

# The influence of hydrogeological properties, seawater intrusion and refreshing on the quality of groundwater used for irrigation in an agricultural coastal plain in North Sardinia, Italy

Daniele Pittalis<sup>1,2</sup> · Alberto Carletti<sup>2</sup> · Giorgio Ghiglieri<sup>2,3</sup> · Fulvio Celico<sup>1</sup>

Received: 17 February 2015 / Accepted: 23 May 2016 / Published online: 4 June 2016  
© Springer-Verlag Berlin Heidelberg 2016

**Abstract** Intensive agriculture can influence groundwater composition, aquifer biogeochemistry and soil properties; this is especially true in coastal areas where groundwater is the main source of irrigation water. Depending on the irrigation efficiency, the aquifers may suffer from pollutant contamination and salinization caused by the encroaching sea. Information about the chemical composition of the groundwater is not sufficient to permit an evaluation of either the suitability of the water for irrigation or its negative impacts on the quality of the aquifer. In this study, a method for evaluating the suitability of groundwater for irrigation, from the perspective of water quality, is proposed suggesting that groundwater use should depend on the degree of salt-water contamination. A classification of the quality of irrigation water, based on quantifying elements potentially harmful for agricultural productivity, was revised to consider the dynamic movement of the seawater interface (intrusion and freshening phases) and hydrogeological properties. The effectiveness of this method was tested in a cropland-dominated coastal alluvial aquifer (Turritana Plain, Sardinia, Italy) that is irrigated by unconfined groundwater stored in sedimentary deposits. Results show that freshening processes cover almost 53 % of the alluvial aquifer. While the groundwater may be suitable for irrigation from a quality perspective, seawater intrusion affects 47 % of the aquifer,

mainly the coastal margins. This method, based on index technique, is a useful tool to help policy makers understand the important role of water resources in an area that is vulnerable to desertification and where semiarid climatic conditions are developing.

**Keywords** Water quality · Seawater intrusion · Hydrogeology · Desertification · Sardinia

## Introduction

Groundwater is a major source of water for domestic, industrial and agricultural uses in many parts of the world. In many places, however, constituents derived directly or indirectly from agricultural practices and additives (Böhlke 2002) have dominated the major chemical compounds found in groundwater in phreatic aquifers in recent decades.

In particular, agricultural chemicals such as fertilizers, pesticides and lime affect the water quality of alluvial groundwater (Kraft et al. 1999; Jayasingha et al. 2011). Seawater can also be a pollutant in places where freshwater is replaced by the encroaching sea. Nonetheless, the salinization of aquifers in coastal areas may be the result of concomitant processes related to seawater intrusion and water–rock interactions, which are almost indistinguishable in some cases (Mongelli et al. 2013). Human activities are a particular threat to the quality of fresh groundwater in coastal aquifers of arid and semi-arid regions such as the Mediterranean basin (Celico and Rotigliano 2002; Somay and Gemici 2009; Slama et al. 2010). In particular, constant increases in the water demand, especially for agricultural purposes, compete with limited opportunities for natural recharge and high rates of evapotranspiration (Qadir et al. 2003; Angelakis et al. 1999). The availability

✉ Daniele Pittalis  
daniele.pittalis@unipr.it

<sup>1</sup> Department of Physics and Earth Sciences, University of Parma, Parco Area delle Scienze 157a, 43124 Parma, Italy

<sup>2</sup> Desertification Research Centre (NRD), University of Sassari, Viale Italia, 07100 Sassari, Italy

<sup>3</sup> Department of Chemical and Geological Sciences, University of Cagliari, Via Trentino 51, 09127 Cagliari, Italy

of high-quality groundwater, especially for irrigation, is expected to decrease (Bouwer 2000), so information about the quantity and quality of groundwater that can be used for managing irrigation *vis-a-vis* aquifer status is essential. In most cases, the quality of an irrigation water source is assessed as a function of both quality parameters and some specific impact hazard related to the irrigation practice as: potential salinity, permeability hazard, specific ion toxicity, trace element toxicity and its impacts on susceptible crops (Bauder et al. 2011; Simsek and Gunduz 2007; Prunty et al. 1991; Vomocil and Hart 1990; El-Ashry et al. 1985; Ayers 1977). In other cases, quality is assessed based on the concentrations of different chemical constituents (Ketata et al. 2012; Gibrilla et al. 2011; Nagarajan et al. 2010). Although information about the water's chemical composition is necessary, this information is not sufficient to support a robust evaluation of either its suitability for irrigation or its impacts on the aquifer status, especially if seawater is a pollutant. Freshwater stored in coastal aquifers is particularly susceptible to degradation due to its proximity to seawater and requires different management solutions (Bouchaou et al. 2008; Rao et al. 2005; Stuyfzand and Stuurman 1994). Different hydrogeological processes are recognized for their relevance to saltwater intrusion, specifically in a shallow unconfined aquifer: heterogeneity in aquifer properties and geometry, dispersion and diffusion, degree of aquifer confinement, hydrogeochemical processes, etc. (Werner et al. 2013).

In detail, saltwater intrusion influences the hydrodynamic conditions related to the hydraulic gradient by lowering the local freshwater water table and determining the direction and rate of groundwater movement (Davis and De Wiest 1966; Johnson 1975). Salt water also contributes to the development of ion exchange reactions (Appelo and Postma 2005). The resulting hydrochemical variations can be interpreted relative to the pattern of seawater intrusion, groundwater quality status, aquifer behaviour and hydrodynamic conditions (Gimenez-Forcada 2014; Pulido-Bosch et al. 1999). Therefore, the influences of other factors, including the dynamic movement of the seawater interface (intrusion and freshening phases) and hydrogeological properties, should be considered in combination with the water quality.

The relationship between the dynamic movement of the seawater interface and the groundwater hydrochemistry can be synthesized through cation exchange, which is driven by the differences in cation dominance in seawater and fresh groundwater (Werner et al. 2013). Depending on whether the ion exchange is direct or reverse (Ghiglieri et al. 2012), it is possible to determine whether seawater is encroaching [seawater intrusion (SwI), also called the intrusion phase] or whether freshwater is cleansing the salinized aquifer [freshwater intrusion (FwI), also called

the freshening phase]. Several case studies (Gimenez Forcada 2010; Stuyfzand 1999; Valocchi et al. 1981) have shown, along flow paths, the development of characteristic water types and chromatographic patterns (sequential exchange that, during saltwater intrusion and freshening, acts as a separation mechanism that develops characteristic ion concentrations), which can be used as an indicator of freshening or salinization of coastal aquifers.

In this study, a method for evaluating the suitability of groundwater for irrigation related to the degree of saltwater contamination in a coastal aquifer is proposed. An accurate delineation of the extent of saline groundwater in coastal aquifers is usually difficult, due to the scarcity of water salinity measurements and because the process is typically slow (Werner et al. 2013). Therefore, this method can be also a useful tool, especially for the decision-makers, to obtain a preliminary representation, analysis and interpretation about the degradation of both the water resources and the aquifer.

It was applied to the Turrutana Plain, a coastal area characterized by seawater intrusion processes mainly related to intensive water use for agriculture (although tourist resorts and increasing urbanization in the area are also augmenting the competition for water resources). The method combines the hydrochemical facies evolution of groundwater (Gimenez Forcada 2010) and a quality index for irrigation (Fiorucci 2007) that has been revised. Then, the combination effect of deriving data has been evaluated according to hydrogeological condition to: (1) consider the potential environmental impacts on the aquifer and (2) define its proper use by creating restricted classes.

## Materials and methods

### Study area

The study area is in the lowland part of the Turrutana Plain, commonly called the Piana Turrutana, and is bounded to the south-west by the basin of the Porto Torres Riu Mannu and to the east by the Anglona mountains; the north of the study area is in the central part of the Asinara Gulf (Fig. 1). The study area runs parallel to the coastline for approximately 20 km, is approximately 4–5 km wide and covers an area of approximately 50 km<sup>2</sup>.

The area has a semi-arid climate with large variations in temperature and rainfall. In Fig. 2, the average annual temperature and rainfall for the hydrologic year of observation (2006) are shown.

The plain is characterized by a poorly developed cataclinal hydrographic network that gives rise, with a few exceptions, to modest torrential rivers. One such exception is the Rio Silis, which has a hydrographic basin of 120 km<sup>2</sup> and has perennial flow, even in the driest periods of the

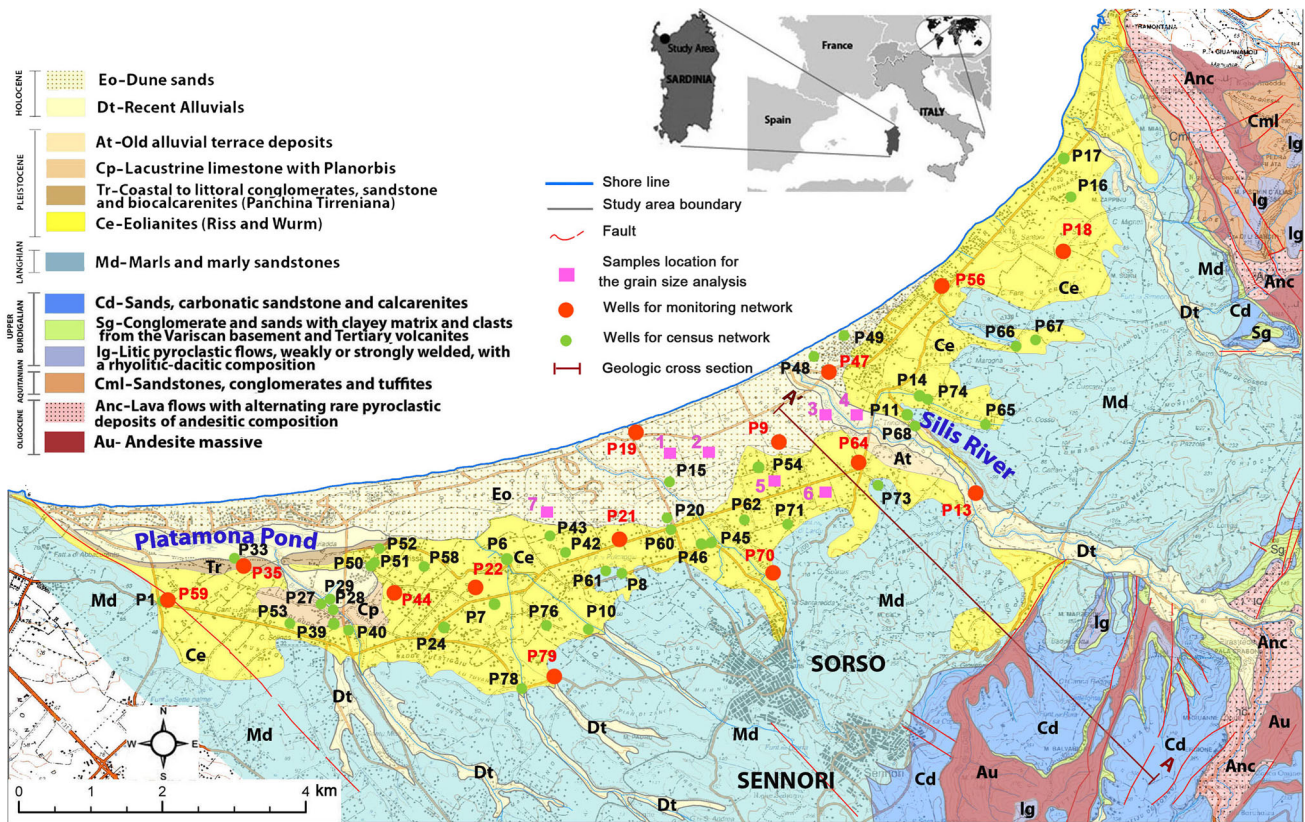
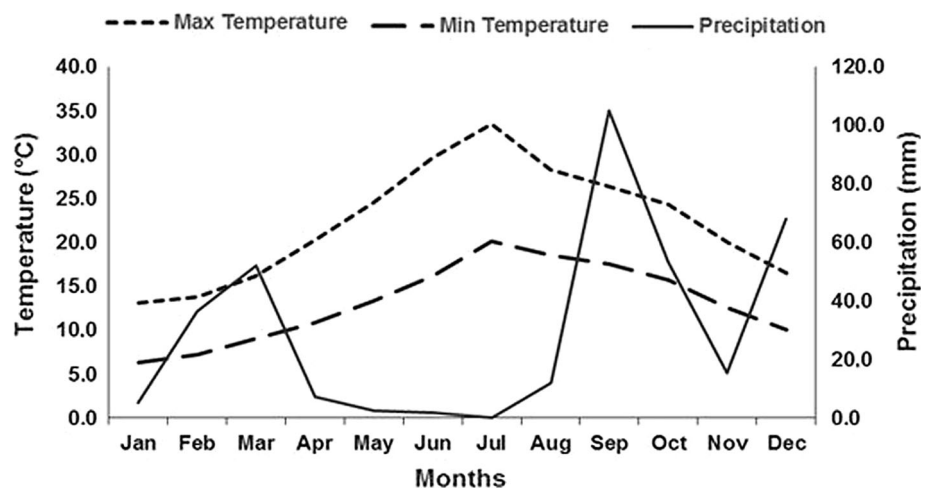


Fig. 1 Geological map of the study area (modified from Oggiano 1987)

Fig. 2 Monthly temperature and precipitation values in the study area for the hydrologic year 2006



year. The economy of the area is mainly based on agricultural activities. Information derived during field observations and from a 1:25,000 land-use map of the Autonomous Region of Sardinia (<http://www.sardegnaeportale.it/argomenti/cartetematiche.html>), showed that the area covers 2600 ha of crops and vegetables, comprising horticultural greenhouses and open fields. In general, because the farms are small, agricultural areas are

heterogeneous and have complex cultivation patterns mainly parcels with market-garden crops and fruit trees, especially in the southern area. Vineyards (300 ha) and olive crops (550 ha) are concentrated in the east and south-central parts of the Turrutana Plain, respectively. While some farms use drip and sprinkler irrigation, the furrow technique is still used in this area, even for market-garden crops (Cordoni 2007).



## Geology

The region consists of two distinct areas with different geomorphological and geological features: (1) a 2-km-wide flat coastal plain that forms a strip which runs parallel to the shoreline for 10 km and (2) an inner zone comprising a surface of sedimentary deposits, mainly marlstone from the Langhian age (Fig. 1), that dips gently to the north-west (i.e. seaward). The area is bounded to the east and south-east (Oudet et al. 2010) by structural elevations where Oligocene–Miocene andesitic lava flows and rhyolite ignimbrite outcrop, together with regional normal faults. The base of the marly deposits consists of a transgressive sequence of conglomerates, sands and bioclastic limestones. The thickness of the marlstones, which contain thin, interbedded clay layers, is unknown. This layer diminishes towards the south-east and lies on upper Burdigalian limestones, which, in turn, cap the sands and the transgressive conglomerates above the volcanic basement. The coastal flat is composed of Quaternary deposits principally composed of aeolian sandstones from the Rissian and Würmian ages, which are mostly buried by Holocene sand dunes (Oggiano 1987). There is also a Tyrrhenian-related (M5 stage) transgressive deposit embedded between the Rissian and Würmian aeolianites; this deposit is characterized by coastal sandstones and conglomerates with “panchina” facies. A small lagoon stretches for 3 km behind the shore. There are outcrops of lacustrine to brackish environmental deposits (travertine and silty sediments) related to the M5 stage behind the old Tyrrhenian coastal barrier.

## Hydrogeology

Groundwater circulation in the Turritana Plain (Cordoni 2007) relies on two main hydrogeological units (HU): the Quaternary hydrogeological unit (QHU) and the Miocene hydrogeological unit (MHU). The QHU, characterized by a phreatic aquifer within the topmost permeable layers of the Quaternary aeolian complex and the alluvial sediments along the main rivers, occurs in flat and gently dipping areas. For the most part, the QHU is supplied by zenithal infiltration from rainfall and run-off into the aeolian beds near the coast. Moreover, within the lowest layers of the same aeolian deposits, the aquifer is multilayered and characterized by various hydraulic conductivities. This aquifer, which occurs at different depths in the same areas, is also supplied negligibly by azimuthal infiltration from the groundwater that circulates within the colluvial beds of the steepest slopes below the Miocenic terraces.

The MHU is a multilayer phreatic, semiconfined/confined aquifer within the most permeable horizons in the Miocenic transgressive sequence. This aquifer, which

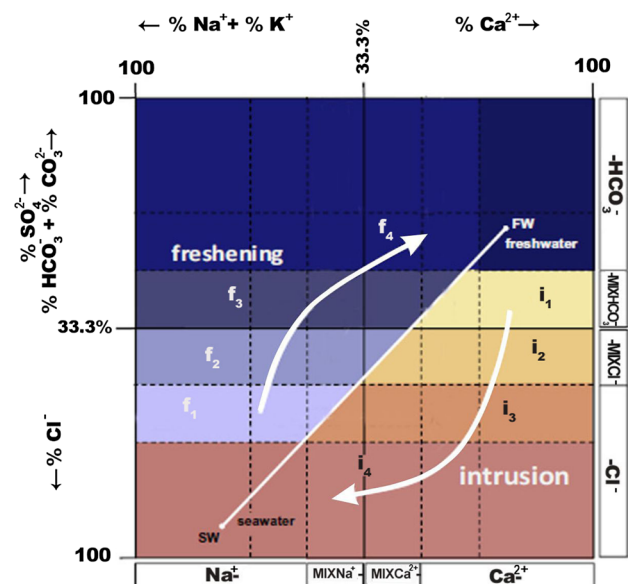
occurs at different depths in the highest part of the study area, is mostly fed by rainfall that infiltrates through marls and bioclastic limestones (Ardau et al. 1994).

The present study is limited to the groundwater quality in the QHU.

## Theoretical approach

The proposed method was implemented by combining the hydrochemical facies evolution model (Gimenez Forcada 2010) and the quality index for irrigation water (Fiorucci 2007), with the hydrogeological characteristics of the aquifer. The degree of saltwater contamination was defined using the classification system created by Gimenez Forcada (2010) that determines the relationship between the dynamic movement of the seawater interface and the hydrochemistry of the groundwater through the evolution of the hydrochemical facies (HFE-D).

Gimenez-Forcada (2014) defined the HFE-D diagram into nine main heteropic hydrochemical facies ( $\text{Ca}^{2+}\text{-HCO}_3^-$ ,  $\text{Ca}^{2+}\text{-SO}_4^{2-}$ ,  $\text{Ca}^{2+}\text{-Cl}^-$ ,  $\text{Mg}^{2+}\text{-HCO}_3^-$ ,  $\text{Mg}^{2+}\text{-SO}_4^{2-}$ ,  $\text{Mg}^{2+}\text{-Cl}^-$ ,  $\text{Na}^+\text{-HCO}_3^-$ ,  $\text{Na}^+\text{-SO}_4^{2-}$  and  $\text{Na}^+\text{-Cl}^-$ ). Each of the nine heteropic facies includes four isopic facies (sensu Gimenez Forcada 2010) with similar characteristics (i.e. the  $\text{Ca}^{2+}\text{-HCO}_3^-$  heteropic facies includes the  $\text{MixCa}^{2+}\text{-MixHCO}_3^-$ ,  $\text{Ca}^{2+}\text{-MixHCO}_3^-$ ,  $\text{MixCa}^{2+}\text{-HCO}_3^-$  and  $\text{Ca}^{2+}\text{-HCO}_3^-$  isopic facies). The diagram (Fig. 3) accounts for the ability of alternating groundwater flows



**Fig. 3** Hydrochemical facies evolution diagram (HFE-D) showing the main hydrochemical facies and substages for intrusion and freshening periods (modified from Gimenez-Forcada 2014). Chemical facies and substages for intrusion and freshening periods are, respectively, represented in orange and blue gradation

(related to the flow direction and the variability in chemical composition) to simulate chemical reactions during intrusion and freshening (regression of the saline front caused by natural recharge).  $\text{Ca}^{2+}$  and  $\text{HCO}_3^-$  ions typically dominate the composition of fresh groundwater in coastal aquifers, and  $\text{Na}^+$  and  $\text{Cl}^-$  dominate in seawater (Appelo and Postma 2005), so the water evolves from a  $\text{Ca}^{2+}$ - $\text{HCO}_3^-$  facies to a  $\text{Na}^+$ - $\text{Cl}^-$  facies (Ghiqlieri et al. 2012) via an intermediate  $\text{Ca}^{2+}$ - $\text{Cl}^-$  facies. This change is characteristic of the seawater intrusion process, during which seawater invades the aquifer.

Table 1 shows the different classes that are used to classify the substages of each phase. The lowest value (1) is assigned to freshwater, and the maximum value (10) is assigned to salt water. In the freshening substages f1, f2, f3 and f4, the values increase from 2 to 5; in the intrusion substages i1, i2, i3, i4, the values increase from 6 to 9. A value of 5.5 represents the boundary between the two stages.

The quality of water for agricultural use was obtained using the classification system created by Fiorucci (2007) that determines a quality index for irrigation (*QI*) according to the standards of the California State Water Quality Control Board (Todd 1970). Fiorucci (2007) categorizes the *QI* into three quality classes taking into account the following six components ( $n = 6$ ): total dissolved solids (TDS), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), electrical conductivity (EC) and the concentration of other specific ions, such as chlorine and sulphate (Table 2). Of particular importance is TDS, a measure of the combined content of all inorganic and organic substances dissolved in a water sample. The primary sources of TDS in receiving waters are agricultural and residential run-off, contaminants leached from soil, saltwater intrusion and point source water pollution

discharges. SAR is the proportion of sodium ( $\text{Na}^+$ ) ions relative to the total concentration of calcium ( $\text{Ca}^{2+}$ ) and magnesium ( $\text{Mg}^{2+}$ ) ions. RSC is an index of irrigation/soil water that is used to indicate the alkalinity level of soil. These hydrochemical indicators are well known and have been widely used (Bauder and Brock 2001; Ashraf et al. 2011; Beltrán 1999; among many others).

For this study, the index *QI* was modified according to Backman et al. (1998), with the aims to assess groundwater quality and also to automate the calculation process. Specifically, the *QI* was derived as the sum of the individual factors of the components that exceeded the threshold values for irrigation water, and was calculated by Eq. 1:

$$QI = \sum_{i=1}^{n=6} Q_F \tag{1}$$

where  $Q_F$  (the quality factor for the  $n$ th component) was based on the ratio between the analytical value of the  $n$ th component ( $C_{Ai}$ ) and the superior threshold concentration of the  $n$ th component ( $C_{Ni}$ ) defined for each class in Table 1, as described by Eq. 2:

$$Q_F = \frac{C_{Ai}}{C_{Ni}} - 1 \tag{2}$$

The *QI* was then categorized into three classes according to its quality grade: excellent (1), acceptable (2) or polluted (3).

The *QI*, similar to other indexes that assess quality of irrigation water, is solely based on the concentrations of elements that are potentially harmful for agricultural productivity, and does not consider any aquifer-related interactions. Therefore, the three classes were revised to express groundwater use suitability (*QI-R*), depending on

**Table 1** Summary of the criteria used to assign a numerical value to each substage (modified from Gimenez-Forcada 2014)

Substage	Anion facies	Ion percentage (%)	Value	Range in heatmap
Fresh water	$-\text{HCO}_3^-$	$\text{HCO}_3^- > 50.00$ $\text{Ca}^{2+} > 66.60$	1	$\leq 2.50$
f4	$-\text{HCO}_3^-$	$\text{HCO}_3^- > 50.00$	2	2.50–2.60
f3	$-\text{MixHCO}_3^-$	$50.00 \geq \text{HCO}_3^- > 33.30$	3	2.60–3.50
f2	$-\text{MixCl}^-$	$33.30 < \text{Cl}^- \leq 50.00$	4	3.60–4.50
f1	$-\text{Cl}^-$	$50.00 < \text{Cl}^- < 66.60$	5	4.60–5.40
Boundary			5.5	5.50
i1	$-\text{Mix HCO}_3^-$	$50.00 \geq \text{HCO}_3^- > 33.30$	6	5.60–6.50
i2	$-\text{MixCl}^-$	$33.30 < \text{Cl}^- \leq 50.00$	7	6.60–7.50
i3	$-\text{Cl}^-$	$50.00 < \text{Cl}^- < 66.60$	8	7.60–8.50
i4	$-\text{Cl}^-$	$\text{Cl}^- > 66.60$	9	$> 8.50$
Salt water	$-\text{Cl}^-$	$\text{Cl}^- > 66.60$ $\text{Na}^+ > 50.00$	10	

**Table 2** Permissible values for irrigation water (modified from Fiorucci 2007) for the quality index (QI) components and groundwater potential use classes for the revised quality index (QI-R)

Class	Components of QI					QI-R potential use				
	EC (µS/cm)	Cl <sup>-</sup> (mg/dm <sup>3</sup> )	SO <sub>4</sub> <sup>2-</sup> (mg/dm <sup>3</sup> )	TDS (mg/dm <sup>3</sup> )	SAR (mg/dm <sup>3</sup> )	RSC (mg/dm <sup>3</sup> )	f3 ÷ FW	f2 ÷ f1	i1 ÷ SW	
1 Excellent	<750.00	<100.00	<200.00	<500.00	<45.00	<10.00	1, E-S	1/2, E-S/M*	3, E-R	
2 Acceptable	750.00–2500.00 (1700.00)	100.00–350.00 (225.00)	200.00–1000.00 (600.00)	500.00–1500.00 (1000.00)	45.00–120.00 (80.00)	10.00–20.00 (14.50)	2, A-M	2/3, A-M/R*	3, A-R	
3 Polluted	>2500.00	>350.00	>1000.00	>1500.00	>120.00	>20.00	3, P-R	3, P-R	3, P-R	

E-S quality excellent/use suitable, A-M quality acceptable/use moderate, P-R quality polluted/use restricted, E-M quality excellent/use moderate, A-R quality acceptable/use restricted  
 \* Class attribution according to hydrogeological condition

the aquifer response and hydrogeological conditions (Fig. 4).

If irrigation water comes from an aquifer in a saline intrusion phase with a medium–low permeability, but still has an acceptable *QI* class, there is a high risk that the groundwater composition and the state of the aquifer will be compromised. The concentration of Na<sup>+</sup> in the mixed water will increase with only a modest input of seawater (Appelo and Postma 2005), promoting mostly sodium exchange in a reaction that is assumed to be instantaneous. In such a situation, in spite of an acceptable *QI* class and independently from the permeability grade, the use will be restricted (namely *QI-R* = 3, A-R; polluted–use restricted).

If the irrigation index quality grade is excellent or acceptable, but groundwater is exploited in substages f1–f2, its use needs to be carefully considered. The earlier phase of direct ion exchange needs a much longer supply of Ca<sup>2+</sup>, with relatively long periods of rinsing. The Ca<sup>2+</sup>–HCO<sub>3</sub><sup>-</sup> water type will appear earlier when flushing is more rapid or where the cation exchange capacity is smaller (Appelo and Postma 2005). Therefore, in case of medium–high permeability of the aquifer and preferential flow paths it will be most appropriate indicate a use of groundwater in class 1 (suitable) or 2 (moderate). Even under favourable hydrogeological and hydrochemical conditions, when there is a clear interface between the first phases of freshwater (f1–f2) and intruding seawater (i1–i2), the *QI-R* will be classified as class 3 (restricted). This is because there is a high risk of the intrusion phase becoming enhanced, given that the concentration of Cl<sup>-</sup> is higher than that of HCO<sub>3</sub><sup>-</sup>. This is especially true in the period immediately preceding the dry season, when the effect of the recharge phase will soon expire.

When the water quality suitability is classified as polluted for both crop tolerance and the freshening substages, the *QI-R* class will be always the worst (*QI-R* = 3, P-R; polluted–use restricted). When allocating the class, this method accounts for the worst-case scenario.

**Field data collection and analytical procedures**

A set of 56 private wells that intercept the QHU were identified and included in the monitoring network. Most of these wells are used for irrigation purposes and sometimes as potable water supplies. The wells chosen were known to draw from the QHU aquifers. It was possible to define the thickness of the QHU, which varies from 40 to 50 m (Fig. 5), from the combination of stratigraphic columns and the scheme of stratigraphic relationships. It was also possible to identify impermeable clay lenses within the aeolianitic formation (Ce), which suggest the presence of several, partially connected, subaquifers.

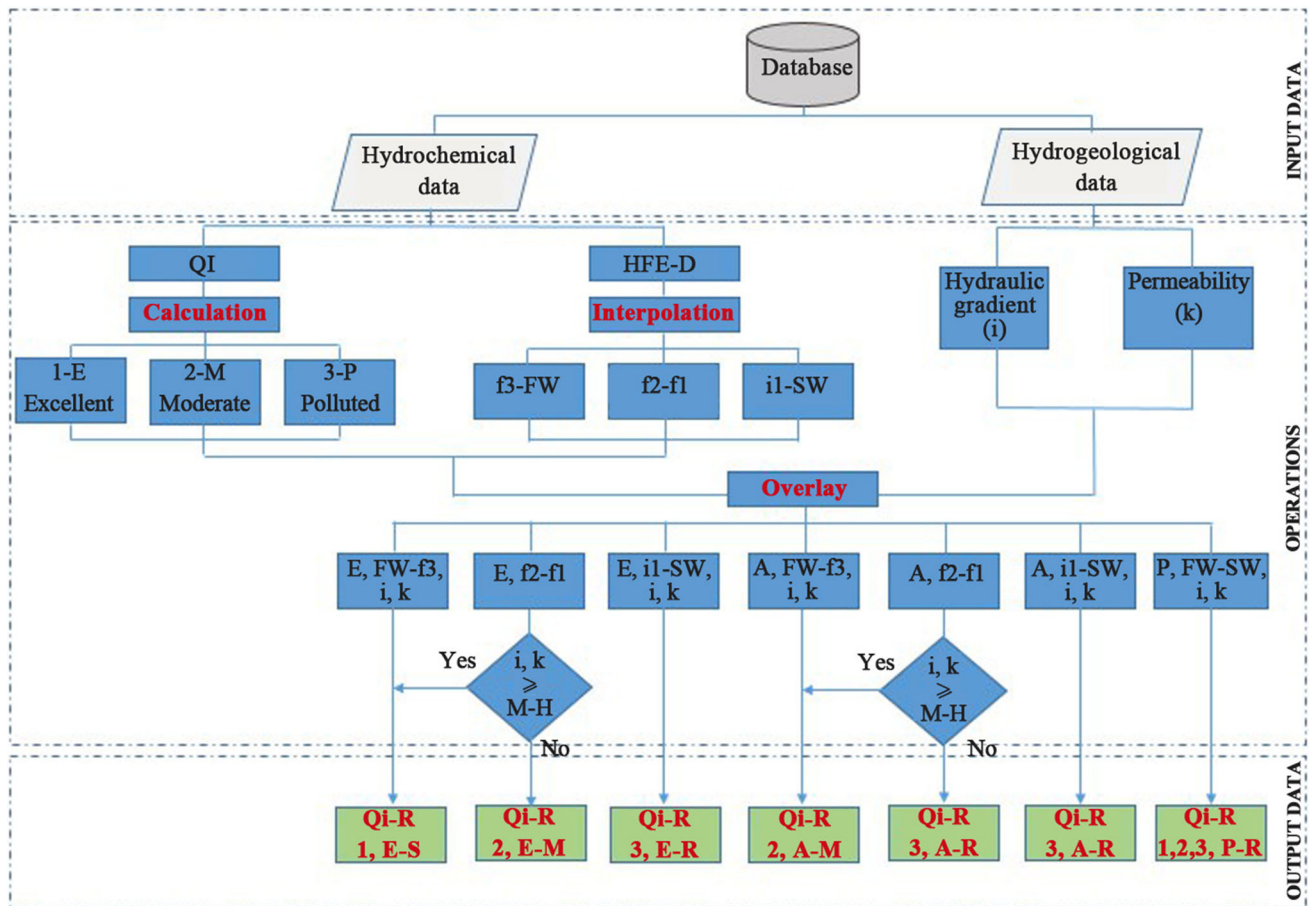


Fig. 4 Conceptual workflow of the proposed method

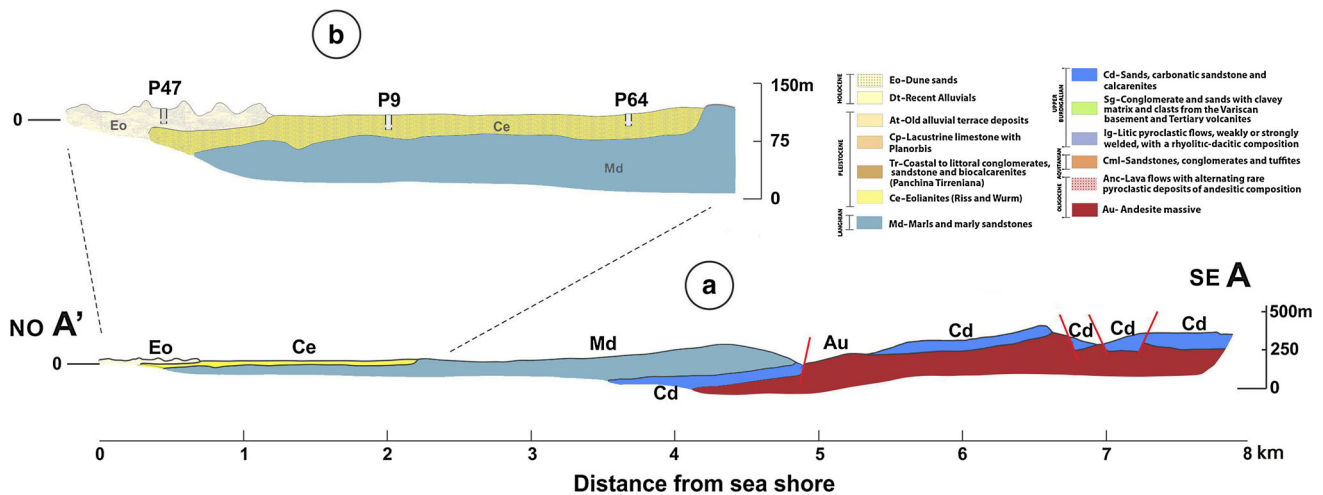


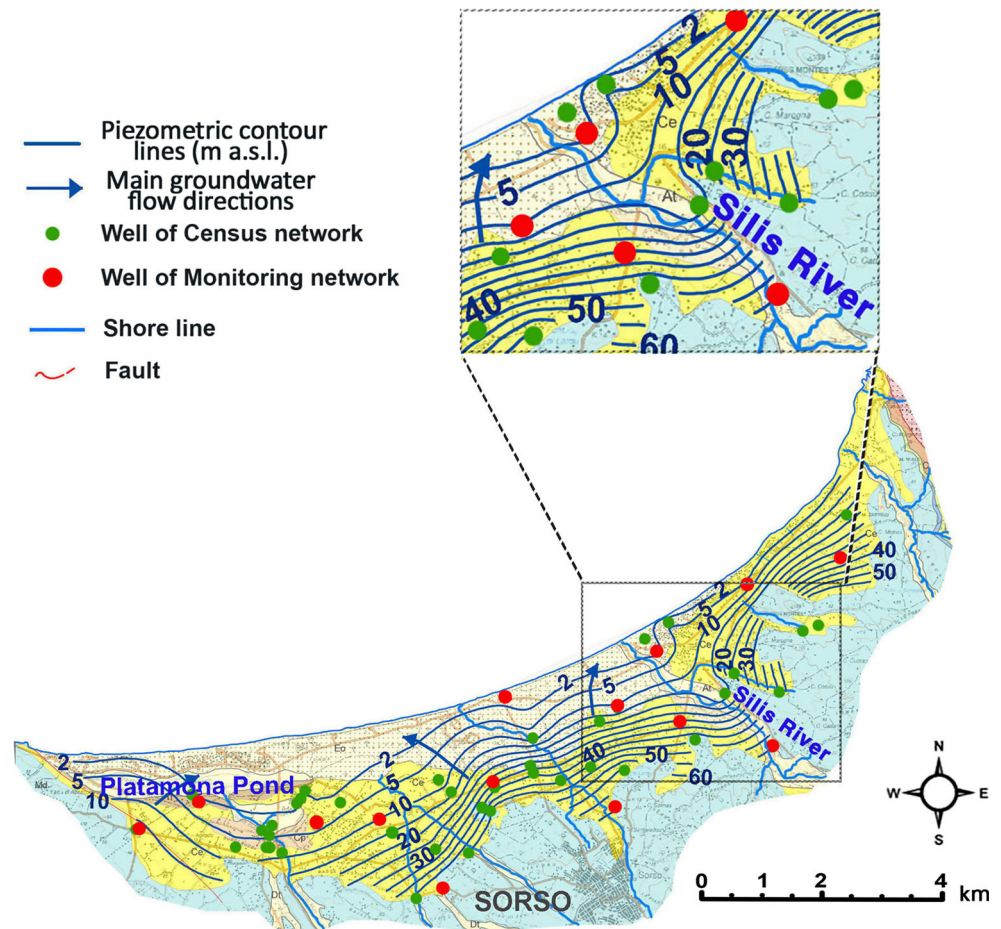
Fig. 5 a Geological cross section (modified from Oggiano 1987) and b detail of the geological cross section with vertical ( $\times 5$ ) and horizontal ( $\times 2$ ) exaggeration

Hydraulic head measurements were taken using a water level metre in February, May and December 2006. Electrical conductivity, pH and temperature were also measured

using a portable metre (WTW 340i, Munich, Germany) during the same survey. Groundwater samples were collected from 14 wells in May 2006 to determine the main



**Fig. 6** Piezometric contour line for the census activity of May



physicochemical features. The sampled wells had similar characteristics (e.g. depth) and were uniformly distributed throughout the area. According to the sample method standard of Weaver et al. (2007), the collected samples were filtered (0.45  $\mu\text{m}$ ) into 1-l polythene bottles that had been thoroughly prewashed with distilled water. The samples were transported in low-temperature thermal bags and stored in a refrigerator.

Major ions in water samples were determined using standard methods (APHA 1992) at the University of Sassari, Italy. Cation concentrations ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) were determined by atomic absorption spectrometry (PerkinElmer AAnalyst 200, Waltham, Massachusetts, USA), and anion concentrations ( $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ) were determined by ion chromatography (Alltech; Allsep Anion Exchange column 7  $\mu\text{m}$ , 100 mm, W. R. Grace & Co.-Conn, USA). The carbonate and bicarbonate concentrations were obtained by titration, while silicate was measured by a colorimetric technique. The errors related to the ion balance analyses were within  $\pm 5\%$ .

## Results and discussion

### Groundwater flow paths

The piezometric morphology shows an obvious general flow towards the sea with a decreasing gradient towards the north (Fig. 6). Except during December, no appreciable variations about morphology were found during the three surveys. In December, in fact, the piezometric level was zero in correspondence with the area of Platamona Pond moving further inland in December than in the other months.

The piezometric levels were also higher for the eastern side of the coastal strip in December than in the other months. In general, the piezometric level remained above sea level in inland areas, whereas the levels were close or equal to sea level in the coastal strip (Table 3).

The interpretation of the hydraulic head interpolation indicated that the Silis River drained the aquifers of the aeolian complex and the old alluvial deposits, whereas



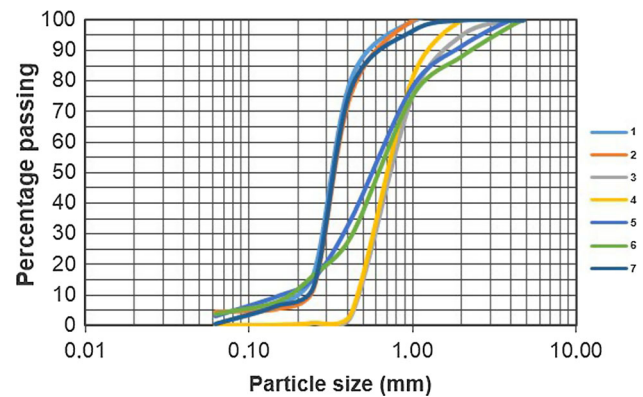
**Table 3** Wells depth and hydraulic head measured during the three surveys

ID well	Depth (m b.g.)	Hydraulic head (m a.s.l.) (February)	Hydraulic head (m a.s.l.) (May)	Hydraulic head (m a.s.l.) (December)
P 1	8.00	17.15	16.10	15.55
P 2	9.00	9.95	8.35	9.15
P 4	7.00	12.20	9.25	10.35
P 5	7.00	52.40	n.d.	51.60
P 6	9.00	6.40	n.d.	6.05
P 7	12.00	n.d.	15.10	n.d.
P 8	8.00	56.20	54.50	n.d.
P 9	16.00	16.90	12.50	18.10
P 10	6.00	51.85	51.05	51.45
P 11	18.00	21.00	n.d.	19.10
P 13	8.00	56.50	53.10	57.20
P 14	8.00	26.10	25.55	26.45
P 15	9.00	10.10	9.80	9.10
P 16	9.00	20.01	17.20	20.70
P 17	8.00	1.60	n.d.	1.75
P 18	9.50	35.65	35.20	35.80
P 19	10.00	0.95	0.80	0.50
P 20	12.00	32.80	32.10	32.60
P 21	9.00	38.60	36.70	36.05
P 22	8.00	11.60	9.70	10.35
P 24	9.00	16.20	n.d.	n.d.
P 27	7.00	4.80	4.65	4.45
P 28	8.00	5.50	5.10	4.95
P 29	11.00	3.60	3.30	2.90
P 33	8.00	2.80	2.10	1.94
P 35	4.50	2.85	2.35	2.05
P 39	7.50	6.80	6.40	n.d.
P 40	11.00	10.70	10.25	10.35
P 42	10.00	15.50	15.30	15.35
P 43	14.00	9.30	8.70	9.10
P 44	10.00	4.90	4.20	5.01
P 45	12.00	44.30	n.d.	44.60
P 46	8.00	44.30	44.10	44.40
P 47	16.00	1.98	2.07	3.95
P 48	8.00	1.30	1.70	2.00
P 49	8.00	1.10	2.50	2.38
P 50	6.00	2.20	2.01	2.10
P 51	6.00	3.10	2.80	n.d.
P 52	7.00	3.10	2.35	2.55
P 53	14.00	6.40	6.15	5.85
P 54	25.00	22.20	21.80	23.90
P 56	16.00	15.50	14.60	16.00
P 58	7.00	4.10	3.50	3.10
P 59	11.00	14.10	12.20	13.70
P 60	16.00	30.50	30.10	30.30
P 61	15.00	n.d.	n.d.	36.10

**Table 3** continued

ID well	Depth (m b.g.)	Hydraulic head (m a.s.l.) (February)	Hydraulic head (m a.s.l.) (May)	Hydraulic head (m a.s.l.) (December)
P 62	16.00	45.10	45.00	45.30
P 64	15.00	36.10	34.30	35.20
P 65	13.00	44.10	44.00	45.30
P 66	17.00	67.90	67.10	67.60
P 67	16.00	69.10	68.60	69.40
P 68	12.00	20.10	19.50	20.30
P 70	14.00	67.80	64.50	65.10
P 71	12.00	60.10	58.80	60.20
P 73	7.00	45.82	45.10	45.40
P 74	14.00	26.10	n.d.	26.70
P 76	7.00	30.30	30.00	30.10
P 78	8.00	48.90	48.30	48.90
P 79	7.00	50.10	49.80	50.30

The depth of the wells is expressed as metre below ground (m b.g.) and hydraulic head as metre above sea level (m a.s.l.)



**Fig. 7** Grain size curves for the samples 1, 2, 7 (dune sands), 3, 4 (recent alluvials) and 5, 6 (aeolianites)

moving towards the sea, within the Holocene sand dunes, the same river drained the aquifer in left bank and it was drained from the aquifer in the right one. The greater hydraulic gradient of the aeolian complex compared to that in correspondence of Holocene sands dunes, particularly in the central-eastern part of the plain, suggests for this formation a lower permeability. The permeability has been defined in terms of degree of permeability (Civita 2005; Celico 1986), in which, based on field observations and according to the lithological unit, the classes high, medium, low and impermeable were qualitatively stated. This classification is consistent with the values of permeability (Fig. 7; Table 4) obtained in the Turrutana Plain by Oggiano (2006). These values were derived from the grain size measurement according to Hazen (1911); coarse

fraction of seven samples (Fig. 1) was analysed using eight sieves between 0.063 and 4.76 mm. The Hazen's equation can be used for determining permeability values in the range of fine to very coarse sand size, 0.1–3.0 mm, with a uniformity coefficient ( $C_u = d_{60}/d_{10}$ ) less than 5.

Also taking into account these values, the medium (M) class was attributed to the unit sandstones and conglomerates with “panchina” facies, the class from medium to low (M–L) was attributed to the aeolian sandstones and old alluvial deposits, whereas the class from medium to high (M–H) was attributed to the sand dunes and the recent alluvial.

## Hydrochemistry

Summary statistics of the physicochemical properties are presented in Table 5.

The concentrations of the  $\text{Na}^+$  and  $\text{Cl}^-$  ions ranged from 94.7 to 488.3 (4.2–21.3) and 185.7 to 905.5 (5.5–25.6) mg/L (meq/L), respectively. Electrical conductivity, chloride and sodium concentration strongly express the effect of saline sources in a coastal region. Electric conductivity values were below the permissible limits in the central part of the region (from the coast to the inland areas associated with the Silis River) and in the eastern inland portion of the

plain. Values above the permissible limit were detected in the other parts of the plain with the highest in the eastern coastal strip and in the central-western inland portion of the plain (EC values of approximately 3800  $\mu\text{S}/\text{cm}$ ). The 50 % of the  $\text{Cl}^-$  concentrations exceeded the groundwater  $\text{Cl}^-$  standard for agriculture (350 mg/L as defined in Fiorucci 2007), and it is mainly distributed in the central-western inland portion of the study area, as well as the  $\text{Na}^+$  concentration. The standard deviations of the  $\text{Na}^+$  and  $\text{Cl}^-$  ions were high, and there were also large variations in the concentrations of  $\text{Ca}^{2+}$ ,  $\text{HCO}_3^-$  and  $\text{SO}_4^{2-}$ . High concentrations of  $\text{HCO}_3^-$  and  $\text{Ca}^{2+}$  reflect contributions from water–rock interactions. The TDS values range between 606.7 and 2386.0 mg/L with the highest values occurring in the central-western inland portion of the plain. Nitrate pollution was detected in the study area mainly linked to fertilizer use and, in specific areas of the plain, linked to the presence of residential houses. Although nitrate pollution was not considered in this study, groundwater concentrations of nitrate were much higher than 50 mg/L in many cases. The hydrochemistry of the groundwater in the study area indicates that no single hydrochemical type dominated, but that the groundwater was a mix between the  $\text{Ca}^{2+}\text{--HCO}_3^-$  and  $\text{Na}^+\text{--Cl}^-$  types.

## HFE-D and QI on the Turrutana Plain

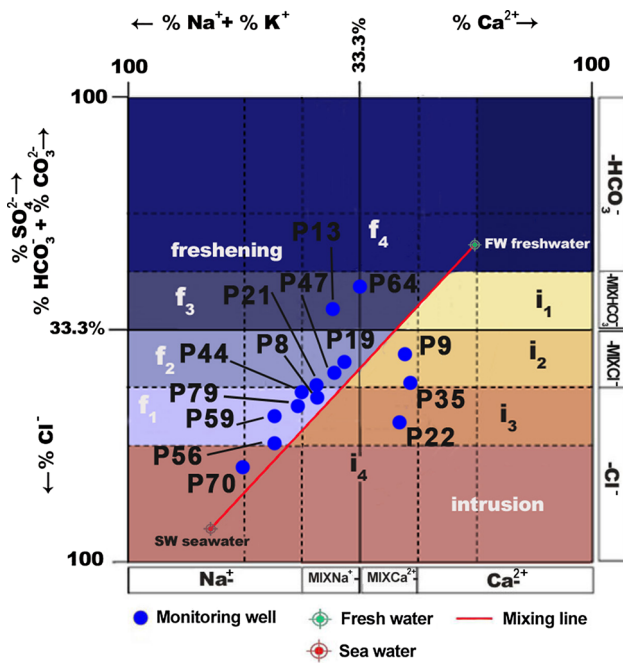
The heteropic facies  $\text{Na}^+\text{--Cl}^-$  and five isopic facies ( $\text{MixCa}^{2+}\text{--MixCl}^-$ ,  $\text{MixCa}^{2+}\text{--Cl}^-$ ,  $\text{MixNa}^+\text{--Cl}^-$ ,  $\text{MixNa}^+\text{--MixCl}^-$  and  $\text{MixNa}^+\text{--MixHCO}_3^-$ ) were identified in the Turrutana Plain from the HFE-D diagram (Fig. 8). In general, the samples followed the succession of facies along the mixing line, although the  $\text{Ca}^{2+}\text{--HCO}_3^-$  facies was not observed. Most (78.6 %) of the samples were located above the mixing line in the freshening field. In this part of the HFE-D, the freshening process is influenced by direct ion exchange and develops through the substage sequences (f1, f2, f3). This reaction takes place when a salinized aquifer is flushed by fresh  $\text{Ca}^{2+}\text{--HCO}_3^-$  water and is

**Table 4** Permeability values defined according to Hazen (1911) for the samples 1, 2, 7 (dune sands), 3, 4 (recent alluvials) and 5, 6 (aeolianites); (modified from Oggiano 2006)

ID	$D_{10}$ (mm)	$D_{60}$ (mm)	$K$ ( $\text{mm}^2$ )
1	0.26	0.35	$9.50 \times 10^{-4}$
2	0.19	0.37	$5.10 \times 10^{-4}$
7	0.27	0.35	$1.00 \times 10^{-3}$
3	0.49	0.81	$3.30 \times 10^{-3}$
4	0.47	0.79	$3.10 \times 10^{-3}$
5	0.16	0.69	$1.10 \times 10^{-4}$
6	0.18	0.73	$1.50 \times 10^{-4}$

**Table 5** Summary statistics for groundwater samples of QHU

Statistical parameters	T ( $^{\circ}\text{C}$ )	pH	EC ( $\mu\text{S}/\text{cm}$ )	$\text{Ca}^{2+}$ ( $\text{mg}/\text{dm}^3$ )	$\text{Mg}^{2+}$ ( $\text{mg}/\text{dm}^3$ )	$\text{Na}^+$ ( $\text{mg}/\text{dm}^3$ )	$\text{K}^+$ ( $\text{mg}/\text{dm}^3$ )	$\text{HCO}_3^-$ ( $\text{mg}/\text{dm}^3$ )	$\text{Cl}^-$ ( $\text{mg}/\text{dm}^3$ )	$\text{SO}_4^{2-}$ ( $\text{mg}/\text{dm}^3$ )	$\text{NO}_3^-$ ( $\text{mg}/\text{dm}^3$ )
$n = 14$											
Minimum	13.30	6.52	850.00	88.32	23.00	105.00	1.51	309.93	142.66	55.72	3.00
Maximum	21.50	7.40	3800.00	216.00	80.20	488.29	19.00	544.81	904.12	269.95	137.60
Average	18.79	7.04	2063.57	141.71	44.51	229.93	8.03	414.12	374.91	145.75	49.65
Median	19.80	7.04	2265.00	137.30	40.50	182.45	8.00	406.93	317.01	139.54	33.80
Standard deviation	2.55	0.22	862.68	39.61	15.73	118.01	5.32	67.69	224.20	58.60	39.88
Skewness	−0.96	−0.70	0.41	0.28	1.37	1.15	0.70	1.68	0.20	0.62	0.93



**Fig. 8** HFE-D diagram (modified from Gimenez-Forcada 2014) for the Turritana Plain. Freshwater (FW) from a representative aquifer recharge area in the southern sector of the study area; seawater (SW) from the literature (de Montety et al. 2008)

generally associated with the wet seasons, when there are relatively long periods of rinsing (Gimenez-Forcada 2014). This pattern is in accordance with the results of monitoring activities, i.e. showing that the end of the rainy season has a positive influence on the freshening phase.

Reverse cation exchange reactions may occur in a limited number of samples. These samples are located beneath the mixing line and are not completely included in the  $Ca^{2+}-Cl^{-}$  facies. The  $MixCa^{2+}-MixCl^{-}$  and  $MixCa^{2+}-Cl^{-}$  facies were most representative of the intrusion phase for the study period.

The distribution of the phases and their respective sub-stages relative to the sampling period was displayed through HFE-D points. As reported by Gimenez-Forcada (2014), the “spline with barriers” method of spatial analysis was used to interpolate the hydrochemical facies evolution map. The elaboration has been implemented in GIS environment (Arc Map v. 10.0) as a grid layer based on the spline with barriers interpolator. The spline with barriers is a deterministic interpolation method (spline) that fit a function to sampled points (Garnero and Godone 2013). It is based on the minimum curvature surface technique. Taking in account the input point data and discontinuities encoded in the barriers, the approximation to a minimum curvature surface is achieved by an iterative deformation applied to each cell of the grid layer (Terzopoulos 1988). During this iteration, the weighted

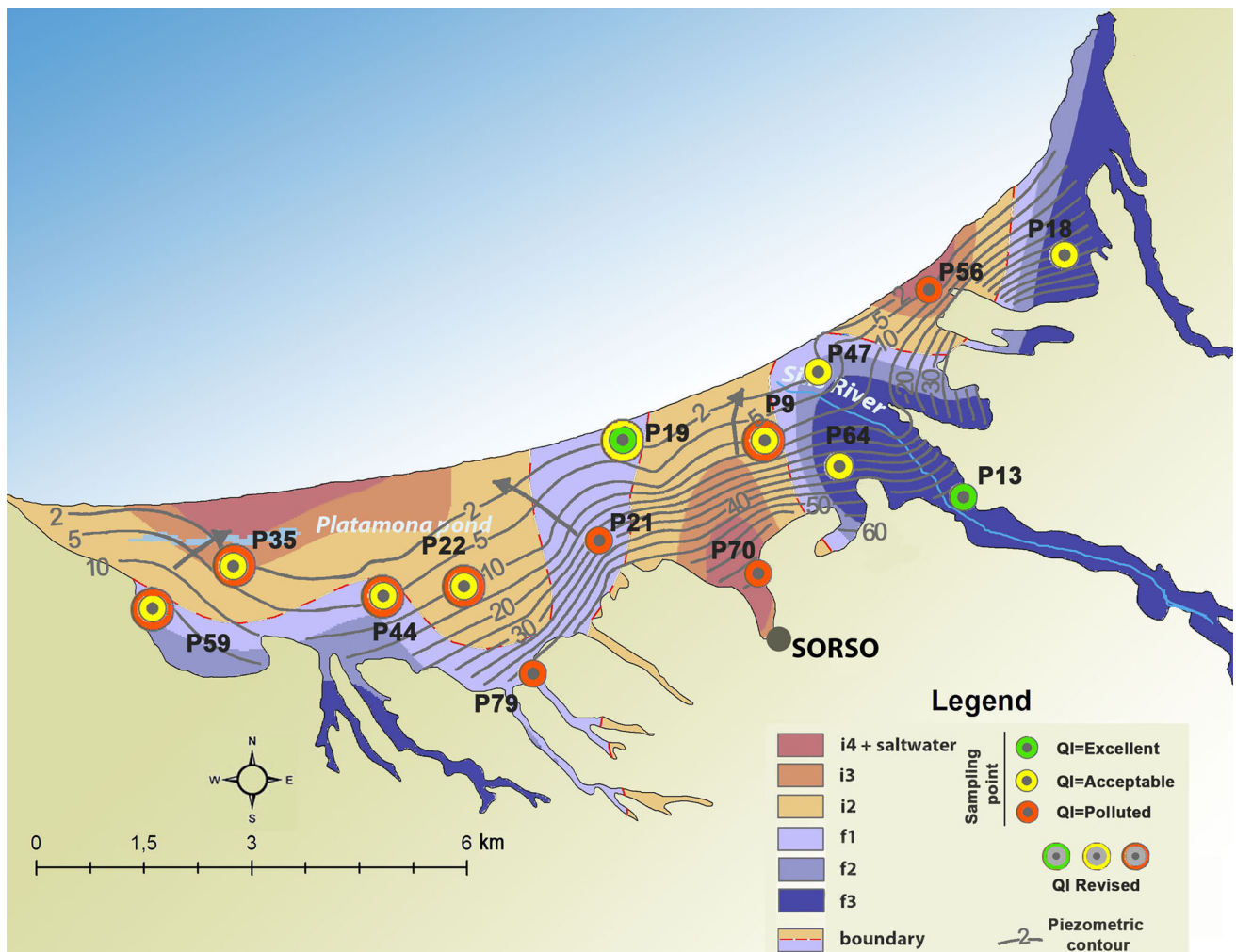
summation of twelve neighbouring cells is compared with the current value of a central target cell to calculate a new value for the target cell. The interpolation procedure was applied using the data from the 14 monitoring wells and defining the QHU boundary as a barrier. The selected output cell size was 25 m × 25 m with a smoothing factor of 0.5.

The status of the QHU related to both intrusion and freshening fields is shown in Fig. 9. A boundary was defined to outline the main recharge areas and the areas salinized the most by seawater intrusion (Gimenez-Forcada 2014). The curvature of the boundary reflects the competition between freshwater recharge and intruding seawater. The substage belonged to the freshening substages (f3, f2 and f1), covering almost 53 % of the coastal plain. The freshwater process was represented by the distal facies (or the initial stages of freshening) to the proximal facies of that process. The freshwater domain (FW + f4), as previously defined, was not recorded for this campaign. However, a refreshing process occurred during the monitoring period as a result of the influence of the main recharge areas (as highlighted by the curvature of the boundary), most likely owing to zenithal infiltration. A particular development of this phase was highlighted in the Silis River and in a portion of the central-eastern part of the area.

The most saline areas, those characterized by substages i2, i3 and SW + i4 (47 % of the plain), were located in the coastal fringe, although inland intruding areas were also included (close to the village of Sorso and over the Platamona Pond). The initial stage of the intrusion process (i1) was not observed during the monitoring period.

The groundwater in the study area that was suitable for irrigation was distributed among the three classes, as follows (Table 4): excellent (14 %), acceptable (57 %) and polluted (29 %). Thus,  $Cl^{-}$ , TDS and EC concentrations were above the upper permissible thresholds (350 and 1500 mg/L for  $Cl^{-}$  and TDS and 2500  $\mu S/cm$  for EC) in 29 % of the samples. To account for the above hydrogeological and hydrochemical properties, the groundwater quality suitability had to be modified, particularly the groundwater use potential reported in Table 6 and displayed in Fig. 9.

In the eastern part of the plain, the water quality was acceptable for use within the portion of the QHU that was influenced by the freshening stage. In this phase, the main proximal facies f3 and, to a lesser extent, f2 and f1 indicated an advanced phase of freshening that followed a period of salinization. In contrast, the most salinized zones of the east coast coincided with waters classified as polluted. This part of the plain is where agricultural activities (specifically horticulture, heterogeneous agriculture and irrigated vineyard) are most concentrated; it is also



**Fig. 9** Distribution of facies representing substages in the QHU and groundwater quality suitability distribution according to QI-R, with respect to hydrogeological and hydrochemical consideration.

Chemical facies and substages for intrusion and freshening periods are, respectively, represented in orange and blue gradation

underlain by part of the aeolian complex, whose lower permeability causes a slowdown of both freshwater and saltwater transport in groundwater. In this case, and also taking account of previous similar studies (Gimenez-Forcada 2014), it is possible that a higher hydraulic gradient prevents the development of exchange reactions and, consequently, hinders changes in the chemical composition of the water. In addition, EC values measured in both the census and the monitoring campaign were above the allowable limits, and concentrations of chloride were elevated.

The central part of the area shows a different scenario. As reported earlier, freshening substages dominated in the Silis River area, indicating that the QHU is influenced by an advanced phase of freshening in this area. The curvature boundary of the recharge zones follows the river channels, indicating that freshwater recharge to the coastline

corresponds with the groundwater flow path and the EC values. The water quality in this area ranges from excellent to acceptable. Acceptable water is distributed along the alluvial and old sediments of the Silis River, which is dominated by olive growing. The stable refreshing phase and favourable conditions for cation exchange there mean that the water quality is not likely to change.

In the western part of the Silis River, the salinization front may have reached a considerable distance from the coast, close to the municipality of Sorso. In contrast to the rest of the upstream areas of the plain, no freshwater recharge was observed, and the evolution of the intrusion from the coast to the inland area was apparently too gradual to be distinguished. The intrusion likely took place over the previous months. Additionally, there may have been excessive pumping of wells to supply drinking water to Sorso, the largest urban centre in the plain, just upstream



**Table 6** Quality factor (QF) for the *n*th component, quality index (QI) and revised quality index (QI-R) for the irrigation water

ID	Q <sub>F</sub> of the components for the irrigation water						QI	QI-R	
	TDS (mg/dm <sup>3</sup> )	SAR (mg/dm <sup>3</sup> )	EC (μS/cm)	Cl <sup>-</sup> (mg/dm <sup>3</sup> )	SO <sub>4</sub> <sup>2-</sup> (mg/dm <sup>3</sup> )	RSC (mg/dm <sup>3</sup> )		Class	Class
P9	0.24	-0.75	-0.23	-0.01	-0.75	-4.29	2	3	P-R
P13	0.48	-0.47	0.47	1.34	-0.74	-1.56	1	1	E-S
P18	0.15	-0.62	-0.16	0.24	-0.84	-2.28	2	2	A-M
P19	1.08	-0.57	0.79	0.85	-0.57	-2.08	1	2	E-M
P21	0.09	-0.66	-0.07	0.19	-0.77	-2.50	3	3	P-R
P22	0.27	-0.70	0.38	0.55	-0.80	-4.61	2	3	A-R
P35	0.45	-0.73	0.29	0.27	-0.70	-5.67	2	3	A-R
P44	0.52	-0.61	0.47	0.64	-0.70	-3.08	2	3	A-R
P47	0.37	-0.65	-0.23	0.12	-0.69	-3.50	2	2	A-M
P56	0.36	-0.54	0.28	1.36	-0.70	-3.56	3	3	P-R
P59	0.23	-0.37	0.53	0.58	-0.87	-2.50	2	3	A-R
P64	0.48	-0.76	-0.50	-0.37	-0.84	-0.87	2	2	A-M
P70	-0.41	-0.42	0.52	1.58	-0.95	-2.81	3	3	P-R
P79	-0.29	-0.65	0.03	0.23	-0.92	-2.87	3	3	P-R

*E-S* quality excellent/use suitable, *A-M* quality acceptable/use moderate, *P-R* quality polluted/use restricted, *E-M* quality excellent/use moderate, *A-R* quality acceptable/use restricted

from this area. The proximity of Sorso and the primary agricultural activities in this area suggest that the groundwaters may be subject to other sources of contamination. Because of these reasons, the water use in this part of the plain should be restricted as for the sample P9 (QI-R = 3, A-R).

The area of the central plain to the west of Sorso displayed a different scenario. Here, the distal freshening stage f1 dominated the QHU, reflecting an initial recharge phase; this is the result of a combination of factors. For example, there are no inhabited areas upstream and no lacustrine deposits, as are present in the area of Platamona Pond. Furthermore, the distance between the surface soil and the water table decreases in the upper part of the area, facilitating easier groundwater recharge by rainfall via zenithal infiltration. Potential irrigation return flow and the proximity to seawater, however, may reduce the development of freshwater stages. Specifically, infiltration of polluted groundwater via irrigation contributes to the continued deterioration of the aquifer state and dilutes the intensity of the freshwater. Close to the coastline, however, the aforementioned medium high class of permeability of the Holocene sand dunes contributes to the development of the freshening stage.

The classification of the western part of the study area reflects its position close to the coast and upstream. The former, mainly related to the area of Platamona Pond, is the most saline area among the study locations and is characterized by the distal substage i2 and the proximal substages i3 and SW + i4. The distal substage, which represents the initial stage of intrusion, shows a boundary much further

inland, indicating that salinization moves quite a distance inland from the coast. Given that the May monitoring campaign preceded the dry season, these results indicate a meaningful increase in salinization over the subsequent months. The proximal substage phases are, however, quite delimited. In this case, the hydraulic connection between the sea and the Platamona Pond plays an important role in the salinization dynamics. Moreover, the outcrops of brackish and lacustrine deposits in the area possibly contribute to increases in the concentrations of groundwater salt. Therefore, a concomitant process related to both seawater intrusion and water-rock interactions can be observed in this area. Despite their classification as acceptable, the samples P35 and P22 were not suitable for irrigation, because of the possible increase in boundary intrusion from the coast to the inland areas (HFE-D classes from i1 to SW) joined with a medium-low class of permeability of the aeolian complex. In this case, the QI-R = 3, P-R defined groundwater as polluted and restricted for use.

The upstream portion of the western plain showed a freshening phase dominated by the distal substage f1, which was not sufficiently developed to counteract the salinization. In this area, the refreshing phase, which usually needs much longer periods of rinsing with freshwater than the intrusion phase, seems to be scaled down. Also in this case it is possible an increase in salinization over the subsequent months. Taking into account the medium-low permeability of the aeolian complex, the samples with acceptable quality class (P44, P59) will be restricted for use (QI-R = A-R). Furthermore, sample P79

was classified as polluted most likely because of the presence of intensive agricultural activities (the  $\text{NO}_3$  concentration, for example, ranged from 70 to 108 mg/L).

## Conclusions

This study describes a management tool that can be used to assess the suitability of groundwater in coastal aquifers for irrigation use when these waters are influenced by seawater intrusion. Competition between the constantly increasing water demand, especially for agricultural purposes, limited natural recharge, and decreasing availability of groundwater of an acceptable quality is becoming an urgent problem. An existing quality index (based on the concentrations of elements potentially harmful for agriculture) was revised taking into account the hydrochemical facies evolution and the hydrogeological characteristics of the aquifer, to identify the relationship between the dynamic movement of the freshwater–seawater interface and the hydrochemistry of the groundwater. In addition, classes to determine the suitability of water for irrigation were integrated into the quality index. Although the results were derived from a single monitoring campaign, the influence of saltwater intrusion on groundwater quality was notable in some locations of the study area. This suggests that use of groundwater for irrigation should be restricted in these areas. The exclusive use of groundwater for irrigation in the Turritana Plain and the leaching of the same water into the aquifer, through irrigation return flow processes, do not allow improvements in water quality by rainwater recharge. Groundwater use should therefore be limited based on data regarding refreshing or intrusion phases. Moreover, a water management strategy should be developed, for example, to channel water from areas with an abundant supply of high-quality freshwater. The results indicate that the most cost-effective option may be to increase water-use efficiency and to design new groundwater exploitation schemes (Khan et al. 2006; Chartzoulakis et al. 2001). The present method, especially where the distribution of primary properties is not known or very poor, acts as a preliminary representation, analysis and interpretation about the issue of the influence of saltwater intrusion on groundwater quality. The information provided in this study can be used to promote the careful use of groundwater for irrigation, although monitoring campaigns at other times of the year could provide additional, more detailed information. This aspect has to be evaluated applying the method to others area, as temporal information is needed to determine the parts of the aquifer that remain virtually unchanged over time, so that the main recharge areas and the zones affected by salinization can be precisely identified.

## References

- Angelakis AN, Marecos Do Monte MHF, Bontoux L, Asano T (1999) The status of wastewater reuse practice in the Mediterranean basin: need for guidelines. *Water Res* 33(10):2201–2217. doi:10.1016/S0043-1354(98)00465-5
- APHA (1992) Standard methods for examination of water and wastewater. America Public Health Association, Washington
- Appelo CAJ, Postma D (2005) Geochemistry, groundwater and pollution. CRC Press, Taylor & Francis Group, New York
- Ardau F, Ghiglieri G, Vernier A (1994) Salinization of coastal aquifer of the Turritana Plain: an important factor conditioning land planning and use. In: Giovanni B (ed) XIII salt water intrusion meeting (SWIM), Cagliari
- Ashraf S, Afshari H, Ebadi A (2011) Geographical information system techniques for evaluation of groundwater quality. *Am J Agr Biol Sc* 6(2):261–266. doi:10.3844/ajabssp.2011.261.266
- Ayers RS (1977) Quality of water for irrigation. *J Irr Drain Div ASCE* 103(2):135–154
- Backman B, Bodiš D, Lahermo P, Rapant S, Tarvainen T (1998) Application of a groundwater contamination index in Finland and Slovakia. *Environ Geol* 36(1–2):55–64
- Bauder JW, Brock TA (2001) Irrigation water quality, soil amendment, and crop effects on sodium leaching. *Arid Land Res Manag* 15(2):101–113
- Bauder TA, Waskom RM, Davis JG, Sutherland PL (2011) Irrigation water quality criteria. Colorado State University Extension, Fort Collins
- Beltrán JM (1999) Irrigation with saline water: benefits and environmental impact. *Agr Water Manage* 40(2):183–194
- Böhlke JK (2002) Groundwater recharge and agricultural contamination. *Hydrogeol J* 10(1):153–179
- Bouchaou L, Michelot JL, Vengosh A, Hsissou Y, Qurtobi M, Gaye CB, Bullen TD, Zuppi GM (2008) Application of multiple isotopic and geochemical tracers for investigation of recharge, salinization and residence time of water in the Souss-Massa aquifer, southwest of Morocco. *J Hydrol* 352(3–4):267–287
- Bouwer H (2000) Integrated water management: emerging issues and challenges. *Agr Water Manage* 45(3):217–228
- Celico P (1986) *Prospezioni Idrogeologiche*. Liguori Editore
- Celico F, Rotigliano E (2002) Saline groundwater problems in the Gaza Strip: causes and integrative management solutions. *Boll Soc Geol It* 121:139–146
- Chartzoulakis KS, Paranychianakis NV, Angelakis AN (2001) Water resources management in the island of Crete, Greece, with emphasis on the agricultural use. *Water Policy* 3(3):193–205
- Civita M (2005) *Idrogeologia Applicata e Ambientale*. Casa Editrice Ambrosiana
- Cordoni F (2007) Assessment of intrinsic vulnerability and integrated pollution of groundwater in Turritana Plain (North Sardinia). Dissertation, University of Sassari
- Davis SN, De Wiest RJM (1966) *Hydrogeology*. Wiley, New York 463 pp
- de Montety V, Radakovitch O, Vallet-Coulomb C, Blavoux B, Hermitte D, Valles V (2008) Origin of groundwater salinity and hydrogeochemical processes in a confined coastal aquifer: case of the Rhône delta (Southern France). *Appl Geochem* 23:2337–2349
- El-Ashry MT, van Schilfgaarde J, Schiffman S (1985) Salinity pollution from irrigated agriculture. *J Soil Water Conserv* 40(1):48–52
- Fiorucci A (2007) Diagrams for evaluating groundwater quality. *Water Sci Technol* 7(3):111–119
- Garnero G, Godone D (2013) Comparisons between different interpolation techniques. In: Proceedings of the international

- archives of the photogrammetry, remote sensing and spatial information sciences XL-5 W, 3:27–28
- Ghiglieri G, Carletti A, Pittalis D (2012) Analysis of salinization processes in the coastal carbonate aquifer of Porto Torres (NW Sardinia, Italy). *J Hydrol* 432–433:43–51
- Gibrilla A, Bam EKP, Adomako D, Ganyaglo S, Osaë S, Akiti TT, Agyeman EK (2011) Application of water quality index (WQI) and multivariate analysis for groundwater quality assessment of the Birimian and Cape Coast Granitoid Complex: Densu River Basin of Ghana. *Water Qual Expo Health* 3(2):63–78
- Gimenez Forcada E (2010) Dynamic of seawater interface using hydro chemical facies evolution diagram. *Ground Water* 48(2):212–216
- Gimenez-Forcada E (2014) Space/time development of seawater intrusion: a study case in Vinaroz coastal plain (eastern Spain) using HFE-Diagram, and spatial distribution of hydrochemical facies. *J Hydrol* 517:617–627
- Hazen A (1911) Discussion of “Dams on sand formations”, by A.C. Koenig. *Trans Am Soc Civ Eng* 73:199–203
- Jayasingha P, Pitawala A, Dharmagunawardhane HA (2011) Vulnerability of coastal aquifers due to nutrient pollution from agriculture: Kalpitiya, Sri Lanka. *Water Air Soil Poll* 219(1–4):563–577
- Johnson JH (1975) Hydrochemistry in groundwater exploration. In: *Groundwater symposium Bulawayo*
- Ketata M, Gueddari M, Bouhlila R (2012) Suitability assessment of shallow and deep groundwaters for drinking and irrigation use in the El Khairat aquifer (Enfidha, Tunisian Sahel). *Environ Earth Sci* 65(1):313–330
- Khan S, Tariq R, Yuanlai C, Blackwell J (2006) Can irrigation be sustainable? *Agr Water Manage* 80(1):87–99
- Kraft GJ, Stites W, Mechenich DJ (1999) Impacts of irrigated vegetable agriculture on a humid north-central US sand plain aquifer. *Ground Water* 37:572–580
- Mongelli G, Monni S, Oggiano G, Paternoster M, Sinisi R (2013) Tracing groundwater salinization processes in coastal aquifers: a hydrogeochemical and isotopic approach in the Na–Cl brackish waters of northwestern Sardinia, Italy. *Hydrol Earth Syst Sc* 17(7):2917–2928
- Nagarajan R, Rajmohan N, Mahendran U, Senthamilkumar S (2010) Evaluation of groundwater quality and its suitability for drinking and agricultural use in Thanjavur city, Tamil Nadu, India. *Environ Monit Assess* 171(1–4):289–308
- Oggiano G (1987) The Turritana coastal plain, Geological map 1:50000. In: Federici PR (ed) *Genesi ed evoluzione della pianura costiera turritana (Sardegna settentrionale)—Geografia Fisica e Dinamica Quaternaria*. Stamperia Editoria Brigati, Genova, pp 113–115
- Oggiano G (2006) *Studi Ambientali nella Piana Turritana. Relazione Tecnica per la Provincia di Sassari*, 38 pp
- Oudet J, Münch P, Verati C, Ferrandini M, Melinte-Dobrinescu M, Gattacceca J, Cornee JJ, Oggiano G, Quillevère F, Borgomano J, Ferrandini J (2010) Integrated chronostratigraphy of an intra-arc basin:  $^{40}\text{Ar}/^{39}\text{Ar}$  datings, micropalaeontology and magnetostratigraphy of the early Miocene Castelsardo basin (northern Sardinia, Italy). *Palaeogeogr Palaeoclimatol* 295(1):293–306
- Prunty L, Montgomery BR, Sweeney MD (1991) Water quality effects on soils and alfalfa: 1. Water use, yield, and nutrient concentration. *Soil Sci Soc Am J* 55:196–202
- Pulido-Bosch A, Tahiri A, Vallejos A (1999) Hydrogeochemical characteristics of processes in the Temara aquifer in northwestern Morocco. *Water Air Soil Poll* 114:323–337
- Qadir M, Boers TM, Schubert S, Ghafoor A, Murtaza G (2003) Agricultural water management in water-starved countries: challenges and opportunities. *Agr Water Manage* 62(3):165–185
- Rao NS, Nirmala IS, Suryanarayana K (2005) Groundwater quality in a coastal area: a case study from Andhra Pradesh, India. *Environ Geol* 48:543–550
- Simsek C, Gunduz O (2007) IWQ Index: a GIS-integrated technique to assess irrigation water quality. *Environ Monit Assess* 128:277–300. doi:10.1007/s10661-006-9312-8
- Slama F, Bouhlila R, Tarhoun J (2010) Hydrochemical processes at the seawater/freshwater interface as indicators of seawater intrusion evolution: case of Korba coastal plain (Tunisia). *SWIM21-21st salt water intrusion meeting, Azores*
- Somay MA, Gemici Ü (2009) Assessment of the salinization process at the coastal area with hydrogeochemical tools and geographical information systems (GIS): Selçuk plain, Izmir, Turkey. *Water Air Soil Poll* 201(1–4):55–74
- Stuyfzand PJ (1999) Patterns in groundwater chemistry resulting from groundwater flow. *Hydrogeol J* 7:15–27
- Stuyfzand PJ, Stuurman RJ (1994) Recognition and genesis of various hypersaline groundwaters in the Netherlands. In Barrocu G (ed) *Proceedings of 13th SWIM, Cagliari*, pp 125–136
- Terzopoulos D (1988) The computation of visible-surface representations. *IEEE T Pattern Anal* 10(4):417–438
- Todd DK (1970) *The water encyclopedia*. Water Information Center, New York
- Valocchi AJ, Street RL, Roberts PV (1981) Transport of ion-exchanging solutes in groundwater: chromatographic theory and field simulation. *Water Resour Res* 17:1517–1527
- Vomocil JA, Hart JM (1990) *Irrigation water quality*. Oregon State University, Extension Service, Corvallis
- Weaver JMC, Cavé L, Talma AS (2007) *Groundwater sampling*, 2nd edn. WRC Report No. TT 303/07. Water Research Commission, Pretoria
- Werner AD, Bakker M, Post VE, Vandenbohede A, Lu C, Ataie-Ashtiani B, Craig TS, Barry DA (2013) Seawater intrusion processes, investigation and management: recent advances and future challenges. *Adv Water Resour* 51:3–26