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Estimating the freshwater-lens reserve in the coastal plain of the middle Río de la Plata Estuary (Argentina)

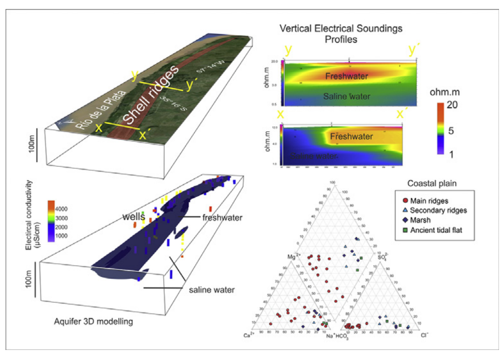
Francisco Cellone [a,*], Luigi Tosi [b], Eleonora Carol [a]

[a] *Centro de Investigaciones Geológicas (CIG). Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET-UNLP), diagonal 113 N°275, B1904DPK La Plata, Argentina*
[b] *Institute of Marine Sciences, National Research Council, Arsenale Tesa 104, Castello 2737/F, 30122 Venezia, Italy*

HIGHLIGHTS

- Freshwater source in the Río de la Plata littoral is stored into groundwater lenses.
- Freshwater lenses distribution is linked to the litho-morpho-stratigraphic setting.
- First information is provided to set a preliminary groundwater management plan.

GRAPHICAL ABSTRACT



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ABSTRACT

Drinking-water supply is one of the main issues that populations face in many coastlands. Shallow coastal aquifers are often characterized by the presence of lens-shaped freshwater floating on the saline groundwater plume of marine origin. These groundwater lenses are commonly associated with landforms, such as littoral ridges and dunes and in many cases they represent the main source of water supply in remote coastal areas. At the right side of the middle Río de la Plata estuary (Argentina) the aquifer system is generally saline. Elongated and thin sandy beach ridge systems emerging from the general flat morphology of the marsh-flood plain are capable of storing precipitations forming freshwater lenses, which to date are the main freshwater supply for inhabitants. The aim of this study is to identify and delimitate the presence of such valuable freshwater reserves in order to provide the first necessary guidelines for the water management plan in this area, which has never been implemented since, to the Authors' knowledge, no specific investigation had been carried out before this study. To achieve this goal, Vertical Electrical Sounding, groundwater electrical conductivity measurements, water balances and groundwater chemical analyses were performed and interpreted together. The whole dataset was processed to define the electro-stratigraphic model of the study area and to produce the map of the electrical conductivity of the shallow aquifer. In addition, a three-dimensional model of the fresh water reservoir has been implemented for a better understanding of the relationship between geomorphology and groundwater. Results point out that a total freshwater volume of 78,259,700 m^3 is stored into a continuous lens and the annual average recharge from precipitation amounts to 6,303,500 m^3. Although preliminary, this work provides the basic knowledge on the potential fresh groundwater lenses and provides important information for addressing a sustainable use of the freshwater resource.

* Corresponding author.
E-mail addresses: fcellone@fcnym.unlp.edu.ar (F. Cellone), luigi.tosi@ismar.cnr.it (L. Tosi), eleocarol@fcnym.unlp.edu.ar (E. Carol).

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1. Introduction

The majority of the world's population living in coastal areas depends on groundwater for freshwater human consumption, irrigation, farming, industry, tourism and other economic activities. However, many coastal aquifers are severely impacted or threatened by various natural and human-induced processes, among all, saltwater contamination is the most common one (e.g., Pousa et al., 2007; Akinbinu, 2015; Sathish and Elango, 2016; Argamasilla et al., 2017). The distribution of fresh- and salt- groundwater in coastal aquifer systems has been shaped by natural processes acting at geological and continental time scale (e.g., Kooi et al., 2000). However, human activities, such as river diversions, water reclamations, lowland drainage, groundwater exploitation, urbanization and mining, have modified the natural relationship between continental and marine water exchanges leading to a global depletion of freshwater reserves (e.g., Oude Essink, 2001; Antonellini et al., 2008; Bobba, 2017).

Numerous studies document the occurrence of freshwater lenses floating on saltwater in coastal aquifers. Freshwater lenses in coastal aquifers and oceanic islands are the result of rainfall infiltration that accumulates above saline groundwater derived from the sea. In general, the Ghyben–Herzberg theory (Verruijt, 1968) describes the relationship between saltwater and freshwater bodies; it specifically states that the thickness of the freshwater lens is directly related to the elevation of the water table above sea level. Nevertheless, size and shape of the freshwater lenses are controlled by many factors, including subsoil architecture, ground elevation, vegetation covering, land use and groundwater exploitation and recharge. Since the peculiarity of the freshwater presence in atolls and barrier islands, many studies focus on such environments but coastal plains are also relatively well documented. Among such studies addressing atoll groundwater, the knowledge base on the occurrence of freshwater lenses has been consolidated by Werner et al. (2017) who summarized the key processes, investigation techniques and management approaches of atoll island groundwater systems by means of an up-to-date literature review. Regarding the freshwater lenses in coastal plain aquifers, Cozzolino et al. (2017) determined the presence of freshwater lenses below coastal dunes in the north Adriatic Sea (Italy) and highlighted natural and anthropogenic factors affecting groundwater resource such as land cover, local drainage network, and beach erosion. Vandenbohede and Lebbe (2012) studied the presence of freshwater lenses occurring in the central part of the Belgian coastal plain where land reclamation in the past caused freshwater recharge and displacement of the older saltwater. de Louw et al. (2011) investigated the south-western delta of the Netherlands where freshwater availability is limited to shallow rainwater lenses and performed a detailed measurement of the mixing zone between infiltrating fresh rainwater and saline groundwater.

The coastal plain located at the right margin of the Río de la Plata estuary, in the NE sector of the Buenos Aires Province (Argentina), is characterized by a flat morphology drawn by the Pleistocene and Holocene deposits (Cavallotto et al., 2004; Violante and Parker, 2004) in which the aquifer systems and related water quality are strictly linked to the stadial/interstadial sedimentary cycles and controlled by the physiographic setting (Carol et al., 2015a).

The littoral zone is dominated by low-permeability surface sediments associated with coastal plain and marsh environments. The water table is <2 m deep and the hydraulic gradients of both the surface water and groundwater are extremely low. In general, soils and groundwater in the coastland are highly salinized. Freshwater is scarce and stored into shell ridge deposits and thin sandy layers forming lenticular shape reservoirs. Its availability is strictly connected to the amount of local rainfall, which are the only source of aquifer recharge (Carol and Kruse, 2012; Carol et al., 2013). In addition, the freshwater reserve, as well as the wetland ecosystem, is severely compromised by the drainage of excessive water volumes through the system of canals, groundwater mismanagement and exploitations, shell ridge quarry (mining activities) and disposals of sewage (Carol et al., 2015a).

Punta Indio district encompasses a littoral zone extending about 30 km along the middle estuary of the Río de la Plata, 7 km of which are occupied by the homonymous town (Fig. 1). The population of Punta Indio town consists of less than 600 residents (INDEC, 2010). Such number is decreasing (Stratta Fernández and De los Ríos Carmenado I., 2010) because of transformations in the Pampas agriculture (Rabinovich and Torres, 2004) and probably due to the continuous reduction of inhabitants, no water supply network has been already set up and domestic wells are used to supply water for the local residents.

Over the last decades, tourism activities have been developed in the littoral of Punta Indio leading to an increase of 5000 people during summer and weekends (Punta Indio Tourism Authority, personal communication, September 12th, 2017). Consequently, the freshwater demand has increased and new wells were drilled without a specific exploitation planning to prevent the depletion and degradation of fresh water resources.

The aim of this work is to estimate the potentiality of the fresh groundwater reserve in Punta Indio littoral to cope with a sustainable economic development of this sector in the Buenos Aires Province. We used an integrated approach consisting of geophysical surveys, well measurements, geological and geomorphological characterization, and chemical analyses. This study was developed as follows: firstly, morpho-stratigraphic characterization; secondly, groundwater analysis; thirdly, water balance and finally, quantification of the fresh groundwater availability, achieved by a 3D model of the aquifer architecture. A discussion to meet a sustainable groundwater management and the summary of the results conclude our work.

2. Material and methods

The geological setting has been identified by 10 litho-stratigraphic logs obtained by boreholes drilled for water supply and their correlation with those reported in previous studies carried out near the study area (e.g., Cavallotto, 1995; Fucks et al., 2010; Richiano et al., 2012). Furthermore, 20 new exploration sediment cores, about 4-m depth, were taken in order to reach to a better characterization of the stratigraphic architecture of the shallow deposits. Geomorphological units have been identified by field reconnaissance and mapped by satellite images and aerial photographs available from Google Earth and Bing Imagery (Cellone et al., 2016). The regional digital elevation model (DEM) of the Instituto Geográfico Nacional (IGN) Argentino (http://ign.gob.ar/node/987), which consists in the Shuttle Radar Topography Mission (SRTM) data specifically updated for Argentina (IGN, 2016), was used to compute the elevation of the sandy ridges.

A regional groundwater monitoring network based on 29 mills and household wells between 8 and 30 m depth, selected from a census ad-hoc done within this study, has been setup. Hydrological data consists of electrical conductivity (EC) and water level (WL) measures carried out in the monitoring network using portable conductivity meters and water level sensors. Specifically, three groundwater monitoring campaigns have been carried out in September 2015, February 2016 and July 2016.

Additional chemical analyses have been done on 25 water samples taken in July 2016. Water sample collection, preservation and chemical analysis were carried out according to the standard methods proposed by the American Public Health Association (APHA, 1998). Carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), calcium (Ca^{2+}), magnesium (Mg^{2+}) and chloride (Cl^-) were determined by volumetric methods, whereas sodium (Na^+) and potassium (K^+) were determined by flame photometry and sulphates (SO_4^{2-}) were measured by turbidimetry. The analytical error of the samples was, on average, below 4%. Chemical analysis of the major elements was conducted at the Centro de Investigaciones Geológicas (CIG).

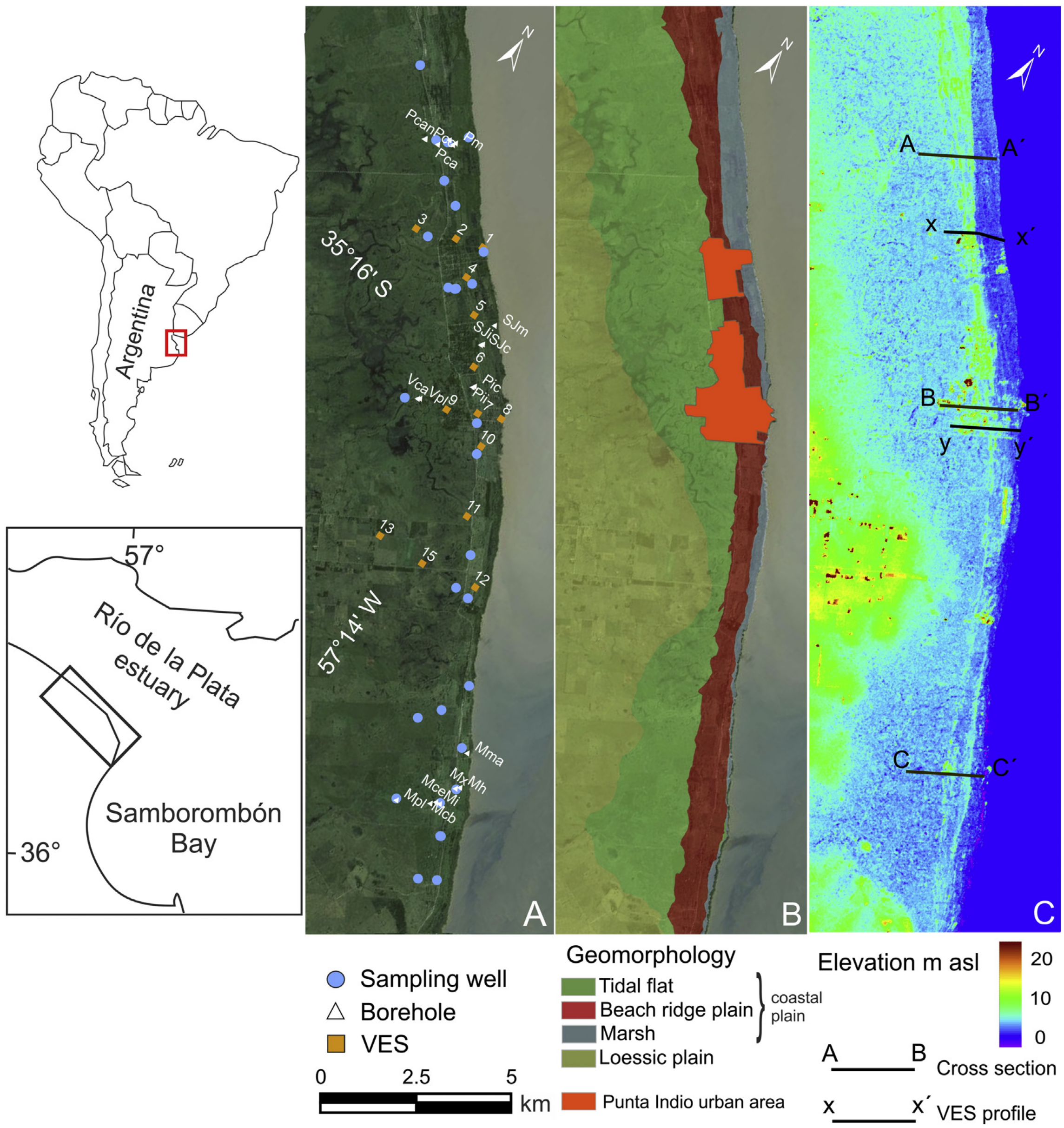

Fig. 1. A) Satellite image of the study area showing the locations of sampling wells, boreholes and VES. B) Maps of the main geomorphological units of the Río de la Plata coastal plain at Punta Indio. C) DEM and positions of the cross sections and VES profiles.

Raw data from 14 Vertical Electrical Soundings (VES) acquired using 300-m AB spacing Schlumberger configuration, was made available by the "Servicio Provincial de Agua Potable y Saneamiento Rural (SPAR), Buenos Aires, Argentina". Schlumberger VES method has been widely used for the identification of seawater intrusion in coastal aquifers worldwide (e.g., Frohlich et al., 1994; Sathish and Elango, 2016). We have re-processed the VES data using the ZondIP software (available from http://zond-geo.ru/english/zond-software/ert-and-ves/zondip1d/) taking advantage of the data not available at the time of their acquisition, i.e. litho-stratigraphic logs and EC measurements. A 4 layers model has been used and the inversion, set up in "standard" mode, stopped after 50 interactions, RMS value of 0.01 and field reduction error of 0.1. Field Iteration's number sets the maximum number of iterations and the automatic interpretation process stops when this is achieved. On the other hand, Field Reduction error sets the discrepancy value and the inversion process stops if this value repeatedly increases (in the specified value (%)) for three sequential iterations. After the automatic inversion, theoretical curves were manually edited and corrected.

Resistivity values were interpreted with hydrogeological criteria to define the electro-stratigraphic model of the area regarding both well electrical conductivity measurements and lithology data. Values higher than 10 ohm·m were interpreted as freshwater or as part of the non-saturated zone when being near the surface, values from 5 to 10 ohm·m as brackish water or silt, depending on its relative position with respect to the other layers. Values lower than 5 ohm·m were read as salt water. Two resistivity cross sections (x–x′ and y–y′) along VES profiles were constructed using ZondIP perpendicularly to the coast.

Short- (2015–2016) and long-term (1997–2016) soil water balances were carried out, respectively, to characterize the fresh water lenses and to determine excess and deficit water periods using monthly temperature and rainfall, making use of Thornthwaite and Mather (1957) method. Potential evapotranspiration (PET) is computed as:

$$PET = K \cdot \varepsilon$$

where:

$$\varepsilon = 16(10t/I)^a$$

$$I = \sum i$$

$$i = (t/5)^{1.514}$$

$$a = \left(6.75 \times 10^{-9}\right)I^3 - \left(7.71 \times 10^{-5}\right)I^2 + \left(1.792 \times 10^{-5}\right)I + 0.49239$$

$$K = \left(\frac{N}{12}\right)\left(\frac{d}{30}\right)d$$

and, of the month being calculated, t is the average daily temperature (degrees Celsius), N the average day length (hours), d the number of days and I a heat index which depends on the 12 monthly mean temperatures.

Soil characteristics of the beach ridge plain were determined by the National Institute of Agricultural Technology (Salazar et al., 1980). Horizon A is composed by clays (12.7%), silt (15.8%) and sand (71.5%), which represents a loamy sand texture, and has a thickness of 50 cm. Available water capacity for this texture, based on Saxton and Rawls (2006), is 7% with a field capacity of 12% and a permanent wilting point of 5%. Considering a radicular zone of 50 cm and a bulk density for this texture of 1.46 g/cm^3 (Saxton and Rawls, 2006), the total available water is about 51 mm.

Precipitation and temperature data from Base Aeronaval de Punta Indio station, located 8 km from the study area, pertaining the 1997–2016 period were gently provided by the National Meteorological Service of Argentina.

Due to the very flat morphology of the area no contribution was attributed to surface runoff. Therefore, only vertical water movements were considered.

Water balance was calculated as:

$$ET = PET \text{ if } P > PET.$$

$$ET = P + [\Delta AW] \text{ if } P < PET.$$

$$P - ET = \Delta AW.$$

$$P - ET = I \text{ if } AW \text{ reaches 51 mm}.$$

Where:

P: precipitation.
PET: potential evapotranspiration.
ET: evapotranspiration (real).
AW: soil available water.
ΔAW: variation in soil available water from one month to the other.
I: infiltration.

3. Results

3.1. Morpho-stratigraphic characterization

A regional morpho-stratigraphic analysis and characterization of the Punta Indio coastland was performed combining in-situ data with remote sensing observations. The geomorphology map and the DEM are shown in Fig. 1. Four main units have been identified from coastline to mainland, i.e. marsh, beach ridge plain, ancient tidal flat and loessic plain (Fig. 1b). The ground elevation of the coastland ranges from the sea level to about 6 m with some local higher up to 10 m because of the presence of buildings and trees (Fig. 1c).

Correlations between new sediment cores, available lithological logs from boreholes, and morphological data allowed to setup three detailed litho-morpho-stratigraphic sketches perpendicularly to the coast, which have been assumed to be representative of the northern, central and southern sectors of Punta Indio littoral (Fig. 2).

The uppermost deposits, as already pointed out by the geomorphologic characterization at regional scale, are formed by marsh, tidal flat and beach ridge deposits. However, at local scale, two types of deposits forming the beach ridge units have been recognized: shell-rich fragments with a coarse sandy matrix and fine sand-rich with rare shell fragments. The former constitutes the transition between the main ridges and the marsh environment and does not take place along the whole coast. Both types are characterized by high-permeability while marshes and the ancient tidal flats, mainly composed of clay, show low permeability.

The uppermost units of the Río de la Plata coastal plain lie on the Pleistocene deposits formed by silts of loessic origin and where the phreatic aquifer is mainly stored. The high-permeability units (beach ridges) constitute a preferential recharge zone of the aquifer. All these coastal plain deposits are 2–3 m thick on average with a maximum thickness of about 5 m in the main ridges. The loessic deposits have a thickness of approximately 47 m and below them sand deposits are found (Fig. 2).

3.2. Groundwater analysis

Time series analysis of EC data shown that the difference between dry (summer, i.e. February) and humid (winter, i.e. September) periods are negligible and therefore groundwater salinity in the short term is quite stable independently from the aquifer recharge (Fig. 3).

The extent of the freshwater lens was mapped taking it as representative of the average condition of Punta Indio groundwater the EC values detected in September 2015 and referring to 2000 μS/cm, the maximum value for the freshwater. Results showed that while EC lower than 2000 μS/cm are typical of the main ridge groundwater, those values greater than the previous ones have been found in the other units, i.e. saltmarsh, ancient intertidal flat, fine sand ridges (Fig. 4). The superposition of the area characterized by the presence of groundwater EC $<$ 2000 μS/cm with the geomorphological unit map enabled the delimitation of the freshwater lens to be improved.

The chemical analysis of the groundwater sampled in July 2016 points out a noteworthy difference between the main coastal ridges and the other units. The water contained in the main ridges (shelly and coarse sands) is Ca-Mg to Na-HCO_3 type while that found in the fine sand ridges, saltmarshes and ancient tidal flats is Na-Cl type (Fig. 5).

The analysis of VES data shows that the shallowest electro-stratigraphic layer with resistivity ranging between 10 and 80 Ω·m refers to the unsaturated zone. Below this layer, resistivity values between 9 and 20 Ω·m delineate the second and third layers, which are attributed to the freshwater zone of the aquifer stored in the loessic sediments. Its bottom placed between −30 and −40 m above msl indicates that most of the aquifer is stored in the loessic sediments. The fourth layer shows resistivity lower than 2 Ohm·m that correspond to a saline aquifer (Fig. 6 and Fig. 7).

In general, in the salt marsh sector (VES 1 and VES8) and in the ancient intertidal flats, i.e. the eastern and western sectors, respectively, resistivity values are significantly lower than in the beach ridge plain.

3.3. Water balances

The freshwater lens recharge is directly linked to precipitation and excess water. According to the 1997–2016 water balance, the mean annual precipitation is 1050 mm, the mean annual ET is 786 mm and the excess water represents 264 mm. The latter is equal to the infiltration that contributes to groundwater recharge. If the 2015–2016 period is considered, the result is a recharge of 254 mm, much more heterogeneously distributed throw out the year (Fig. 8). Both short and long term soil water balances show that infiltration occurs in winter whereas

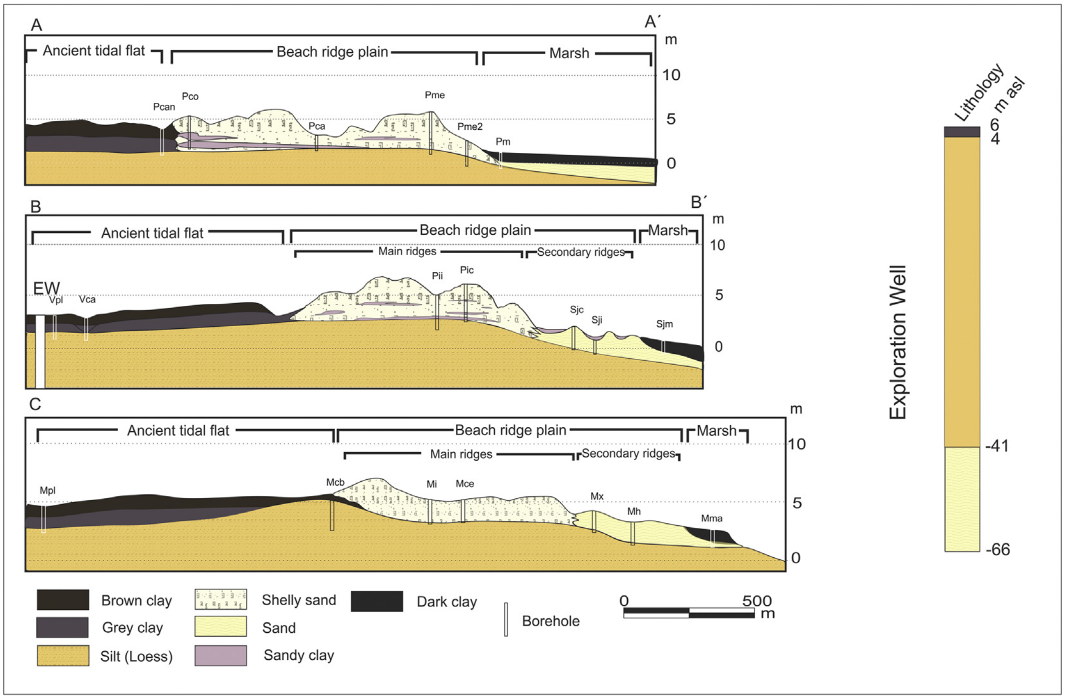

Fig. 2. Cross sections showing the main lithological characteristics distributed among the various morphological units forming the coastal plain (see locations in Fig. 1).

summer months show water deficits. This assumption allows us to state that the comparison between a humid period (September 2015) and a dry period (February 2017) (Fig. 3) may be representative of the extreme climate conditions.

Considering the total area of the main ridge (Fig. 1), the recharge zone of the phreatic aquifer correspond to 23,904,200 m^2 and the recharge volume per year for the 1997–2016 period (according to the water excess) amounts to about 6,303,537 m^3. If we consider only the town of Punta Indio, the area of the main ridge covers 3,680,800 m^2 and the total volume of the recharge per year for the 1997–2016 period is about 970,600 m^3.

Assuming a water consumption of 500 L/habitant/day, which is the water consumption in Buenos Aires metropolitan area estimated by AySA (2014), the yearly groundwater exploitation for the local 569 residents is 182,785 m^3/year. However, during summer and weekends, tourist activities led to a significant increase in Punta Indio population to approximately 5000. Hence, groundwater exploitation might rise considerably during these periods. Considering the 1997–2016 values of groundwater recharge, the town area can support a permanent population of 5317.

3.4. Delimitation and quantification of freshwater reserves

The quantification of the freshwater volume is another important issue for the groundwater management. This has been achieved by a 3D model of the freshwater aquifer architecture setup, properly integrating all the information available in a dataset, i.e. geophysical, geological, geomorphological, hydrological and chemical data. Assuming

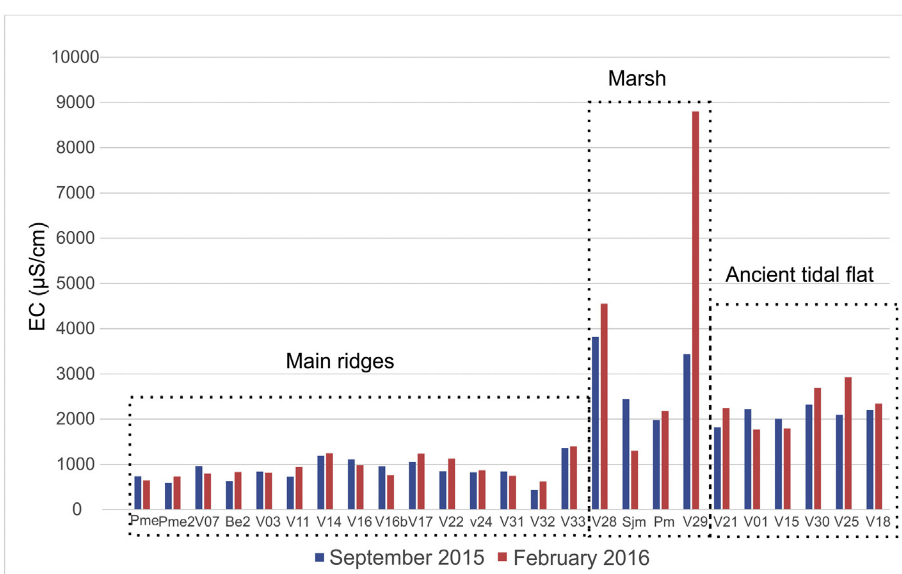

Fig. 3. Comparison between the electrical conductivity values of groundwater in September 2015 and February 2016. The wells (see positions in Fig. 1) are grouped on the basis of the different geomorphological units of the coastal plain.

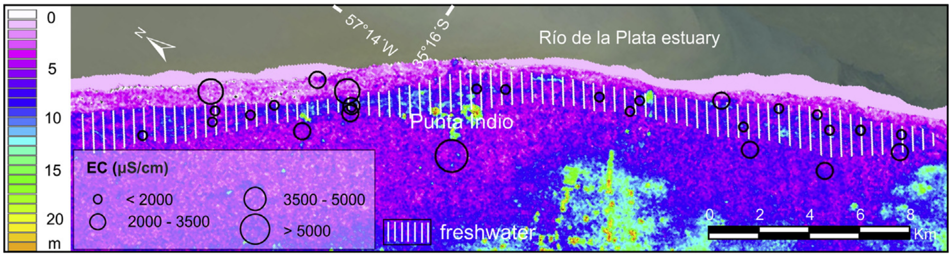

Fig. 4. Electrical Conductivity of groundwater measured in the monitoring wells of the coastal plain. White line pattern refers to EC < 2000 µS/cm and shows the presence of freshwater. The colour map in the background represents the DEM.

that EC values > 2000 µS/cm correspond to the saline aquifer, the dataset has been interpolated by inverse distance statistical method with anisotropy, as suggested by the elongated shape of the aquifer body revealed by VES data and EC measurements. The selected dimensions are the following: X length: 50,000 m, Y length: 5000 m and Z length: 50 m. The total volume of the aquifer containing the freshwater lens results in 869,552,120 m^3 (Fig. 9).

Assuming the storage coefficient of 0.09 calculated by Varni et al. (2010) and Quiroz-Londoño et al. (2012) for the loess sediment where the freshwater are mainly stored, the total fresh groundwater resources available in the lenses are about 78,259,700 m^3.

4. Discussion

The socioeconomic development of Punta Indio depends on the tourist activities taking place in the coastal zone. At the same time, with the development of tourism, a number of environmental problems began to affect the littoral zone. Many wetland sectors have been lost due to their transformation into beaches by mean of cutting down the natural vegetation. The lack of native wetlands vegetation led to a severe process of coastal erosion, which is expected to worsen in the future (Cellone et al., 2016). Since Punta Indio does not have a water supply network, the population growth has required the installation of numerous private domestic wells. Especially during summer, the freshwater resource is jeopardized by excessive groundwater exploitation, which might lead to its depletion and saltwater contamination.

To date, no groundwater management plans or basic guidelines for the conservation of freshwater reserves have been envisaged. Anyhow, these issues would require specific knowledge on the hydrogeological setting not available before our study.

This study provides the first information suitable for preliminary sustainable groundwater use. The well network setup for monitoring groundwater and water analyses show that freshwater storage strictly depends on local precipitation and is shaped into a lens that floats above saline waters. Therefore, it is necessary to take into account that freshwater reserves can be likely influenced by climate changes, as their effects are closely related to precipitations, and sea level rise (e.g., Carol et al., 2010; Tosi et al., 2013). While the present study cannot

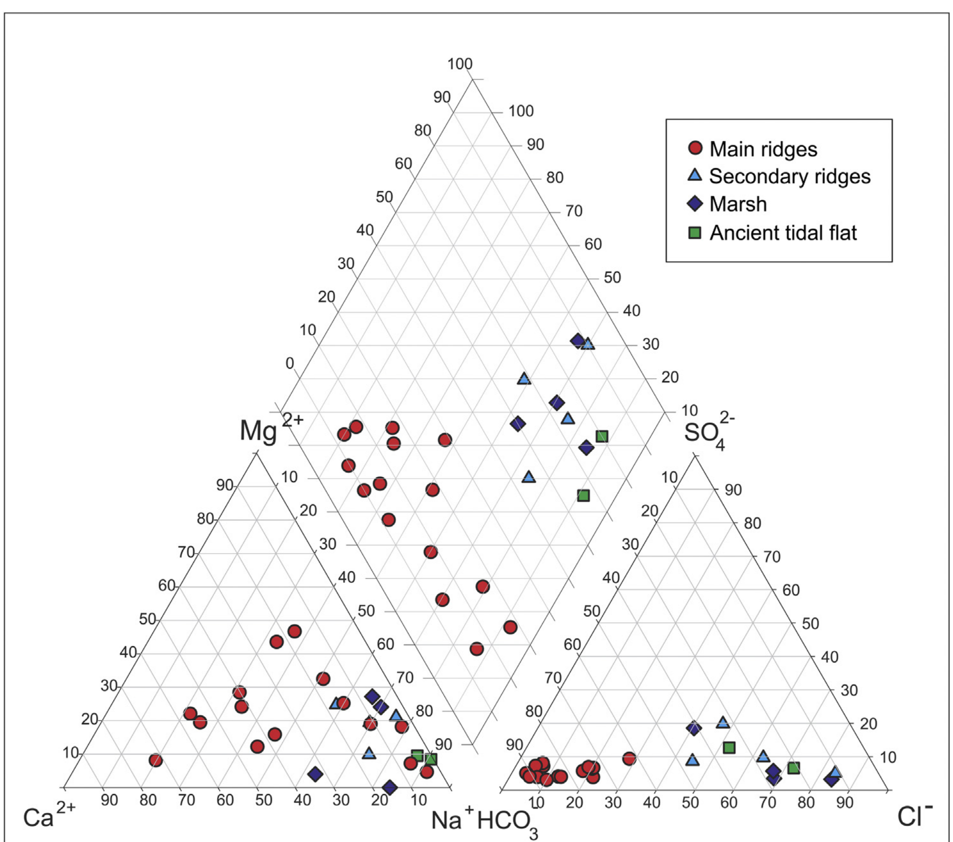

Fig. 5. Chemical classification (Piper diagram) of the groundwater present in the different morphological units of the coastal plain. Water analysis refers to the July 2016 sampling.

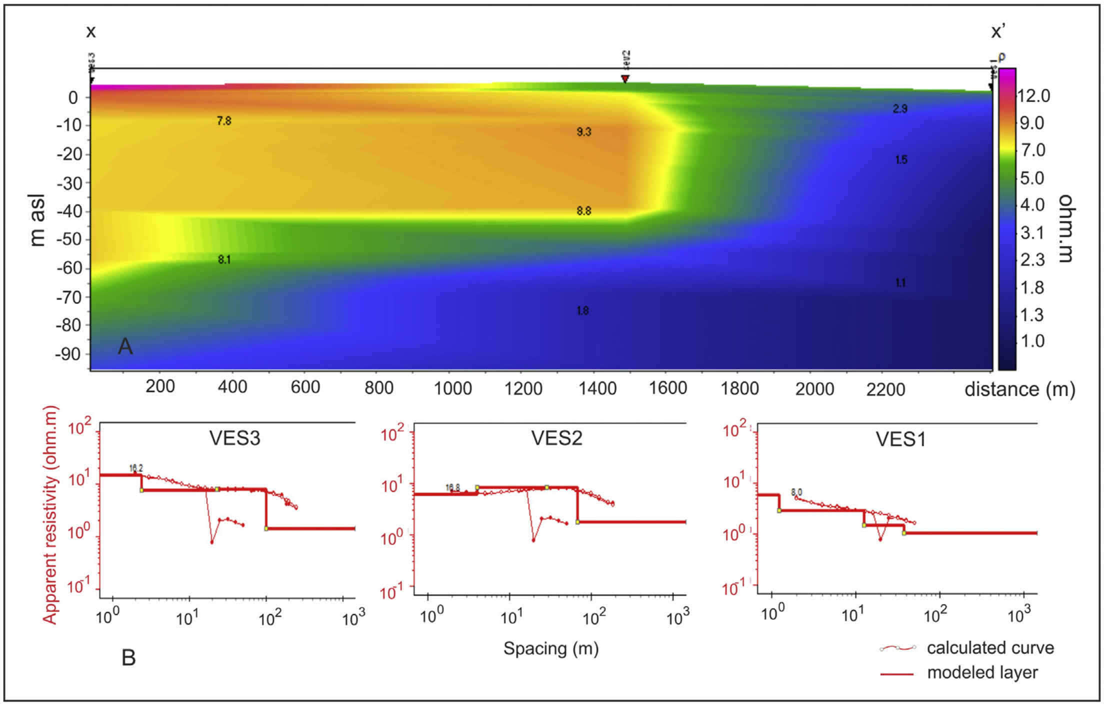

Fig. 6. Resistivity cross sections x–x′ along three VES profiles (A) and calculated curves and modeled layers (B) (see location in Fig. 1).

show any changes in salinity because of the short period of analysis, a further proper plan of monitoring, which includes the installation of sensors for continuous data recording, will benefit from the groundwater monitoring network already set up.

Another important aspect of groundwater management is the delimitation and quantification of the total freshwater reserves. This has been achieved by the 3D model of the freshwater aquifer that establishes its boundaries of the freshwater lens and a total freshwater volume of about 78,259,700 m^3. On the basis of the yearly average precipitation, evaporation and groundwater exploitation to supply the permanent residents, the water balance shows that the total groundwater net recharge amounts to about 787,850 m^3/year. This value is a conservative estimation since the population increase due to tourism is not considered. Considering the values of groundwater recharge obtained for the 1997–2016 period, the Punta Indio town can support a permanent population of 5317. Regarding the future prospects of the Punta Indio littoral, this study shows that the protection of the freshwater aquifer becomes essential, and the implementation of management plans designed to allow a sustainable development of the coastland is quite urgent. However, data for a successful result is not yet fully

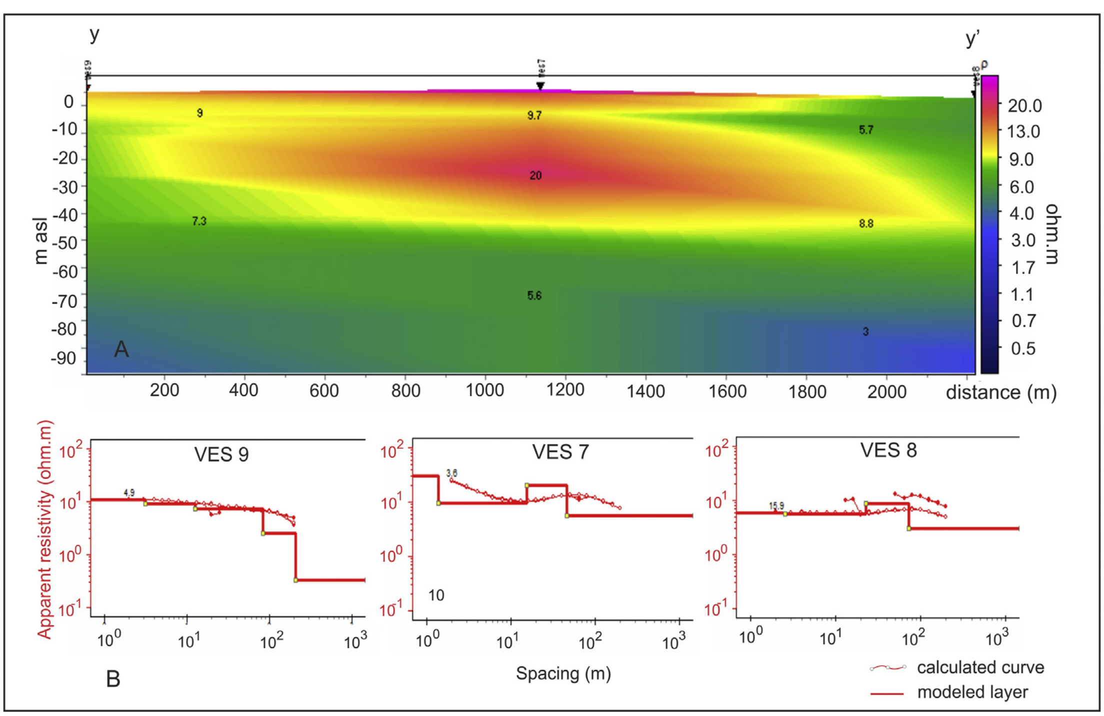

Fig. 7. Resistivity cross sections y–y′ along three VES profile (A) and calculated curves and modeled layers (B) (see location in Fig. 1).

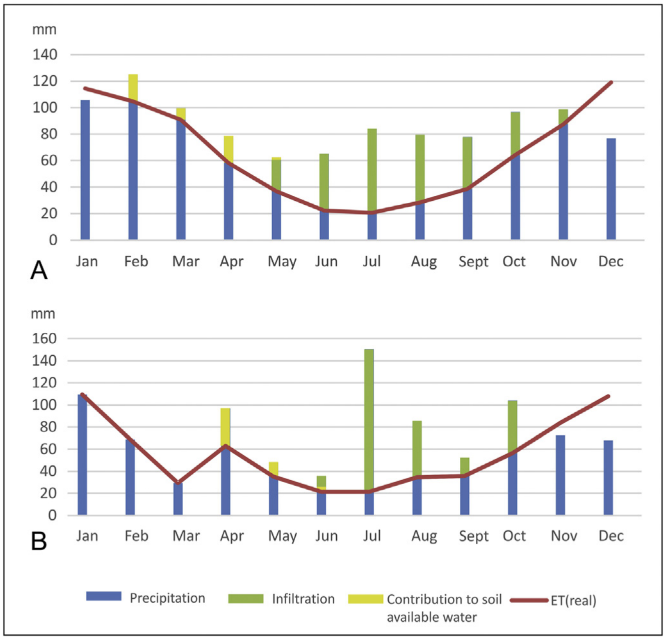

Fig. 8. Water balance for the 1997–2016 period (A) and for the 2015–2016 period (B).

available and the outcome of this study can only support the implementation of basic guidelines for limiting the freshwater depletion of the reserve by groundwater pumping. Anyhow, on the basis of other studies carried out in coastal areas with similar characteristics, we propose the following further in-situ investigations: i) mapping of the coastal aquifers and surface water-groundwater interaction in an onshore-offshore continuum (inland-coast-estuary) (e.g., Teatini et al., 2011), for instance by the use of advanced geophysical prospections, such as the Airborne Electromagnetic (e.g., Siemon et al., 2009); 2) the shaping of the seasonal freshwater-saltwater changes, e.g., by Time Lapsed Electrical Resistivity Tomography (de Franco et al., 2009). Furthermore, it would be also necessary to characterize the groundwater-surface water exchanges by radium isotopes to understand the potential of submarine fresh-groundwater discharges (e.g., Rodellas et al., 2017; Moore, 2003) and a more detailed evaluation and quantification of evaporation processes (Da Lio et al., 2015; Carol et al., 2015b). A better estimation of the soil water balances and estimation of the actual groundwater exploitation would give an improved quantification of the net recharge (Knott and Olimpio, 1986; Coes et al., 2007). Finally, we believe that it is mandatory to develop a coupled density-dependent groundwater flow and transport model in porous media to investigate the evolution of the saltwater intrusion (Kolditz et al., 1998; Huyakorn et al., 1987).

5. Conclusions

Freshwater supply to Punta Indio population is exclusively from groundwater pumping and so far no water network or other water supply systems, at least, have been constructed. Although the number of

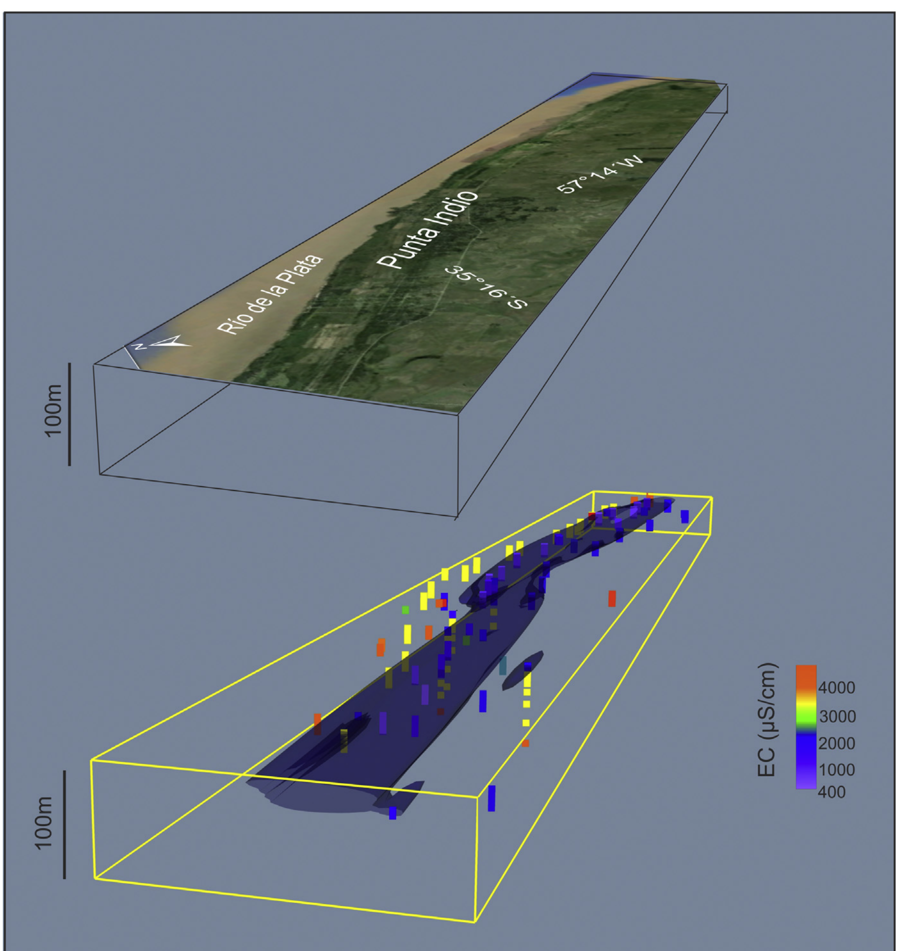

Fig. 9. The 3D model of the lens-shaped freshwater aquifer (transparent blue colour, vertical exaggeration = 10). The satellite image at the top shows the location of the model and colored bars refer to the groundwater EC values measured at each well. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

inhabitants has been steadily declining over the last decades, tourism has increased significantly, giving hope for the economic development of this coastal area.

Multiple conclusions were drawn from the study: freshwater lenses distribution is clearly linked to the coastal plain litho-morpho-stratigraphic setting. The water contained in the main ridges is Ca-Mg to Na-HCO_3 type with EC lower than 2000 μS/cm while that from the rest of the coastal plain is Na-Cl with EC higher than 2000 μS/cm.

Freshwater lenses are recharged from precipitation in the coastal plain high permeability units (beach ridges) and are mainly stored in the Pleistocene loessic sediments. The freshwater – saltwater interface is placed between −30 and −40 m asl in the central sector of the lens.

Assuming a storage coefficient of 0.09 the total amount of freshwater contained in the lens is about 78,259,700 m^3.

Freshwater lens depends on rainfall and the recharge volume per year for 1997–2016 period of the total area is about 6,303,500 m^3. Considering only the town of Punta Indio, the area of the main ridge represents 3,680,815 m^2, then, the recharge volume per year in this area is about 970,630 m^3.

We are aware that our study is not exhaustive enough to comprehend the hydrogeology of the Punta Indio coast therefore further research is necessary so as to understand the sustainable amount of groundwater that can be withdrawn. Hence, new geophysical prospections, simulation of groundwater flow and solute transport numerical models need to be performed. However, by means of this study, the Water Authorities in charge of the management of the Punta Indio area district will be provided with the hydrogeological knowledge suitable for developing first basic guidelines for preventing the depletion of the freshwater reserve occurring in the Punta Indio coastland.

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