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Deterioration of a Tunisian coastal aquifer due to agricultural activities and possible approaches for better water management

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agricultural activity; economic instruments; groundwater pollution and overexploitation; Korba, Tunisia.

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Abstract

The purpose of this study is to provide a better understanding of the impact of agricultural activities on groundwater quality in a semi-arid coastal environment (Korba, Tunisia). Impacts have been assessed through groundwater samples that were analysed for a range of chemical and biological parameters. Results indicate that groundwater overexploitation for irrigation and fertiliser use have affected the quality of the groundwater not only by direct contamination but also seawater intrusion. The implementation of appropriate regulatory and economic instruments to foster sustainable practices in the agricultural sector have been analysed within the framework of the EC (European Community) FP6 (funding program 6) INECO (Institutional and Economic Instruments for Sustainable Water Management in the Mediterranean Region) Project. Through stakeholder involvement processes, the project analysed issues relating to the regulation and control of groundwater abstractions, the promotion of wastewater reuse, efficiency improvements in irrigation water use, as well as instruments to strengthen the socioeconomic and institutional environment towards better managing and conserving available groundwater resources.

Introduction

In most semi-arid areas, groundwater constitutes an important and strategic resource, particularly as water stress increases and water resources of good quality become scarce (Beltran 1999; Saidia *et al*. 2009). In Tunisia, the total annual volume of exploitable water resources is about 4670 MCM, of which 57% (2700 MCM) is surface water and the remaining 43% (1970 MCM) is groundwater. Tunisia is a water-stressed country with a per capita renewable water availability of 486 m^3, well below the average of 1200 m^3/capita average in the Middle East and North Africa (MENA) region (Shetty 2004). Deep groundwater exploitation rates reach 73% of annual recharge, whereas the corresponding rate for shallow groundwater in coastal and central regions of the country is equal to 97% (DGRE 1997).

On the other hand, groundwater resources are also threatened by pollution from industrial and urban waste, livestock breeding and crop cultivation activities. Agriculture consumes 80% of available water resources in the country. The sector further contributes to groundwater exploitation and increases the risk of quality degradation in shallow aquifers (Trabelsi *et al*. 2005), particularly in the coastal areas. Kouzana *et al*. (2009) note that groundwater overexploitation of littoral aquifers for agricultural purposes has damaged groundwater resources both quantitatively and qualitatively. Effects concern the decrease of piezometric levels, sea water intrusion (Richer & Kreithler 1993), salinisation of soils (Bear *et al*. 1999), and seepage of nitrates, pesticides and faecal matter (Hudak 2000; Nolan 2001). These are measured through increased concentrations of nitrates, salts and bacteria (Oren *et al*. 2004). The higher salinity levels of water used for irrigation increase the salinity of soils and reduce land productivity, often resulting in the complete loss of agricultural land (Gaaloul *et al*. 2003), whereas the high concentration of nitrates, which in some case exceeds 300 mg NO_3/L, and that of faecal matter render the water unsuitable for potable use and exacerbate health hazards.

One of the Tunisian national strategies adopted during this last decade is the reuse of the treated wastewater either by direct use in irrigation or by an indirect way by using this nonconventional water to refill the aquifer in order to improve

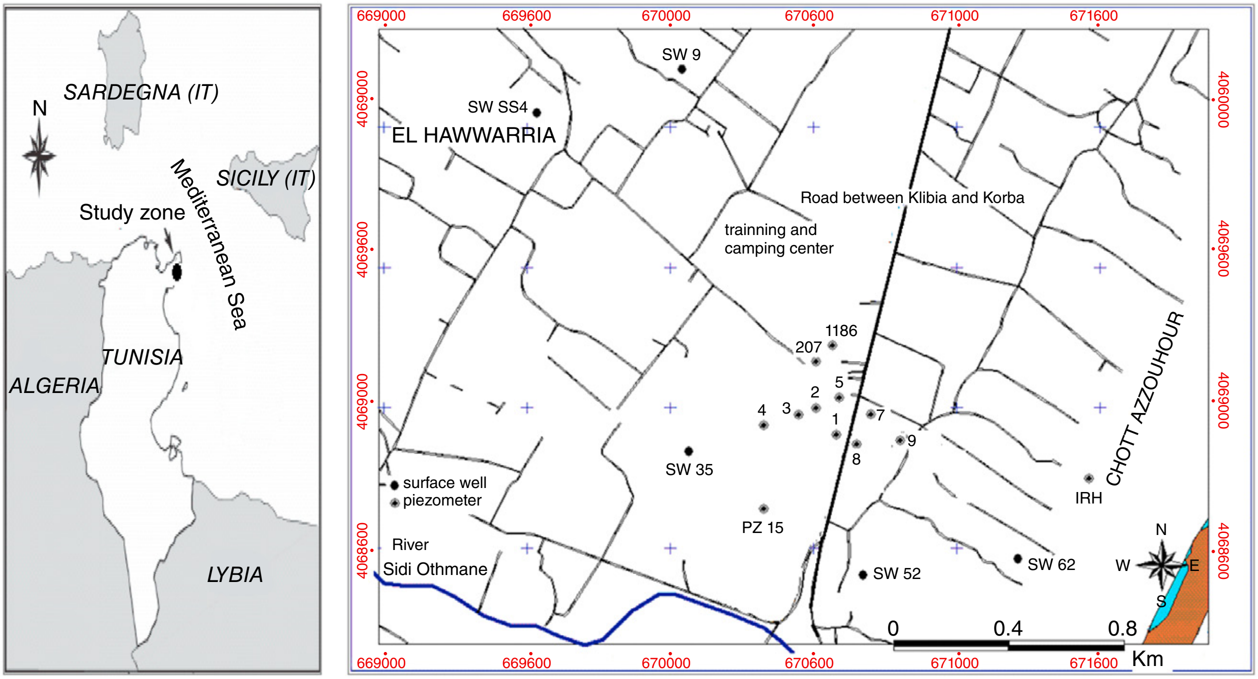

Fig. 1. Location of the study area and sampling points.

its quality, but this project faced many problems like the bad quality of treated wastewater and the farmers' beliefs.

In response to the observed trends of aquifer degradation and overexploitation, the Tunisian government has initiated efforts towards the mobilisation and safeguarding of water resources. However, population growth, urbanisation and the expansion of agriculture activities have led to uncontrolled situations regarding both quantitative and qualitative aspects and threatening future water availability and economic development. To that end, alternative approaches need to be introduced, focusing not only on technical interventions but also appropriate policy instruments to facilitate the wider implementation of conservation measures.

The aim of this study is to assess the impact of agricultural activities in a coastal aquifer of the Korba region (Tunisia). Impacts are assessed through the monitoring of salinity, chlorides, sodium, potassium, calcium, magnesium, nitrate and heavy metal concentrations, as well as bacteriological parameters in 18 shallow wells (SWs) of the area. Furthermore, this study presents the results of a participatory exercise undertaken within the framework of the EC-funded INECO project ('Institutional and Economic Instruments for Sustainable Water Management in the Mediterranean Region', Contract No: INCO-CT-2006-517673) aimed at identifying jointly with local stakeholders, policy instruments and pathways for mitigating groundwater overexploitation.

The study area

The Korba coastal aquifer, with an area of about 400 km^2, is located in the Cape Bon peninsula (Fig. 1) at the northeastern part of Tunisia and administratively belongs to the Nabeul district. The climate of this region is semi-arid with a 370-mm mean annual precipitation and high variability. Mean monthly precipitations vary from 5 mm in July to 59 mm in January. The annual mean temperature is 20°C, with variations from 14 (December, January and February) to 27°C in August (NIM 2011). Geologically, the region is formed by Pliocene and Quaternary deposits and is mainly composed by sandstones, conglomerates and clay. The main economic activities comprise tourism and most importantly irrigated agriculture, whereas some agro-industries also form part of the local economic structure. The total population is 100 000 inhabitants (Paniconi *et al*. 2001).

The aquifer system (Fig. 2)

The Korba aquifer can be divided into two hydrogeological units: the Plio-Quaternary and the late Miocene units. They are formed by the detritus formations of the oligo-mio-plio quaternary on a total surface of 1400 km^2. The groundwater contained in these quaternary formations is the most important of the region of Cape Bon, corresponding to more than 90% of its available groundwater resources.

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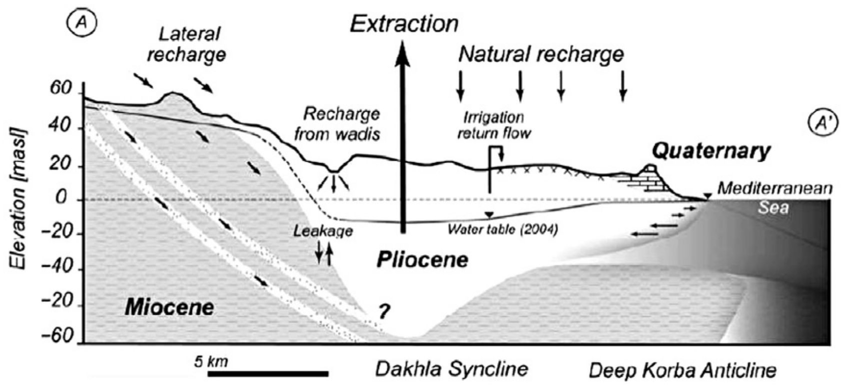

Fig. 2. The aquifer system of Korba: simplified geological cross-section of the Korba aquifer system sketching the conceptual model based on up-to-date geological and hydrodynamic data. The aquifer surface and bedrock topography along with the August 2004 water table are also shown (Kerrou *et al*. 2006).

The aquifer system of the eastern coast corresponds to the central part of the aquifer system of the coastal plain of the Cape Bon (about 400 km^2). It consists of a heterogeneous layer from the Quaternary and a deeper layer corresponding to the Miocene (Ennabli 1980). These two layers are separated by an argillaceous layer corresponding to the Pliocene. There is no impermeable layer between the Pliocene formations and the deposits of the Quaternary, and thus, infiltration to the Quaternary system also recharges the deeper Pliocene layer. Conversely, a discharge of water from the Pliocene could contribute to the flow towards the quaternary formations. The Plio-Quaternary unit is characterised by the highest hydraulic conductivities ranging from 10–6 to 10–3/ms, while hydraulic conductivities at the late Miocene unit are smaller (Ennabli 1980). Additionally, the water table is shallower in the Plio-Quaternary unit (Kerrou *et al*. 2010).

Evolution of the piezometry

The aquifer water balance

The recharge of the aquifer is mainly done by infiltration of precipitations. These infiltration are estimated to be less than 10% of the average annual rainfall (Ennabli 1980; Paniconi *et al*. 2001). As this region has an average annual precipitation of 370 mm and approximatively 400 km^2, the input is about 15 MCM/year. Another water origin for the recharge of the aquifer which is estimated at 3.1 MCM/year is from wadis (dry stream except during periods of rainfall) and topographic depressions (Kerrou *et al*. 2010). There is also an artificial recharge from direct infiltration of surface water from dams or from the Medjerda Cape Bon canal started that never exceeded 1 MCM/year (CRDA 2002). Other sources of recharge not yet evaluated are irrigation return flow and the lateral recharge by leakage or through faults from the underlying Miocene sandstones. The rate of replenishment is estimated at 25 MCM/year (Fig. 2).

The main output of this aquifer is groundwater abstraction mainly for irrigation purposes. This exploitation has increased from 4 MCM/year in 1962 (Ennabli 1980) to 50 MCM/year in the 1985 (DGRE 1985) and 55 MCM/year in 2000 (DGRE 2000). The sebkhas (salt lakes) forming a 5-km^2 strip all along the coastline are suspected to be a groundwater discharge areas. Other outputs like submarine groundwater discharge (SGD) are not yet evaluated.

Piezometric evolution of Korba aquifer

The evolution of the piezometry is shown through four piezometric maps (Fig. 3): 1962 and 1977 (Ennabli 1980), 1996 (Paniconi *et al*. 2001), and 2004 (Kerrou *et al*. 2010). Three of the most important wadis in the region, Chiba, M'laabi and Lebna, were dammed upstream in 1963, 1964 and 1986, respectively. Damming wadi Chiba in 1963 caused a decrease of the water table downstream because of a reduction of recharge by its effluents (Fig. 3a,b), whereas damming wadi Lebna dam had a positive effect on the aquifer recharge (Fig. 3a,b,c). Comparing the piezometric maps of 1977 and 1996 (Fig. 3b,c), there was a reduction of the Korba aquifer to 5 and 4 m below sea level between these years probably because of the aquifer abstractions in the 80s that reached than exceeded 43 MCM/year. This means that the hydraulic gradients were inverted towards the central part of the aquifer leading to an acceleration of seawater intrusion. Indeed, hundreds of wells close to the coastal area were salinised and abandoned displacing the pumping to north. These actions leaded to the disappearance of the –5-m depression but worsened the –4-m depression to –10 m (in 2004, Fig. 3d).

Economic importance and pressures from agricultural activities

Agriculture dominates the economic life of the Korba region, defining its unique character. Field crops are the most important cultivations, particularly tomatoes and peppers. Furthermore, the area is one of the most important winter suppliers of fresh vegetables and fruits to the Tunis metropolitan area,

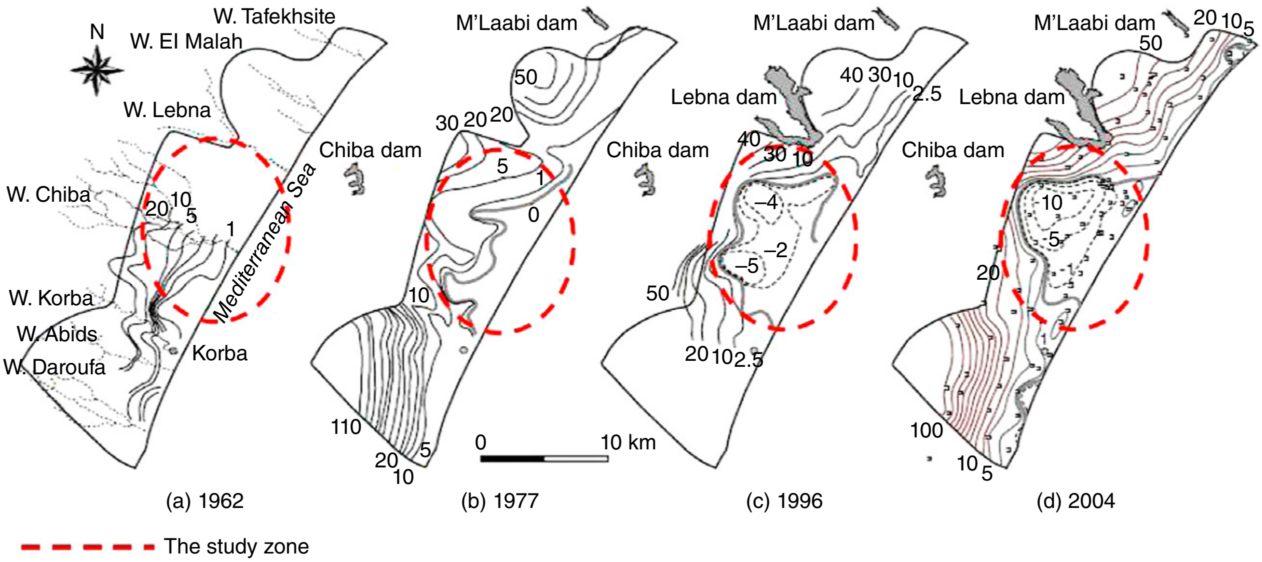

Fig. 3. Piezometric evolution (m.a.s.l.): (a) and (b) from Ennabli (1980); (c) from Paniconi *et al*. (2001); (d). from Kerrou *et al*. (2010). Contour intervals are not standard, and the 0 sea reference ISO-contour is represented by the thick grey line. The hydrological network is depicted by dotted lines and the dams by grey-shaded areas. The dashed red line delimites the study zone.

Table 1 Main agricultural products of the Korba area (CRDA 2008)

Crop	Cultivated area (ha)	Quantity produced (tons)	Importance
Strawberries	270	8000	85% of the national production
Vegetables	1200	1500	The first in Cape Bon regional production level
Potatoes	1010	6700	15% of the governorate production
Tomatoes	3000	165 000	22% of the national production and 35% of the regional production
Pepper	3000	3300	–

whereas strawberry production has also shown a remarkable expansion over the past few years (Table 1).

The type of fertilisers used in the study area was determined through interviews with local farmers. Overall, three types of fertilisers are used: organic (46% nitrogen), mineral (21%nitrogen, 24% sulphur) and mixed (both organic and mineral). Nitrogen fertilisers affect both the volume of production in the harvest season and the length of the cultivation period through their effect on plant growth. Pesticides are used as preventive or curative means of pest infestation control in order to protect crops from damage. Their massive use in the Korba area has disturbed the local ecosystem and increased pest resistance, which results to even more extensive pesticide use.

Sampling, preparation and analysis methods

Groundwater samples were obtained from the aquifer on 15 January 2008 (Fig. 1) from 12 piezometers (identified as 1, 2, 3, 4, 5, 7, 8, 9, PZ15, 1186, 207 and IRH) and five SWs (identified as SW 52, SW 62, SW 35, SW 9 and SW SS4). The location of these points was chosen by the local 'Regional Centre for Agricultural Development (CRDA)' prior to this study in order to allow the control of groundwater quality in this region, which is the purpose of this study. The average sampling depth was 15 m. As there is an evidence of seawater intrusion together with agricultural overexploitation shown by low piezometric levels (Kouzana *et al*. 2009; Kerrou *et al*. 2010), the study region is chosen in order to have water sampling points that begin near the sea up to agricultural fields.

Chemical, physicochemical and microbiological analyses were performed at the laboratories of the International Center for Environmental Technologies of Tunis (CITET), according to ISO and NF standards. Cations and heavy metals were analysed by Perkin Elmer inductively coupled plasma (ICP) atomic emission spectrometer (AES) optima 3300. Nitrates, chlorides, sulphates and bromides were analysed using Dionex ionic chromatography (Table 2).

Table 2 Analysis methods

Parameter	Method	Standard
pH	Electrochemistry	NF T 90-008
CO_3 and HCO_3	Titrimitry	
Conductivity, salinity	Electrochemistry	NF EN 27-888
Al, Cd, Cu, Fe, Pb, Cr, Mn, Ni	Atomic emission ICP	NF EN ISO 11885
Mg, Ca, Na, k	Atomic emission ICP	NF EN ISO 11885
Nitrates, Cl, SO_4, Br	Ionic chromatography	NF EN ISO 10304-1
Phosphorus	Colorimetry	NF EN 1189
Total coliforms	Multiple tube – MPN	NF T 90-413
Faecal coliforms	Multiple tube – MPN	NF T 90-413
Salmonella	–	ISO 6340

ICP, inductively coupled plasma; MPN, most probable number.

Table 3 Physicochemical parameters of the analysed groundwater samples, (pH, electrical conductivity –EC_{25}) and their salinity classification according to EC_{25} (Mulla 2008)

Groudwater samples	pH (temperature, °C)	EC_{25} (dS/m)	Classification[a]
1	7.43 (17.4)	10.6	Strongly saline
2	7.81 (17.3)	4.17	Saline
3	7.70 (17.3)	17.4	Extremely saline
4	7.11 (20.2)	11.4	Strongly saline
5	8.07 (20.5)	0.44	Nonsaline
7	8.85 (18.3)	0.69	Nonsaline
8	8.00 (17.5)	2.50	Slightly saline
9	10.0 (16.9)	0.36	Nonsaline
PZ15	8.72 (18.1)	0.92	Nonsaline
1186	8.41 (19.3)	3.78	Slightly saline
207	7.15 (16.8)	5.37	Saline
IRH	7.26 (19.2)	3.71	Slightly saline
SW 52	7.59 (20.2)	1.56	Nonsaline
SW 62	7.51 (18.7)	2.51	Slightly saline
SW 35	7.05 (19.2)	10.5	Strongly saline
SW 9	6.98 (16.9)	6.82	Saline
SW SS4	6.94 (17.2)	5.98	Saline

[a]Mulla (2008).

Results and discussion

Analysis of groundwater samples

The 17 groundwater samples are analysed for their physicochemical parameters (Table 3). Salinity varies significantly between 0.1 and 10.4 g/L, and is considered high for the majority of samples. The pH is around 7.00 for 65% of samples, whereas 35% of samples are alkaline. A pH value of 10.0 is recorded for the sample from Piezometer 9. The analysis of electrical conductivity results, through Mulla's (2008) electrical conductivity thresholds, leads to the conclusion that almost 50% of samples are saline, with 18% classified as strongly saline and 6% as extremely saline. An additional 24% of samples are classified as slightly saline.

Eight anions and cations concentrations are analysed in the groundwater samples (Table 4): calcium (Ca), magnesium (Mg), sodium (Na), sulphates (SO_4), bicarbonates (HCO_3), chloride (Cl), nitrates (NO_3), phosphorus (P) and potassium (K). Chloride concentrations in our samples vary from 17.0 to 5370 mg/L. As chloride does not adsorb to soil particles and does not undergo biological transformation, it could be a good tracer of seepage from manure (Rodvang *et al*. 2004), as it generally travels at the same rate as groundwater. The localisation of our samples as coastal does not allow to do these connections because of the additional possibility of the marine origin of chloride. Potassium concentrations vary from 6.10 to 77.8 mg/L. Natural groundwater concentrations of potassium are usually less than 5 mg/L (Hydrogeological Consultants Ltd. 2004), and manure tends to contain high concentrations of potassium. Even if potassium is known to be strongly adsorbed by minerals in the soil and thus travels very slowly towards groundwater, the high quantities found in the samples show a clear agricultural contamination. Sodium and sulphate concentrations vary respectively from 43.5 to 2980 mg/L and from 17.0 to 828 mg/L. Even if both of these ions are involved in unpredictable reactions and adsorption in soils, their very high concentrations are surely due to agriculture, as they are known to be present in excess in leachate from manure. Even if sodium can also have some marine origin that cannot be the case of potassium, average seawater concentration of sodium is 380 mg/L. Furthermore, groundwater impacted by manure leachate tends to contain many inorganic ions, particularly chloride, potassium and sodium, and therefore has elevated electrical conductivity values (ASAE 2000; Rodvang *et al*. 2002).

Measured levels of nitrate concentrations are very high in the majority of samples varying between 13.6 mg NO_3/L and 332 mg NO_3/L. Generally, nitrate concentrations in groundwater are less than 10 mg NO_3/L, and nitrate concenrations greater than natural levels are caused entirely by human activities such as agriculture, industry and domestic effluents (Scheidleder *et al*. 1999). The industrial activities in this region are not such high that they can generate groundwater nitrate pollution either by atmospheric emission or effluent disposal. The most probable origin of these high nitrate levels is from regional septic tanks but mainly from nitrogen synthetic and organic fertilisers used in this agricultural region. The low concentrations measured for phosphorus (maximum at 0.38 mg/L) are certainly due to its attenuation by soil and sediment adsorption; its low mobility reduces its value as an indicator ion. As for calcium, magnesium and bicarbonate concentrations, they vary respectively between 5.23 and 769 mg/L, 1.72 and 319 mg/L, and 38 and 453 mg/L (for the measured samples). Manure leachate is known to cause increased concentrations of these three ions in groundwater (Dantzman *et al*. 1983), and the high concentrations of

Table 4 Anions and cations concentrations (mg/L) in the ground water samples: calcium (Ca), magnesium (Mg), sodium (Na), sulphates (SO_4), bicarbonates (HCO_3), chloride (Cl), nitrates (NO_3), phosphorus (P) and potassium (K)

	Ca	Mg	Na	SO_4	$HC0_3$	Cl	NO3	P	K
1	331	123	1400	665	–	2785	114	0.06	48.8
2	160	57.8	578	377	–	1002	185	< 0.05	27.4
3	395	319	2980	828	260	5370	66.8	0.10	77.8
4	578	199	1850	500	231	3750	306	0.38	15.5
5	17.5	1.69	95.2	56.0	119	87.6	13.6	0.12	18.2
7	16.5	9.92	96.1	18.9	188	88.4	21.6	0.26	12.8
8	152	8.4	318	139	38	722	132	0.10	10.6
9	5.23	1.72	50.1	17.0	113	17.0	7.45	0.09	18.8
PZ15	54.6	1.74	43.5	49.0	263	158	24.6	< 0.05	20.1
1186	59.9	30.5	520	168	–	866	36.0	0.15	54.0
207	83	75.4	1024	186	456	1574	112	0.29	48.8
IRH	221	5.84	524	330	–	967	70.5	0.09	19.7
SW 52	117	24.6	167	103	188	358	52.8	0.09	6.10
SW 62	173	251	363	126	200	741	42.6	0.14	7.49
SW 35	769	301	1700	776	–	3600	192	0.08	14.6
SW 9	460	124	700	347	–	1830	225	< 0.05	9.10
SW SS4	463	118	682	350	–	1800	332	0.15	10.2

–, No data.

Table 5 Microbiological parameters of underground water samples

Identification code of the sample	Streptococcus (/100 mL)	Faecal coliforms (/100 mL)	Total coliforms (/100 mL)	*Escherichia coli* (/100 mL)	Salmonella (/100 mL)
3	0.92×10^2	1.1×10^4	1.1×10^4	1.1×10^4	Absence
4	1.1×10^4	0.1×10^4	1.1×10^4	1.5×10^3	Absence
207	9.3×10^2	1.1×10^4	$> 1.1 \times 10^4$	3.5×10^2	Absence

calcium and bicarbonates are above their average values in seawater.

The samples are analysed for nine metals: aluminium (Al), cadmium (Cd), copper (Cu), iron (Fe), lead (Pb), zinc (Zn), chromium (Cr), manganese (Mn) and nickel (Ni). All values are minor and below the ICP detection limits, except for the sample '1' that contains 3.45 mg/L aluminium and 0.279 mg/L iron. As heavy metal contamination is mostly caused by leaching from dumping sites, mining activities and industrial discharges, it is obvious that these have not been found as there are no such activities in this region. The exception of point '1' need to be checked for local contamination.

Microbiological parameters were monitored in three locations, and relevant results are presented in Table 5. In all cases, a contamination of groundwater is observed, with the exception of salmonella, which is always absent. Such contamination can be attributed to different pollution sources, such as animal breeding, which is an important activity in the area, as well as to sludge drying processes in the local wastewater treatment plant. As a result of this analysis, moderate concerns arise with regard to health risks from the use of water for irrigation purposes and from its accidental use as drinking water.

Altogether, the chemical and biological analysis of these waters reveals the double agricultural effect on the quality of the studied region; on one side, there is a direct contamination by fertilisers' leachate and animal breeding, and on the other side, there is a salinisation because of seawater intrusion induced by overpumping. These observations spotlight the need to change the agricultural management in this region by finding institutional and economic solutions.

Identifying institutional and economic instruments for mitigating groundwater overexploitation issues

The importance of groundwater as a strategic resource and the multiple risks to its quantitative and qualitative status in coastal areas call for the development of solutions that encompass both technical interventions and other regulatory and economic instruments to foster more sustainable groundwater management and induce behavioural change (Kampragou *et al*. 2011). Such instruments were analysed through participatory processes within the framework of the EC-FP6 INECO Project ('Institutional and Economic Instruments for Sustainable Water Management in the Mediterranean Region', Contract No: INCO-CT-2006-517673), which focused on issues relating to groundwater overexploitation at the national level and in the Nabeul Governorate.

Within INECO, stakeholder engagement was promoted through the application of the objective-oriented project planning (OOPP) methodology, which has often been applied to frame discussions with stakeholders and support participatory planning in water management, as well as other thematic areas (e.g. UN-Habitat 2001). The methodology, which is based on the logical framework approach, is broadly divided into three stages:

(1) Problem Analysis, involving the mapping of main water management issues, constraints and opportunities, as identified by key stakeholders, and the definition of a key (focal) water management issue in the Cape Bon area, which in this case concerned groundwater overexploitation. In addition, this stage included the identification and analysis of cause and effect relationships between threats and root causes of the selected focal issue;

(2) Objective Definition, including the identification of policy objectives, on the basis of the agreed root causes, the evaluation of their feasibility and the analysis of the relevant means-to-end relationships; and

(3) Option Analysis, concerning the identification of different options that can contribute to the achievement of the agreed objectives. Options are subsequently evaluated to identify appropriate pathways for problem mitigation.

Tools selected to support the implementation of the process for the Cape Bon included individual (preparatory or consultation) meetings with key stakeholders, workshops and public meetings, surveys, discussion fora, and dedicated questionnaires, supported by the distribution of appropriate background material (data, indicators, analysis results) relevant to groundwater overexploitation.

A preliminary step concerned the **identification of key stakeholders**, with a role or interest in groundwater management, including: (1) authorities involved in the management of water resources at the national and local levels (ministries, governorates, water authorities and municipalities); (2) representatives of important users, such as farmer associations, agricultural development groups (GDAs) and hotel owners' associations; (3) professionals dealing with various issues related to groundwater exploitation and management, artificial aquifer recharge and use of treated wastewater for crop irrigation. The following paragraphs elaborate on the process and outcomes of each stage of the followed approach.

Stage 1: Analysis of the focal problem of 'groundwater overexploitation'

The analysis of the issue of groundwater overexploitation was based on the organisation of two stakeholder workshops. The first, preparatory, event was held on May 8, 2007 in Nabeul and had a total of 46 participants [15 decision-makers, 13 water professionals, 5 farmers, 12 representatives of GDAs, and 1 media representative]. Its objective was to introduce the overall approach and identify the main water management issues in Tunisia, focusing particularly on aspects relating to groundwater degradation and overexploitation. Following from this, first event, a second workshop was held in Nabeul on December 6, 2007. Its primary aim was to further discuss the problem with the local stakeholders through the development of a 'Problem tree' qualitatively describing the causes and effects of the problem (Fig. 4).

According to the qualitative 'Problem tree' analysis, groundwater depletion is on the one hand caused by limited recharge and on the other by the overexploitation (abstractions exceeding natural replenishment) of aquifers. Overexploitation can be attributed to illegal borehole drilling, mostly by farmers for irrigation purposes, and to the lack of control over the operation of private boreholes. Abstractions are not metered mostly because of social and political pressures by the affected user groups. Furthermore, the low efficiency in irrigation water use resulting from the limited application of water saving techniques, the adoption of water intensive cropping patterns and the limited technical capacity of farmers exacerbates the problem. Incentives in using alternative nonconventional resources (treated wastewater) are considered inadequate, and the application of water reuse remains limited. Main reasons include the low quality of treated effluents, adopted standards, climate, soil types, choice of crops, land use patterns and particularly the farmers' unwillingness to accept and pay for treated wastewater and public perception issues. Aquifer recharge is still at the experimental stage, and results are encouraging. However, outside the public irrigation schemes, awareness campaigns to promote water reuse and water conservation have not yet managed to adequately address the concerns of end-users, and application remains limited in spite of the governmental subsidies offered. In the long run, it is expected that aquifer overexploitation will have negative impacts on the environment, on agricultural income and on the development of rural areas (Fig. 4).

Stage 2: Definition of objectives for problem mitigation

An intermediate step in defining objectives for problem mitigation is undertaken through the verbal reversing of the Problem tree of Fig. 4, which helps to jointly identify with stakeholders those policy objectives that are most relevant for mitigating the focal water management issue. Subsequently, this 'tree' was further elaborated to define a set of key policy objectives towards the main goal of 'achieving regulated and rational use of groundwater resources',

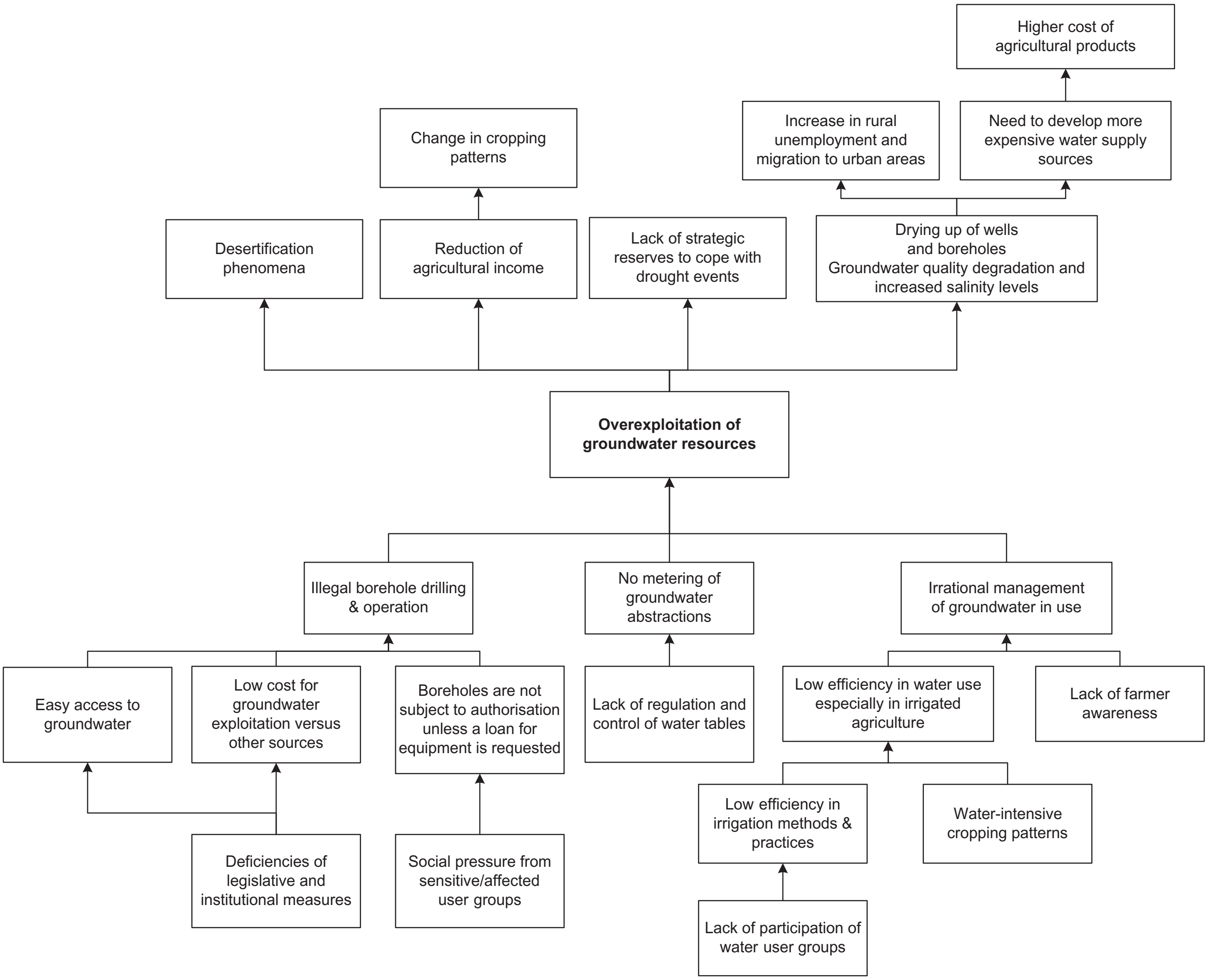

Fig. 4. Problem tree analysis of the causes and effects of groundwater overexploitation in the Cape Bon area.

incorporating the views and goals of all stakeholders. Through this process, the following key objectives are identified:

- Control and regulation of borehole drilling and of groundwater abstractions, particularly outside public irrigation schemes, encompassing also incentives to enhance the use of alternative water supply sources;
- Promotion of efficient groundwater use linked to enhanced efficiency in irrigation water use and change of cropping patterns.

Furthermore, and as all the consulted parties supported (1) the introduction of treated wastewater as means for substituting freshwater use for crop irrigation and (2) the participative management of water tables, suggested options were also oriented towards the promotion of reuse in irrigated agriculture and the reinforcement of end-user participation in decision-making.

Stage 3: Identification and evaluation of options for mitigating groundwater overexploitation

The work towards deriving policy recommendations focused on the suggestion of alternative (institutional and economic) options to achieve the aforementioned objectives. These suggestions, subject to evaluation, were used to formulate a roadmap for the development of strategies suitable for achieving the wider goal. Potential policy instruments, set forth to local stakeholders, were grouped into four main categories and are presented in Table 6, in combination with the objectives identified in Stage 2.

The first step towards the **evaluation of potential instruments/responses** was their prioritisation by local stakeholders on the basis of predefined criteria. This was implemented through a simple, screening survey, where participants were asked to grade broad instrument categories,

Table 6 Policy objectives and instruments for mitigating groundwater overexploitation

Policy objective	Instruments	Prerequisites/potential constraints
Control of groundwater abstractions and incentives towards reduced groundwater usage	Stricter legislation on abstractions and enforcement of the relevant provisions	• Relevant legislative provisions • Capacity to adequately monitor abstractions
	Voluntary schemes with farmers for reducing groundwater abstractions/adopting wastewater reuse	• Financing of relevant compensation and modernisation schemes • Monitoring and provision of technical support
	Reform of irrigation water tariffs (lower tariffs for surface water and treated wastewater) – introduction of abstraction charges	• Legislative provisions • Affordability/impact on poorer farmers • Revenue earmarking mechanisms
Enhancement of efficiency in irrigation water allocation and use	Enhanced economic incentives for modernising irrigation methods	• Consultation with end-users to identify deficiencies and potential needs in relation to current policies
	Training on efficient irrigation practices	• Design and implementation of training programmes for small-scale farmers and landowners
	Incentives for the change of cropping patterns	• Assessment of impacts on agricultural production and rural income • Subsidies for the introduction of new crops in relation to the goals of the National Agricultural Policy
Promotion of treated wastewater use	Establishment of standards and codes of practice for water reuse	• Legislative provisions • Monitoring and enforcement
	Training and information campaigning on water reuse	• Design of tailored programmes for farmers • Awareness campaigns towards the general public
Strengthening of the overall socio-economic and institutional environment	Information sharing and public access to information	• Legislative provisions • Design and implementation of data sharing platforms
	Strengthening of agricultural development groups (GDAs), particularly for the management of groundwater abstraction rights	• Legislative provisions • Capacity building at the GDA level

considering both the instruments identified in Stage 2 as well as others from the pertinent literature. Criteria concerned individual preference [grading using a scale from 1 (least preferable response) to 5 (most preferable response)], feasibility and applicability to the local and the national water management context (yes/no answers), relevance to groundwater overexploitation and future challenges (yes/no answers), and need to prioritise [grading using a scale from 1 (least urgent) to 5 (most urgent)]. The step was implemented from February to June 2008, and replies were collected by 64 stakeholders, including 27 professionals and 12 high-level decision-makers from water management authorities, 11 managers of GDAs, 5 farmers, 7 members of the academia, and 2 hotel owners. Results are summarised in the spider chart of Fig. 5, which presents the score for each instrument category for each criterion. Scores represent the average ranking over all replies received, where values have been scaled from 0 to 1.

A key result was that answers from different stakeholder groups converged with regard to the solutions of the problem under discussion. Instruments and approaches that seemed to be most relevant and applicable comprise public participation in combination with further decentralisation of irrigation water management and enhancement of regulatory approaches (stricter liability rules and enforcement of the pertinent legislation). Voluntary schemes are also considered pertinent and applicable, given the current institutional framework. Stakeholders expect that their combination with stricter legislation enforcement could provide the basis for effective policies to address both current and future water management challenges. Water pricing, as well as measures that could impose additional economic burden on water users, is not favoured when compared with other softer approaches; it can be thus be argued that socio-economic considerations and broader agricultural policy goals are reflected both in the perceptions of the different water user groups, and of secondary stakeholders dealing with everyday water management issues.

The overall process of evaluating potential responses was complemented through a last step, implemented through a survey for evaluating perceptions on potential policy pathways towards water conservation in irrigated agriculture, the development of incentives for water saving and the change of water demand patterns, the regulation of groundwater abstractions, and the enabling of public participation and involvement in decision-making (Table 7).

The survey was implemented from November 2008 to mid January 2009 and was addressed to secondary stakeholders (decision-makers), as well as researchers specialising on water-related issues. Overall, 70 persons were contacted, and 36 replies were received from water authorities and water professionals (15), the local CRDA and GDAs (12), and

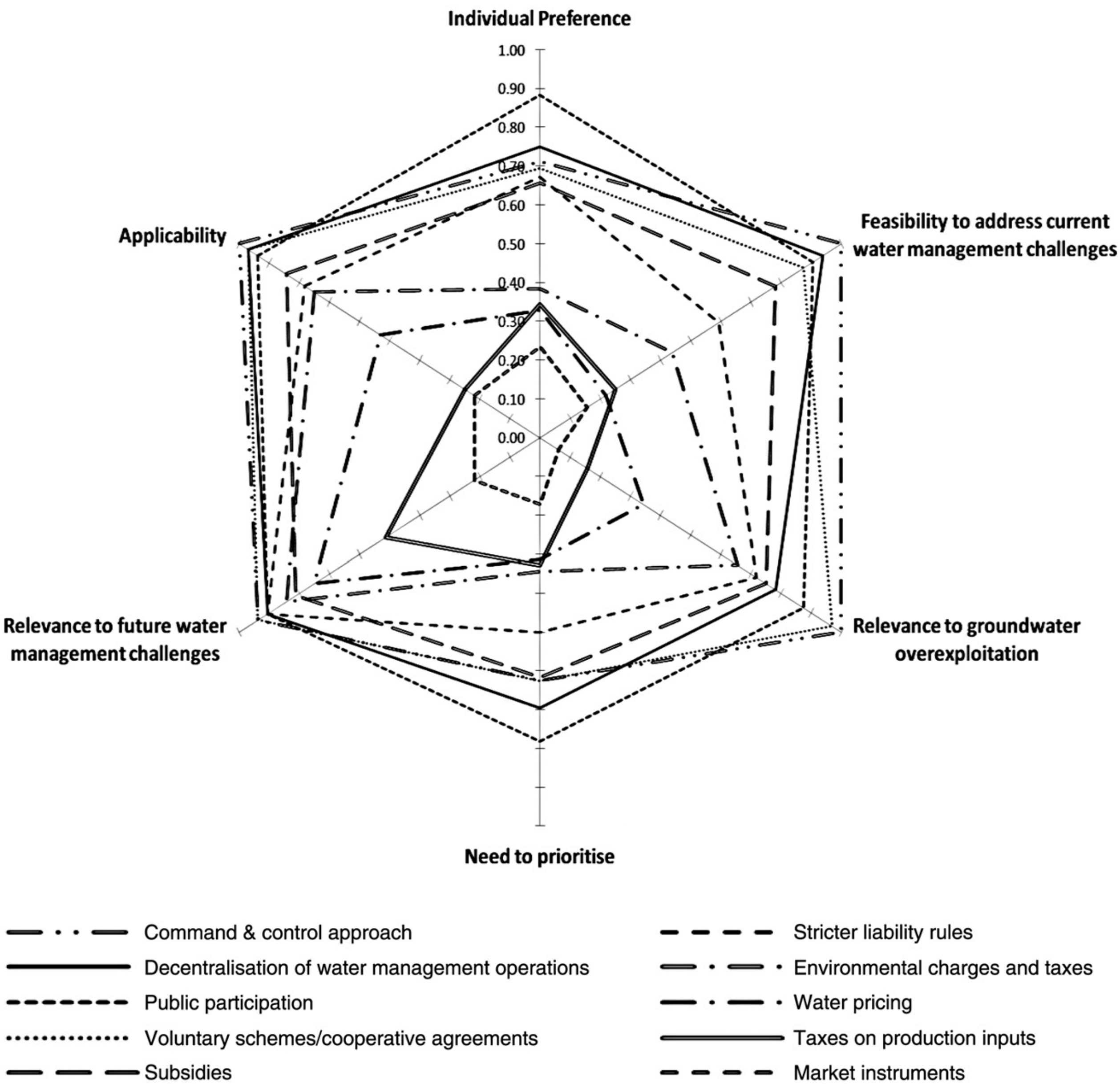

Fig. 5. Ranking of instruments for addressing current and future water management challenges.

researchers (9 replies). The following paragraphs provide an overview of the main results.

Water conservation in irrigated agriculture

The overexploitation of groundwater is interlinked with its use for crop irrigation, especially in areas where no alternative supply is available. As such, ways of promoting water conservation in the agricultural sector are of primary importance. Surprisingly, the consulted stakeholders believe that margins to reduce water use in irrigated agriculture are limited; however, almost 90% of respondents underline that different cropping choices need to be encouraged. Along the same line, 63% of stakeholders perceive that water use rights should not be traded among farmers, commonly sharing the perception that this could eventually favour business agriculture at the expense of subsistence farming. In this regard, it becomes evident that stakeholders emphasise on the role of the state in the development of water and agricultural policies, outlining the need for integrating approaches for sustaining the agricultural sector, while at the same time preventing further degradation of water resources.

Table 7 Survey on potential policy pathways towards groundwater conservation in irrigated agriculture and public participation

Survey theme	Questions
Water conservation in irrigated agriculture	Potential for a further decrease of water use in the agricultural sector
	Requirement for governmental support (subsidies) for the encouragement of different cropping choices
	Equitability of tradable water use rights
Incentives for water saving and change of water demand patterns	Possibility to introduce mandatory efficiency standards for new irrigation projects
	Acceptability of an increase in water tariffs in order to discourage wasteful water use
	Levying of environmental taxes/abstraction charges to provide financial support to farmers that invest in water saving
	Acceptability of potential economic mechanisms for the change of water demand patterns, including the (1) offer of compensation for giving up specific water uses and (2) the significant increase of water-related charges so that high-value uses (e.g. tourism, high-value crops) will continue and low-value ones will give up.
Reduction of groundwater abstractions	Feasibility, applicability and effectiveness of monitoring and control over water abstractions, especially in the case of private boreholes and wells
	Empowerment and political willingness of the state to strictly enforce legislation on groundwater withdrawals
	Introduction of liability mechanisms for the compensation for environmental damage and ways through which relevant fines could be defined and imposed
	Development of collective schemes for irrigation water supply in order to prevent individual abstractions and ways through which the costs for the development of such systems should be recovered
Public participation and involvement	Ways of pursuing more active involvement of the public and water users
	Impartiality of decisions taken – importance given to the interests of specific groups over others
	Trust that the outcomes of a public participation process would be considered by decision-makers
	Sufficient access to information on water-related issues

Incentives for water saving – change of demand patterns

Although it seems to be generally believed that margins to reduce water use in agriculture are limited, further investigation was undertaken as to ways of providing additional incentives for the adoption of more efficient water use practices. These could entail the enhanced application of volumetric charges and the development of financing mechanisms to provide aid to those who decide to invest in new technologies. An increase of water tariffs and the levying of taxes as means to raise revenue for supporting technology shifts receive limited acceptance from the majority; it is thus obvious that there is much concern over the affordability of water-related charges, as well as strong belief that all efficiency improvements should be financed through other sources of funding (e.g. general state budget).

In view of the increasing water stress experienced in some areas and the Cape Bon, in particular the lack of alternative supply and the growing competition over water resources and land use, specific uses might have to be phased out or relocated to other regions, where the stress on the resource side is still limited. In this context, water stress mitigation at local level could be effected by offering the appropriate incentives to water users. This could entail compensation for abandoning low-value uses and shifting to other occupations, or raising water charges so that low value uses would not be economically viable. Half of respondents indicate that the offer of compensation would be a suitable incentive. On the other hand, responses with regard to the setting of water charges portray significant opposition. In general, it is believed that the shift towards economic efficiency would require a strong social component so that the interests and resources already invested in water uses that can no longer be easily sustained would not be compromised.

Regulation of groundwater abstractions

The effective implementation of command-and-control regulatory approaches for individual groundwater abstractions is being advocated as a priority solution for addressing groundwater overexploitation.

Almost 90% of interviewed stakeholders underline the pertinence of potentiating command-and-control regulatory measures. A similarly significant percentage (72%) believes that the state can successfully enforce the pertinent legislation in an effective and efficient way. Stakeholders are also rather favourable towards more stringent fines addressed to those who incur environmental damage. However, the alternative of developing collective water supply schemes is much more broadly supported. More than half of respondents (67%) perceive that the corresponding costs must be partially socialised in order to maintain acceptability and affordability, considering that additional incentives should be offered to users so as to substitute individual (and difficult to control) water supply with other sources.

Public involvement and participation

Enhanced involvement of stakeholders and water users, especially farmers, in decision-making is identified as a key priority in the effort for the protection of groundwater bodies and enhancing the efficiency of agricultural practices. Stakeholder perceptions on how user involvement and public participation should be pursued are diverse based on the common view that current efforts need to be strengthened. Approaches range from enhancing the involvement of the general public and water users to the strengthening of the role of nongovernment organisations (NGOs) for pursuing inclusive processes, and to awareness campaigning and reinforcement of civic responsibility.

Despite the practically unanimous acceptance of the need for public participation, stakeholders do not trust that the outcomes of participatory efforts would be considered by decision-makers and incorporated in water planning. An additional question related to the impartiality of water management decisions leads to the conclusion that 88% of respondents perceives that some stakeholder or user groups are generally given more weight than others in the decision-making process.

Finally, it is considered that any public participation effort should be primarily based on the disclosure of information on significant water management issues; only 14% of respondents, who were in fact decision-makers, indicated that they have sufficient access to relevant data and information.

Conclusion

The analysis of the groundwater quality around the Korba region has demonstrated a high contamination with various ions mainly derived from agricultural activities and high bacteria levels. In the other side, the quality of groundwater has demonstrated an excessive salinity because of the overexploitation of the aquifer leading to sea water intrusion.

In this regard, participatory approaches can help to identify the range of currently acceptable instruments, potential concerns and ways through which these can be overcome. An example of this approach has been demonstrated through the INECO project, which attempted to frame discussions on potential instruments for mitigating groundwater overexploitation.

Results from stakeholder consultation and workshops support a set of main options identified by the project, including approaches for regulation and control of groundwater abstractions, promotion of water reuse, efficiency improvements in irrigation water use, and also the strengthening of the overall socio-economic and institutional environment. Answers indicate strong support for measures related to water saving and particularly towards improving efficiency in irrigation, including the encouragement of different cropping choices by the state, the provision of incentives for water saving and the adoption of water efficiency standards. Emphasis is also placed on the pricing of water services supporting the connection of water users to collective systems that prevent individual abstractions, while charging these connections at partially socialised cost in order to maintain affordability and acceptability. Furthermore, there is some implied support to the generation of cross-subsidies among different water users.

Concerning public involvement and participation, responses indicate that public participation is currently insufficient but very much desired. It is also clearly evident that access to information is considered inadequate by the majority of stakeholders questioned and that the accessibility and relevance of available information need to be improved. However, there is also strong preference towards the enhancement of command and control regulatory measures, and the introduction and strict enforcement of legislation.

The participatory process adopted through targeted surveys and stakeholder workshops enabled the open exchange of ideas and solutions among persons who encounter water stress and groundwater management problems on a day-to-day basis; it also offered alternative perspectives of the problem based on the elaboration of real solutions and options that can be useful, applicable and acceptable for determining suitable strategies for the mitigation of the problems faced. Potentially, the derived recommendations can contribute to the mitigation of the deterioration of groundwater resources, particularly in the Cape Bon region, provided that authorities commit to the implementation of the necessary changes. Furthermore, public participation and community management of resources need to be encouraged through capacity-building initiatives and reforms towards the empowerment of water user associations.

Current impact

Following the recommendations of the present study, some actions have been taken by the government in order to remedy to the current situation. Among these actions, the coastal area was supplied with low-salinity surface water (0.5 g/L) taken from Northern Tunisia that would contribute to counteract seawater intrusion. The farmers chose to use this surface water that enhance their crops' productivity, which made them stop the abstraction of groundwater from wells. Another action was to use the treated wastewaters from the near treatment plant to recharge the aquifer, a project that started in the late 2008 and contributed to the lowering of the salinity in the well waters near the recharge area. On the other side, the most advanced irrigation methods to spare water are now used in this area like drip irrigation and the covering of the soil with black plastic sheets in order to minimise evaporation. These methods are now encouraged by a subsidisation at 70% of the material cost. The farmers are encouraged to spare water by various NGOs in order to avoid overexploitation of the aquifer. The social measures that were recommended, like rising the water price or controlling the flow rate of the water abstraction from wells, are not yet realised.

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