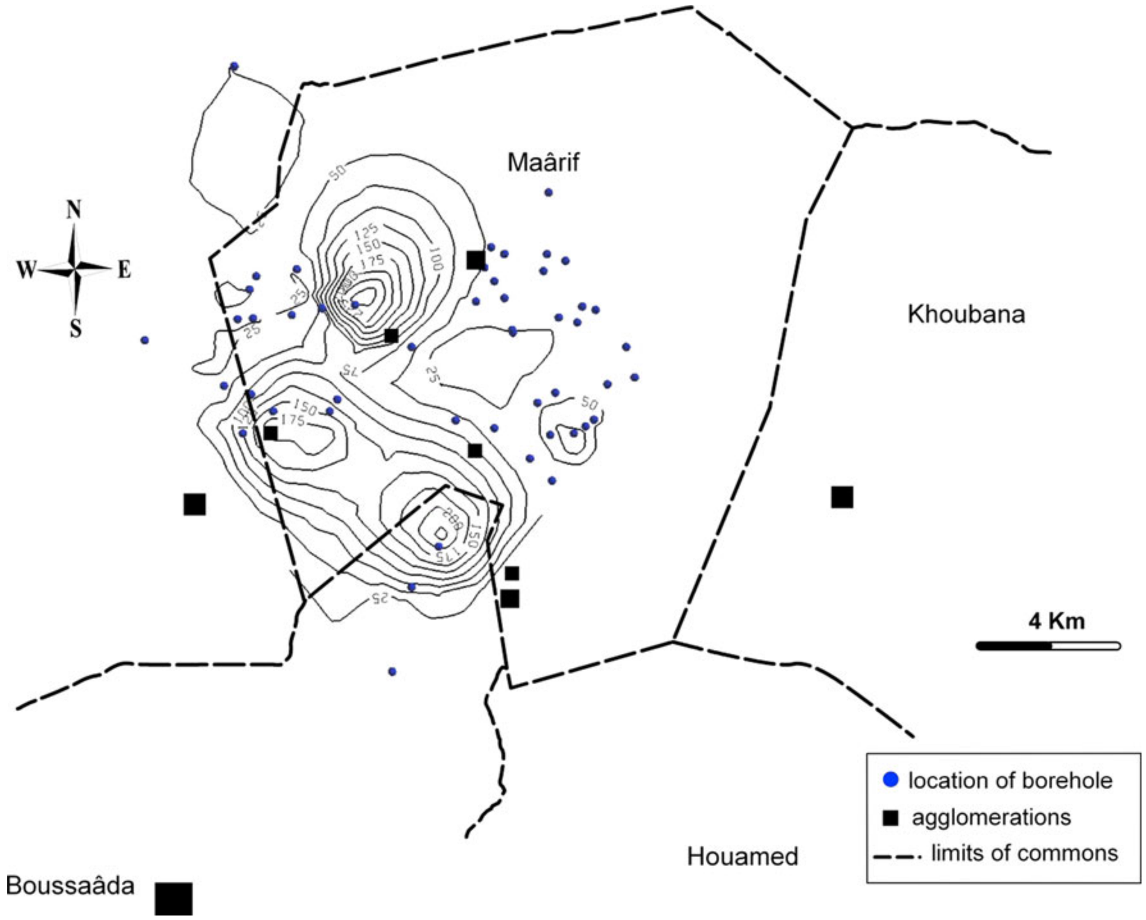


Fig. 4 Situation of boreholes and spatial variability of nitrate in deep groundwater in 1996. Data from ANRH (1996), NO_3^- concentrations / mg L^{-1}

relative proportions of cations and anions in the Piper's diagram are given in Fig. 5.

The facies of all waters is sulphate-chloride-calcium, pH is near neutrality (6.8–8) and alkalinity is moderate.

From Piper's diagram, and standard deviations (see CE and TDS, Table 4) it is clear that the scattering of data is the lowest in 2008. This can be ascribed to:

- better techniques in boreholes;
- sampling in areas where aquifers are better separated;
- an improvement of analytical techniques from 1996 to present.

EC ranges from 644 to 2,780 µS/cm in boreholes in 2008, as compared to 1,500–9,700 µS/cm in 1996 and from 1,011 to 21,900 µS/cm in wells in 1967.

TDS ranges from 512 to 2,510 mg/L in 2008, as compared to 1,066−6,608 mg/L in 1996 and 738 to 20,300 mg/L in wells in 1967.

These large variations contrast with the quasi stability of pH. This implies that despite concentration of solution by evaporation and transpiration, carbonate precipitation regulates pH. According to residual alkalinity concept (Breemen and Wielemaker 1974; Al Droubi et al. 1980), solutions evolve in the neutral pathway and not in the alkaline pathway.

The salinity threshold for water use in agriculture is estimated as 3,000 µS/cm at 25 °C (Ayers and Westcot 1985). In 1996, 42 % of samples showed a larger value as compared to 63 % in well waters in 1967. This threshold severely limits the use of water for irrigation. Values of Cl^- concentration larger than 10 mmole/L are observed in 63 % of samples in 1967. Those excessive values may be responsible for low yields (Mimoune 1995). According to USSL (1954); Durand (1958); Ayers and Westcot (1985), the salinization hazard is light to moderate in 2008 versus moderate to very large in 1996 and 1967.

The risk of degradation of soil structure due to clay dispersion is classically assessed by considering the sodium adsorption ratio (SAR) (USSL 1954) and the ionic strength, or equivalently the EC. In 2008, SAR ranged from 0.57 to 2.8 and these values are acceptable as the EC is larger than 700 µS/cm.

Table 1 Chemical composition of groundwater from wells, 1967 (FAO 1973)

Site no.	Coordinates*		t (°C)	EC (μS cm^{-1})	TDS (mg L^{-1})	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	SAR
	X	Y												
1	640625	217150	20	2,180	1,157	30	185	143.08	0	38	764	210	31	2.15
3	640625	215600	20	2,530	2,040	308	97	177.16	0	98	918	275	89	2.25
19	631650	217440	21		5,229	898	124	305.6	0.24	134	1,873	918	177	2.53
22	647225	218200	19	3,240	2,732	362	138	279.66	0.22	80	1,140	426	88	3.16
29	638700	228450	20	1,445	991	157	51	74.6	1.37	93	432	89	60	1.3
30	639575	233025	17	4,090	3,189	416	107	285.6	0.27	93	1,361	595	89	2.9
121	641200	231500	13.5	3,080	3,084	616	106	34.08	0	103	1,749	59		0.33
122	647750	223450		3,730	3,350	386	257	204.74	0.17	87	1,715	266		1.98
123	647400	223750	15.5	5,450	5,410	508	459	258.84	0.05	87	2,584	463		1.97
124	645750	224050	19	5,050	4,261	580	343	209.88	0.02	81	1,899	559	535	1.7
126	649175	222660	18	7,600	8,246	574	635	766.28	14.42	178	4,250	746	100	5.22
127	650800	221825	17	4,920	4,300	370	225	454.46	13.37	203	1,885	381	0	4.58
128	631575	223325	18.3	4,490	3,924	417	252	346.66	10.21	177	1,810	375	48	3.21
129	652075	225980	18.3	6,570	6,824	648	390	691.37	37.41	267	2,950	884	0	5.28
130	652050	225675	18.8	4,340	4,226	519	236	310.79	7.09	206	1,975	325	32	2.82
131	651650	225460	16.8	4,990	5,614	648	301	354.21	49.75	365	2,400	582	0	2.87
132	652950	220550		1,920	1,337	146	85	166.88	0.05	124	532	209	44	2.6
133	653100	220600	18	1,470	867	106	48	120.09	0	112	221	220	18	2.39
134	654200	222025	18.8	1,820	1,260	133	73	112.95	3.01	255	390	178	52	1.96
135	654100	221760	18.8	1,180	738	82	56	81.04	2.93	241	220	99	43	1.68
136	655040	222360	18.3	2,400	1,501	217	171	61.68	7.31	262	580	337	10	0.77
137	655350	221960	19.2	2,250	1,450	271	129	70.51	2.47	238	330	273	104	0.98
138	655200	222500	17.5	1,910	1,489	168	137	36.21	8.8	216	185	220	150	0.52
139	657960	222560	19.3	1,300	943	85	77	70.71	12.29	213	215	91	132	1.34
140	657160	223750	18.4	1,670	1,122	93	73	139.65	5.3	319	270	169	124	2.61
141	658040	224625	18.2	3,930	3,270	228	219	382.68	32.23	250	1,187	568	130	4.34
142	642875	231125	17.7	6,290	5,578	529	253	727.77	32.99	183	2,400	866	90	6.3
143	643025	230625	17.9	5,900	5,592	545	338	577.39	17.4	193	2,625	650	40	4.75
144	643350	228825	18.3	2,020	1,628	222	96	117.22	4.74	188	700	149	28	1.64
145	643750	228375	18	2,950	2,637	361	139	173.17	5.77	195	1,212	242	45	1.69
146	644775	227750	17	7,080	7,178	556	476	807.95	21.75	224	3,150	1,212	0	6.06
147	644600	226175	19.6	6,160	6,148	534	398	576.97	13.81	214	3,050	458	0	4.72
148	642800	222150	20.8	2,670	1,861	295	105	113.12	5.84	137	850	219	144	1.44
149	647175	226275	20.8	3,730	3,321	361	204	300.02	5.86	189	1,575	249	70	3.12
150	648800	229850	16.2	5,660	5,067	500	261	651.43	58.43	424	2,175	824		5.86
151	649060	230300	18.5	5,660	4,773	578	236	537.73	30.11	165	2,050	909	59	4.75
152	649525	231070	15	6,160	5,710	612	313	599.9	38.93	244	2,950	795	18	4.9
153	648000	232000	13.5	8,850	8,596	623	544	1,076.88	73.82	184	3,375	1,447	78	7.58
154	646625	230450	14.8	17,260	13,362	756	758	2,336.52	79.64	310	3,625	4,047	152	14.25
155	645675	230925	19.7	5,340	6,602	589	390	809.18	9.48	228	2,800	1,179	35	6.32
156	645975	231775	13.3	5,660	5,068	600	266	514.14	78.83	319	2,550	463		4.32
157	651800	226850	18.7	9,130	5,048	723	197	445.43	63.53	145	1,925	994	39	3.78
158	651950	227325	16	10,110	8,367	556	458	1,180.98	74.68	171	3,400	1,349	52	9.28
159	649850	227600	15	8,330	9,015	645	595	1,460.02	61.48	232	3,525	2,095	30	9.93
160	661800	229075	15.9	3,960	7,796	589	450	980.44	78.32	232	3,200	1,357	0	7.4
161	640625	228550	18.3	1,670	1,277	268	54	24.17	12.85	211	600	57	40	0.35
162	654875	227400	13.5	10,110	9,151	731	507	1,427.61	75.95	250	3,750	2,024	22	9.94

Table 1 continued

Site no.	Coordinates*		t (°C)	EC (μS cm^{-1})	TDS (mg L^{-1})	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	SAR
	X	*Y*												
163	657500	227200	16.3	9,440	8,201	567	368	1,406.00	98.63	279	3,625	1,136	12	11.72
164	657325	228100	15	10,340	9,988	523	621	1,474.91	84.65	243	3,775	1,690	20	10.63
165	654600	225925	16	8,250	8,744	567	578	1,050.76	94.01	262	3,400	1,349	66	7.4
166	655550	223150	17.6	1,880	1,394	136	83	113.22	49.85	195	430	136	92	1.88
167	655500	223425	17.5	2,400	1,858	167	120	188.14	49.9	250	625	220	140	2.7
168	657650	221700	18.4	1,880	1,426	115	147	46.78	0.20	290	420	138	92	0.68
169	657725	220500	16.5	1,410	1,026	106	70	73.65	5.33	198	250	106	106	1.37
170	639300	228500	16	1,970	1,606	232	98	80.02	8.97	189	750	82	18	1.17
172	642625	228550	19.5	2,620	2,278	306	152	153.79	3.15	171	1,212	116	23	1.79
173	643000	228750	18.8	3,630	3,180	378	201	253.12	16.81	166	1,475	334	124	2.59
174	639550	232750	18.6	7,870	6,942	411	638	600.25	5.5	234	2,000	1,882	104	4.31
175	637750	233950	13.2	7,410	6,228	577	277	784.09	46.67	222	1,810	1,385	144	6.4
179	640100	237700	12.8	8,700	8,212	580	498	1,124.46	51.17	258	3,800	1,484	50	8.25
185	638250	230500		3,300	2,824	314	206	259.64	0.24	191	1,586	426		2.8
186	646350	230400		21,900	20,300	560	1,340	3,456.51	1.95	351	7,488	4,473		18.03
161	650600	230250	21.8	1,011	1,500	218	68	98.42	8.55	234	600	147	10	1.48

Void cells correspond to not measured. Values for Na^+ and K^+ were tabulated in the archive as sum ($Na^+ + K^+$), both in meq/L and mg/L. From these data, individual values for Na^+ and K^+ were recovered, and SAR values checked. Three values of SAR were found to be in error in the original archive and were corrected

TDS total dissolved salts, *SAR* sodium adsorption ratio $mmol^{1/2}L^{-1/2}$

* Coordinates Lambert Nord Algérien

The deep groundwater is normally of low salinity (FAO 1970). The high values registered in 1996 can be ascribed either to the small depth of some boreholes that do not reach the deep groundwater table or to purely technical problems during the realization of the borehole and bad cementation between the tube and the shallow aquifer.

Contamination of groundwater by nitrates

In this region, groundwater is the only resource for human and animal drinking and for irrigation. From Table 4, it appears that average values for NO_3^- are not significantly different. To extract information from data, the distributions of results must be studied in more detail.

Archive data from wells (FAO 1973) (Table 4) show that 50 % of samples was already over $50\,mg_{NO_3^-}L^{-1}$ in 1967, and 25 % was over $100\,mg_{NO_3^-}L^{-1}$; conversely 21 % was under $20\,mg_{NO_3^-}L^{-1}$, and indeed 12 % of samples was analyzed and showed null values. Rainwater contains non-null values of nitrate in the range $1\,mg_{NO_3^-}L^{-1}$ to $2\,mg_{NO_3^-}L^{-1}$ (Barbier 2011), due to natural oxidation of atmospheric N. This implies that in some cases, biogeochemical cycles are efficient enough to absorb all nitrates present in soil. There existed thus in 1967 both small values, less than *ca.* $20\,mg_{NO_3^-}L^{-1}$, and very large values.

The map of nitrate concentration in wells in 1967 (Fig. 3) shows the concentration increases from the exterior to the centre of the area, where rural population is concentrated. Large values are observed in the south and in the east where populations are gathered near urban areas. This can thus be ascribed to contamination. This contamination may be both from human and animal origin, as a large part of cattle was brought back to the village every night, agriculture being non-existent in 1967.

The data from boreholes in 1996 show 12 % of samples over $100\,mg_{NO_3^-}L^{-1}$, 24 % of samples over $50\,mg_{NO_3^-}L^{-1}$, and 8 % under $20\,mg_{NO_3^-}L^{-1}$. Comparison of the cumulative frequencies of nitrate concentrations (Fig. 6) clearly shows a shift towards larger values from 1996 to 2008. Though detailed knowledge of the exact nature of aquifer exploited by every borehole is lacking, large nitrate concentrations are observed even at depths greater than 50 m (Fig. 7), which shows the qualitative degradation of the deep aquifer. This can be ascribed to the development of irrigated crops in the 1970s (Sebhi 1987; Mimoune 1995), to the increase of population and land use change. Large values are indeed observed in two situations: (1) in the west

Table 2 Chemical composition of groundwater from boreholes, 1996 (ANRH 1996)

Site no.	Coordinates*		pH	EC (μS cm^{-1})	TDS (mg L^{-1})	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	SAR
	X	*Y*												
907	641775	220750	7.4	2,300	1,603	88	90	233	7	88	588	343	22	4.15
916	642350	223250	7.3	2,000	1,575	128	96	143	6	95	378	388	48	2.32
947	644800	232300	7.2	2,000	1,639	163	88	133	6	145	563	240	47	2.08
942	644250	231700	7	1,800	1,416	141	96	83	5	172	600	115	38	1.32
943	644500	232700	7.1	1,500	1,066	192	69	78	4	94	488	125	44	1.22
949	645100	231800	8	1,600	1,285	180	68	73	4	291	490	125	48	1.17
956	645350	230775	7	3,200	2,091	257	114	178	8	66	988	333	42	2.32
957	645325	230850	7.2	4,800	3,886	332	234	420	4	149	1,815	625	11	4.30
959	647250	231075	7.7	2,100	1,408	220	66	73	3	198	608	145	49	1.11
972	647800	231450	7.3	4,500	4,160	440	241	395	18	71	1,925	650	12	3.74
974	646700	231225	7.2	7,100	5,730	332	302	750	23	108	2,350	1,025	12	7.14
982	647400	231550	6.9	1,900	1,337	158	81	75	5	51	638	125	43	1.20
991	646350	233100	7	1,800	1,273	172	79	65	7	203	563	100	44	1.03
1000	646250	232600	7	1,600	1,284	140	67	75	7	82	563	98	46	1.30
1005	646900	232900	7.3	1,700	1,275	164	72	70	3	106	525	155	39	1.14
1009	645100	233100	6.9	1,600	1,075	127	69	68	7	68	558	108	43	1.20
1019	644700	233300	7.2	1,700	1,197	141	77	70	5	144	495	115	44	1.17
1031	646400	234925	6.9	1,600	1,177	133	75	100	6	102	550	140	38	1.71
1035	648150	229250	7	3,900	2,710	229	144	318	10	79	1,188	458	37	4.04
1042	648950	229450	7	2,300	1,503	293	79	108	5	65	695	213	39	1.44
1046	648700	230350	7	3,100	2,361	231	118	215	9	78	983	350	26	2.86
1051	647750	228200	7	2,300	1,476	227	80	93	5	120	670	230	48	1.35
1054	647500	228000	7	1,800	1,269	190	71	73	1	78	295	155	40	1.14
1058	647150	227800	7.3	6,900	5,080	754	265	328	7	160	2,350	865	130	2.61
1066	646500	226400	7.2	2,500	1,943	238	113	120	6	138	900	200	25	1.60
1070	645850	227050	7	3,000	1,998	288	113	133	4	79	745	475	36	1.68
1081	646450	227750	7	4,500	3,268	401	179	250	3	60	1,415	550	39	2.60
1091	646600	229000	7.1	1,500	1,153	153	61	68	3	71	463	160	39	1.17
1094	646075	228700	7	1,900	1,379	183	71	65	4	205	525	145	51	1.03
1104	644800	227950	6.9	3,300	2,873	332	151	208	5	92	1,138	450	36	2.37
1109	643150	224450	7.1	2,800	2,335	290	126	123	5	90	813	385	240	1.51
1118	642350	230350	7	2,200	1,766	188	112	135	4	85	808	213	45	1.92
1125	643650	228175	7.6	2,100	1,379	207	84	78	3	138	625	193	59	1.15
1127	673950	288350	7.2	1,800	1,243	160	76	73	1	162	482	150	80	1.19
1134	640675	231600	7.1	7,100	6,131	584	465	475	17	196	2,900	800	310	3.54
1145	639700	231500	7	4,600	3,635	431	244	220	12	113	1,315	790	22	2.09
1159	638800	231300	7.2	3,200	3,295	334	213	250	10	163	1,225	600	22	2.62
1168	638950	232650	7.3	3,600	2,725	301	169	195	10	268	975	450	34	2.22
1171	637650	231200	7.3	3,900	4,006	308	218	238	12	110	1,575	365	38	2.53
1183	637200	231175	7	4,200	2,915	280	214	225	17	88	1,250	525	23	2.45
1190	637550	232050	7	9,700	6,608	758	431	615	7	69	2,430	1,850	78	4.40
1191	637750	232450	7	4,100	2,835	241	214	245	17	87	1,115	575	18	2.76
1205	637100	238650	7.9	3,500	2,161	104	85	465	16	426	583	513	25	8.16
1254	640150	228800	7	1,800	1,206	223	54	33	2	88	675	75	54	0.51
1257	639925	228450	6.8	2,300	2,099	334	299	38	4	95	895	125	195	0.36
1267	638250	228450	7.3	3,500	1,801	225	105	118	4	88	783	230	185	1.62
1276	637350	227800	7.1	3,400	2,460	295	152	170	13	109	1,113	308	125	2.00

Table 2 continued

Site no.	Coordinates*		pH	EC (μS cm^{-1})	TDS (mg L^{-1})	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	SAR
	X	*Y*												
1279	636800	229200	7	3,600	2,715	276	187	238	15	126	1,088	488	30	2.70
1291	637600	228950	7	2,800	2,029	217	110	160	10	123	800	285	72	2.20
1304	634450	230550	7.6	1,800	1,344	94	101	140	10	204	488	218	30	2.38

TDS total dissolved salts, *SAR* sodium adsorption ratio $mmol^{1/2}L^{-1/2}$

* Coordinates Lambert Nord Algérien

Table 3 Chemical composition of groundwater from boreholes, 2008 (This study)

Site no.	Coordinates*		Elev. (m)	pH	*t* (°C)	EC	TDS (mg L^{-1})	Ca^{2+}	Mg^{2+}	Na^+	K^+	HCO_3^-	SO_4^{2-}	Cl^-	NO_3^-	SAR
	X	*Y*														
1	655472.99	221217.15	454	7.40	21	803	666	92.82	30.89	37.04	0.68	158.6	78	95	118	0.85
2	655165.07	221660.96	449	7.47	20.9	844	786	112.48	33.36	28.25	0.66	158.6	102	125	134	0.60
3	655313.14	222294.05	444	7.44	21.3	644	512	88.93	26.89	23.86	0.46	152.6	74	70	106	0.57
4	654848.15	222790.60	448	7.40	21.1	950	870	112.93	42.54	63.87	0.37	189.1	210	125	82	1.30
5	654518.40	222664.69	451	7.31	22	1,688	1,272	216.95	67.74	62.39	1.03	183	230	330	150	0.94
6	653272.82	222635.66	455	7.28	21.9	1,369	1,358	200.5	60.47	93.37	0.82	183	500	155	92	1.48
7	651665.76	222646.86	454	7.17	21.5	2,500	2,510	280.41	101.26	140.14	0.64	152.5	760	295	6	1.82
8	656815.70	224341.16	445	7.32	21	1,893	1,510	190.98	91.12	141.37	1.59	225.7	476	225	158	2.10
9	654693.46	226446.56	417	7.21	22	2,520	1,680	210.7	100.89	191.19	1	195.2	548	360	60	2.70
20	660271.67	226843.36	432	7.27	21	1,573	1,208	180.34	60.46	116.84	1.06	183	500	160	42	1.92
21	660373.88	223838.65	445	7.10	22.1	2,780	2,250	321.3	118.58	232.18	1.28	207.4	796	405	88	2.80
22	660307.98	222066.75	445	7.30	22.4	909	824	104.71	43.2	72.24	0.44	231.8	242	90	36	1.49
30	656817.26	227678.25	416	7.37	20.7	1,366	1,196	142.45	48.54	130.18	0.73	225.7	404	130	44	2.40
31	657026.41	228016.50	414	7.33	21.2	1,510	1,242	161.28	66.51	122.36	0.78	219.6	500	175	44	2.04
32	657909.45	228712.55	407	7.26	22.4	1,426	1,196	173.36	62.08	112.36	1.03	244	500	115	36	1.86
33	651419.74	224092.11	451	7.20	21.8	2,430	1,746	264.57	91.86	177.86	1.93	183	744	260	66	2.39
34	650740.94	226400.69	444	7.20	22.1	2,540	1,492	249.6	75.64	126.5	0.51	164.7	620	200	76	1.79
41	655283.71	228649.51	412	7.22	24.5	1,643	1,326	215.4	57.81	58.88	0.55	207.4	450	155	35	0.92

TDS total dissolved salts, *SAR* sodium adsorption ratio

* Coordinates Lambert Nord Algérien; Elev. = elevation above sea level; EC: /μS cm^{-1}

(Maârif, Fig. 4) where there exists an agglomeration, close to the limit of commons, but not an agricultural area (compare with Fig. 1, white area); (2) in agricultural areas north and south of Maârif (green areas in Fig. 1).

It is worthwhile to note the spatial coincidence of the contaminated areas of both periods, which suggests strongly a communication between the two aquifers.

Nitrate concentration ranges from $6\,mg_{NO_3^-}L^{-1}$ to $158\,mg_{NO_3^-}L^{-1}$, in 2008, with 27 % over $100\,mg_{NO_3^-}L^{-1}$, 61 % of samples over $50\,mg_{NO_3^-}L^{-1}$, only 1 sample (5 %) under $20\,mg_{NO_3^-}L^{-1}$. Though the direct comparison of average values showed no significant differences, the detailed analysis of the distribution shows an extension of contamination of groundwater by nitrate. This extension progresses both vertically and laterally. Evidence for this is the fact that small values (under $20\,mg_{NO_3^-}L^{-1}$) were observed in the deep aquifer in 1996 and are no more observed in 2008. This indicates a contamination seriously constraining agricultural development and public health. This contamination is of anthropic origin, and could be due to fertilizer input and cattle breeding, or to seepage of water from septic tanks. This hazard is enhanced by sandy texture and direct gravitary irrigation, as irrigation is always in excess as compared to plant requirements and water holding capacity.

The following measures can be taken as a first step in the present irrigation and crop system to remediate to the contamination: (1) water control should avoid exceeding water holding capacity, while considering the necessity of a salt leaching fraction; (2) N-fertilizers should be fractionated and based upon the plant requirements and soil

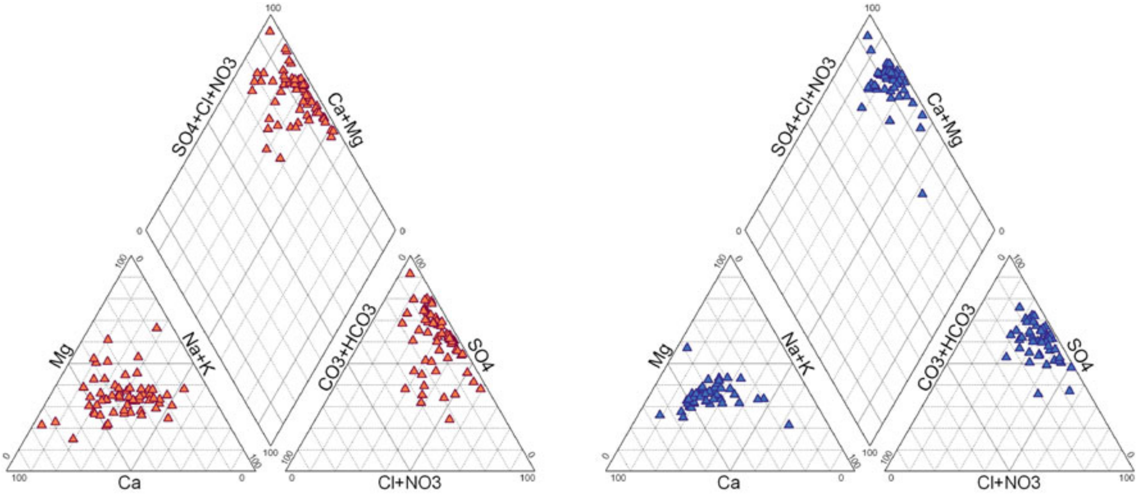
Table 4 Synthetic statistical parameters for the chemical composition of groundwaters of Hodna from 1967 to present (2008)

Parameter	Mean	Median	Minimum	Maximum	Standard deviation
1967 [*N* = 63, except for t (*N* = 59), nitrate (*N* = 56) and EC (*N* = 62)]					
t (°C)	17.55	18.00	12.8	21.8	2.13
Ca^{2+} (mg L^{-1})	411.05	416	30	898	208.77
Mg^{2+}	277.41	219	48	1,340	226.55
Na^{+}	520	300	24	3,456	600
K^{+}	25	9	0	99	29
HCO_3^-	204.62	206	38	424	74.89
SO_4^{2-}	1,882.03	1,810	185	7,488	1,378.04
Cl^-	733.43	426	57	4,473	837.41
NO_3^-	71.41	51	0	535	79.32
CE (μS cm^{-1})	5,036.55	4,025	1,011	21,900	3,793.65
TDS (mg L^{-1})	4,572	3,924	738	20,300	3,530.22
SAR	3.76	2.7	0.33	18.03	3.26
1996 (*N* = 50)					
Ca^{2+} (mg L^{-1})	257.54	226	88	758	141.9
Mg^{2+}	141.76	107	54	465	92.31
Na^{+}	185.9	134	33	750	150.52
K^{+}	7.58	6	1	23	4.99
HCO_3^-	125.72	104	51	426	68.59
SO_4^{2-}	959.8	764	295	2,900	587.75
Cl^-	366.88	262.5	75	1,850	313.01
NO_3^-	58.02	41	11	310	58.44
CE (μS cm^{-1})	3,076	2,400	1,500	9,700	1,707.67
TDS (mg L^{-1})	2,323.56	1,872	1,066	6,608	1,355.33
pH	7.15	7.05	6.8	8	0.25
SAR	2.24	1.96	0.36	8.16	1.48
2008 (*N* = 18)					
t (°C)	21.72	21.65	20.7	24.5	0.88
Ca^{2+} (mg L^{-1})	184.43	185.66	88.93	321.3	67.83
Mg^{2+}	65.55	61.28	26.89	118.58	26.53
Na^{+}	107.27	114.6	23.86	232.18	57.86
K^{+}	0.86	0.76	0.37	1.93	0.41
HCO_3^-	192.49	186.05	152.5	244	28.92
SO_4^{2-}	429.67	488	74	796	229.61
Cl^-	192.78	157.5	70	405	98.97
NO_3^-	76.28	71	6	158	43.39
CE (μS cm^{-1})	1,632.67	1541.5	644	2,780	680.2
TDS (mg L^{-1})	1,313.56	1,257	512	2,510	515.89
pH	7.29	7.29	7.1	7.47	0.1
SAR	1.67	1.81	0.57	2.8	0.69

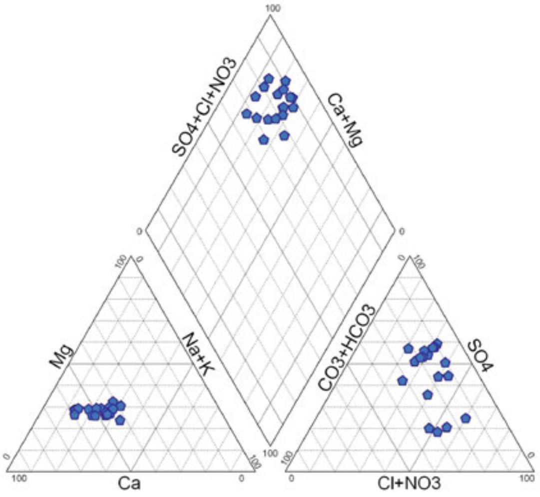
1967 phreatic groundwater, 1996 and 2008 deep groundwater

analyses; (3) soil surface should be covered during the whole year.

As a second step, new irrigation techniques, more efficient such as localized irrigation should be implemented to minimize water requirements and preserve water quality. This implies training farmers, who are numerous in the Southern Hodna region (about 5,000), with mid-term and long term programs. Further research should be initiated on N-cycle and N-fertilization, taking into account the specificities of arid conditions, to obtain local agronomic references.



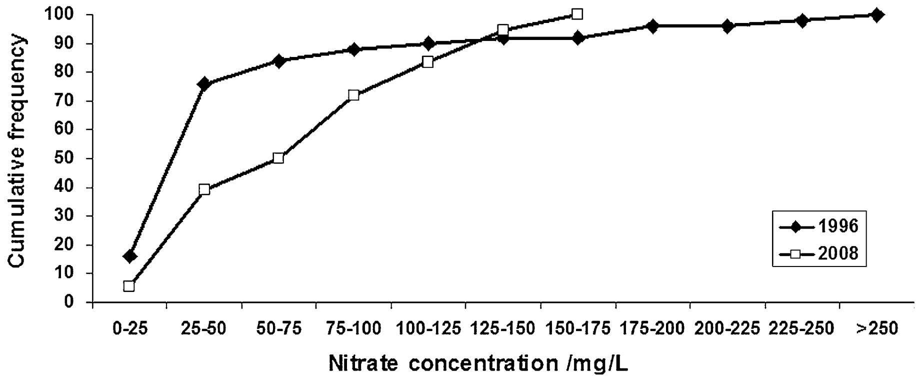
(a) Wells, 1967. **(b)** Boreholes, 1996.



(c) Boreholes, 2008.

Fig. 5 Piper's diagrams for groundwaters from Chott El Hodna

Fig. 6 Distribution of nitrate concentrations in 1996 and 2008. Cumulative frequency versus nitrate concentration



Conclusions

The Hodna region, an arid zone dedicated to pastoralism under severe climatic conditions, has been intensively anthropized as a consequence of agricultural policies of the past decades. Arable land areas increased at the expense of grazing lands on the basis of exploitation of water resources. Salinity of borehole water is moderate, with high

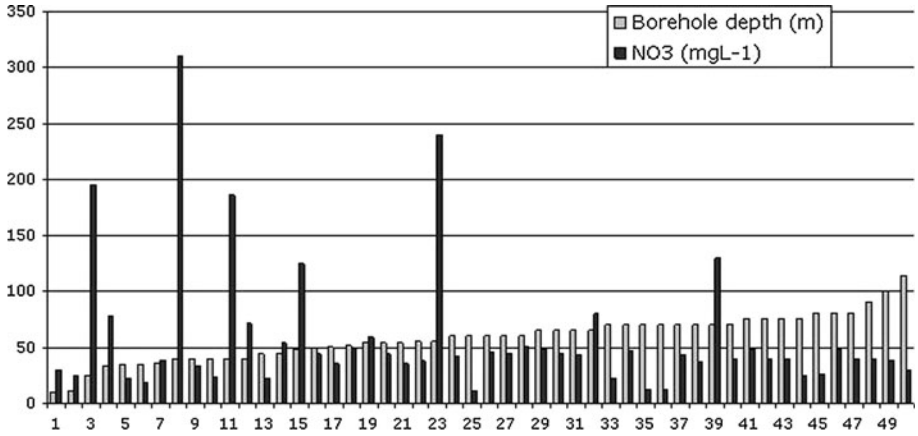


Fig. 7 Nitrate concentration in boreholes of increasing depth. Data from ANRH (1996)

values in the west of the agricultural area, where Cl^- concentrations override regulation thresholds. Waters from recent boreholes are less concentrated. Sodisation hazard is negligible, as estimated by SAR.

However, nitrate contamination affected about half of samples of the phreatic aquifer as early as 1967 (wells), while pastoralism was then dominant. Intensification of agriculture resulted in an increase of nitrate contamination of the deep aquifer, which is the only water resource for irrigation, human and animal needs. This could impair the sustainability of the development of the region.

To remediate this degradation of water quality, measures are proposed at two different time scales. First, in the present irrigation and cropping system, to fractionate N inputs and better control water inputs. Secondly, implement more efficient and less resource consuming techniques, such as localized irrigation, with adaptation of crop systems and fertilizer inputs to arid conditions, based upon farmers' training programs and local agronomic references, that are presently lacking.

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