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Decision tree as a tool for the management of coastal aquifers of limited saturated thickness

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Abstract: In this paper, a decision tree is presented, constructed on the basis of hydrogeological characteristics (water table depth, freshwater thickness, surface area required and distance between wells), to choose the optimal groundwater extraction method in the case of a coastal unconfined aquifer. A comparison is made of the groundwater extraction methods in a freshwater aquifer of limited thickness occurring in coastal dunes in the eastern region of the Province of Buenos Aires (Argentina). The negative effects brought about by the wrong use of the groundwater extraction methods are analysed, because, as a result of excessive extraction, such methods lead to the dramatic decrease of the freshwater reserves. The decision tree is a useful tool to assist decision-makers as it suggests the most suitable groundwater extraction method options (vertical wells or wellpoints), as well as identifying areas that are unsuitable for sustainable groundwater extraction.

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Aquifers that occur in coastal dunes are freshwater reservoirs that may constitute the only source of supply to the population. These shallow aquifers are usually found in Holocene deposits and, in many cases, have a limited saturated thickness.

The potential risk of saline intrusion is a factor that should be taken into consideration in the management of a freshwater coastal aquifer; such management is usually performed by a service provider, or a regional or national government agency. In general, planning begins when a saline intrusion problem has been detected or the risk is perceived in the near future. Long-term planning is more the exception than the rule, owing to, among other reasons, the lack of knowledge of the mechanism of saline intrusion.

There are international programmes that aim at defining guidelines for sustainable use of water, such as the United Nations Educational, Scientific and Cultural Organization's International Hydrological Programme (UNESCO-IHP). Its objective is to reverse the trends towards overexploitation and quality degradation in coastal aquifers by providing adequate capacity and technology for groundwater management. As part of the Integrated Coastal Zone Management (ICZM) protocol, in the Mediterranean, it is required for coastal aquifers to be monitored, so as to prevent the negative effects of groundwater extraction (UNEP-MAP, UNESCO-IHP 2015).

There are different points of view as regards the description of what 'sustainable management' is, and it is practically impossible to give a definition that would include the different systems and that, in turn, would offer useful advice for service providers and decision-makers (Brunner & Kinzelbach 2008). A variable that contributes to the sustainable management of an aquifer is the amount of water extracted; therefore, the method of groundwater extraction becomes an important element. This raises a key question: on what do service providers base the adoption of such methods?

In many cases, poor management of groundwater resources is not due to a lack of scientific knowledge (Foster & Garduño 2012), but to the fact that adequate planning of groundwater extraction is beyond the reach of resource managers (Gleeson *et al.* 2012; Re 2015). In this regard, it is necessary to consider the concepts applied in socio-hydrogeology, a subdiscipline of socio-hydrology (Sivapalan *et al.* 2012), which requires taking into consideration the social dimension of hydrogeological research. The management options should integrate the actual conditions of the social environment and the physical medium that is to be managed, and this approach aims at bridging the gap between scientific theory and practice (Linton & Budds 2014). In general, the population and decision-makers in the coastal regions of Argentina have a rudimentary knowledge of the scientific and technical concepts specific to hydrogeology. Certain misconceptions about the features of groundwater flow in a porous medium, the source of the recharge (supposedly from remote regions) or surficial processes associated with saline intrusion make it difficult to develop guidelines for the sustainable management of natural resources and, in particular, of the water resources.

The objective of the approach adopted in this study is to close the distance between scientists and drinking water suppliers (decision-makers), who, especially in small localities, are competent in the activity, but not specialists in hydrogeology. This is a peculiarity of the study area, but it also applies to other countries and regions where the availability of professional hydrogeologists is limited.

The use of the most frequent mathematical models for the simulation of groundwater flow (e.g. MODFLOW) and other software applications would provide solutions to the problem discussed, but it is not possible to develop robust groundwater models given the lack of trained hydrogeologists. In addition to groundwater models, it is standard practice to undertake pump tests to assess well performance and the impact on the aquifer before an extraction regime is agreed upon. The role of pump tests is, therefore, fundamental. Their application by decision-makers, however, is not often consistent with the need for sustainable water management. Usually, this results in trial-and-error testing, considering an extraction yield regardless of the consequences for the aquifer system. An option to avoid this problem would be the use of a simple diagram of the decision-tree (DT) type.

A DT is a graph that represents every possible outcome of a decision by means of branches and may be created with graphics or specialized software, or hand-drawn (Safavian & Landgrebe 1991). DTs are useful informally in group decision-making to concentrate the discussion, which is the approach this work focuses on. Programmatically, they help assign monetary, time or other values to possible outcomes so as to generate automated decisions. In data mining, DT software is a tool used to simplify complex strategic choices and assess the cost-effective potential of research and business opportunities. The main characteristic of DTs may be their capacity to split complex decision-making into several simpler decisions, offering a solution that may be more easily interpreted (Safavian & Landgrebe 1991).

DTs have been successfully implemented in a wide variety of areas, such as computer science (Buhrman & de Wolf 2002; Jagannathan *et al.* 2009), remote sensing (Simard *et al.* 2002; Brown de Colstouna *et al.* 2003; Pal & Mather 2003; Otukei & Blaschke 2010; Mishra & Singh 2011; Chasmer *et al.* 2014), astronomy (Suchkov *et al.* 2005), education sciences (Hwang *et al.* 2010), agronomy (Omid 2011), linguistics (Gu *et al.* 1983), medicine (El-Bakry & Hamada 2008; Tanner *et al.* 2008; Chieh & Pottie 2012) and engineering (Sugumaran & Ramachandran 2007; Jegadeeshwaran & Sugumaran 2013), among others. There is also a broad range of applications for DTs in natural sciences (Zmazek *et al.* 2003; Tien Bui 2014).

The use of DTs in hydrogeology includes, for example, research on erosion (Geissen *et al.* 2007), data mining to identify sensitivity to groundwater contamination (Yoo *et al.* 2016), estimation of the distribution of snow in a mountain basin (Balk & Elder 2000), prediction of flood-susceptible areas (Tehrany *et al.* 2013) and spatial distribution of hydromorphic landscapes (Bou Kheir *et al.* 2010).

In most of the above-mentioned examples, such applications require algorithms and complex computational systems to solve the DT. However, there is a classical example of their application in hydrogeology where the structure of the DT is respected and the decision is made by the user, based on the knowledge of the variables. It is the GOD (Groundwater occurrence, Overall aquifer class and Depth of water table) method, developed by Foster (1987) and Foster & Hirata (1988), a simple systematic method to assess aquifer vulnerability to pollution. It is used when the data available are limited, unreliable or do not cover the entire area under study. Owing to its simple, practical structure, it is usually the first method of choice.

In this paper, a DT is presented to determine the optimal groundwater extraction method in the case of a coastal unconfined aquifer, as a tool for the sustainable management of the groundwater resources. Also, the characteristics of each type of groundwater extraction are compared, focusing on the geomorphological and hydrogeological similarities and differences in each coastal dune sector. The advantages and disadvantages of the abstraction methods used are highlighted, according to the perturbations they introduce to the aquifer dynamics.

Background: groundwater extraction in unconfined aquifers of limited freshwater thickness

Unconfined aquifers of limited freshwater thickness are not often exploited, as the use of conventional vertical wells is inadequate; however, the implementation of suitable techniques turns them into a valuable resource. Such vertical wells can be used in sandy aquifers thick enough to allow the correct functioning of the pumps.

Horizontal wells are characterized by two configurations. One of them is represented by collectors with a radial drainage pattern (Ranney type), which consist of a large-diameter well, dug and buried in the substrate, from where a series of lateral filters extend radially. The other variant is a perforated pipe laid horizontally below the groundwater level and connected to a suction pump (Cashman & Preene 2001). These systems may also be installed in shallow unconfined aquifers of a limited thickness or in areas where it is necessary to obtain an important yield with little drawdown, as is the case of coastal areas (Custodio & Llamas 1996; Brassington & Preene 2003).

Another form of groundwater extraction is the wellpoint system, which consists of a group of small-diameter vertical wells, separated by a short distance, and connected to each other by a collector and to a central pump that produces the vacuum (Edward E. Johnson 1966). This method may be used to temporarily lower the water table in construction sites (Cashman & Preene 2001; Shaqour & Hasan 2008).

Raghunath (1987) mentioned wellpoints built in shallow coastal aquifers, but he only referred to their use for irrigation. Edward E. Johnson (1966) indicated that they may also work as a supply source for human and industrial consumption but made no specific references to case studies. This multiple-well system may be adapted to different patterns; a circular arrangement of wells gives the system the highest hydraulic efficiency. The placement of wells along a line brings about a lower efficiency, but it has the advantage of occupying a smaller area. An intermediate alternative is the H-shaped arrangement. To use wellpoint systems, there are three necessary conditions: the water table must be at a shallow depth; the aquifer must occur in unconsolidated material (sands or gravels), with a thickness between 6 and 15 m; and the wells themselves must be highly efficient (Edward E. Johnson 1966).

The extraction methods discussed are not the ones most commonly applied in groundwater extraction, especially in coastal regions. However, there are some cases, which are described below.

The use of horizontal wells as a source of permanent water supply is unusual and Brassington & Preene (2003) mentioned an example in the UK where it is used for the irrigation of a golf course. The same researchers cited Pyne (1994), who reported the use of this method for water abstraction in certain cases in the USA, indicating the good results obtained in continuous use for 5 years. Other cases in coastal areas can be found on the island of Borneo, Malaysia (Mailvaganam *et al.* 1993), and on the coast of the Outer Banks, North Carolina, USA (Giese *et al.* 1988).

Modelling has been undertaken of the functioning of horizontal wells in the shallow aquifer of the coastal dunes between Preston and Liverpool, UK (Rushton & Brassington 2016). According to these studies, their use may be appropriate for other shallow aquifers of limited thickness. Rushton & Brassington (2016) also analysed the behaviour of the flow produced by horizontal wells and wellpoint systems in unconfined aquifers, by means of conceptual and computational models. They demonstrated that both extraction methods are efficient to extract water in aquifers of limited saturated thickness. Another form of extraction carried out in coastal aquifers of limited thickness is by means of mixed extraction systems. Although it does not seem to be a widespread practice, there are some cases in the USA and Germany in coastal aquifers in tourist regions, where shallow vertical and horizontal wells are used.

The Outer Banks is a chain of islands off the coast of North Carolina, USA, where an unconfined aquifer with a thickness ranging between 6 and 15 m occurs. To avoid contamination owing to saline intrusion, the groundwater extraction is carried out on the basis of shallow vertical wells or shallow horizontal wells (Giese *et al.* 1988; Campbell & Coes 2010). Water is supplied by 42 shallow groundwater wells (13.7 m) that extract freshwater and five deep wells (76 m) extracting brackish water, which is then treated by reverse osmosis (Currituck County 2013).

The East Frisian Islands include a chain of barrier islands in the Wadden Sea region in the North Sea, Germany. The island of Langeoog has three freshwater lenses (Houben *et al.* 2014), but the supply depends on the water extracted from only the lens located to the west. To prevent the rise of the underlying saltwater, the extraction is distributed between more than 20 shallow wells (10–18 m deep), which pump intermittently at low rates, of the order of 10 $m^3 h^{-1}$.

On the other hand, in other coastal localities in the USA, such as Fire Island, Long Island (Schubert 2010), Emerald Isle (Sisco 2013) and Cape May County, New Jersey (Lacombe & Carleton 2002), even though a shallow aquifer of limited thickness occurs, it is not exploited owing to the occurrence of a deep confined aquifer that is used as a supply source.

In the northern sector of the sandy coast of the Province of Buenos Aires, Argentina, there is a locality whose drinking water supply is derived from a pumping field located in the dunes and whose water abstraction methods consist of wellpoint systems and Ranney-type horizontal wells (Carretero & Kruse 2010). At the southern end, other coastal localities use conventional vertical wells (Rodrigues Capítulo *et al.* 2016).

Study area

The study area consists of the sandy coast of the Province of Buenos Aires, Argentina, which geopolitically includes the districts of Partido de La Costa (northern sector) and Partido de Pinamar (southern sector) (Fig. 1).

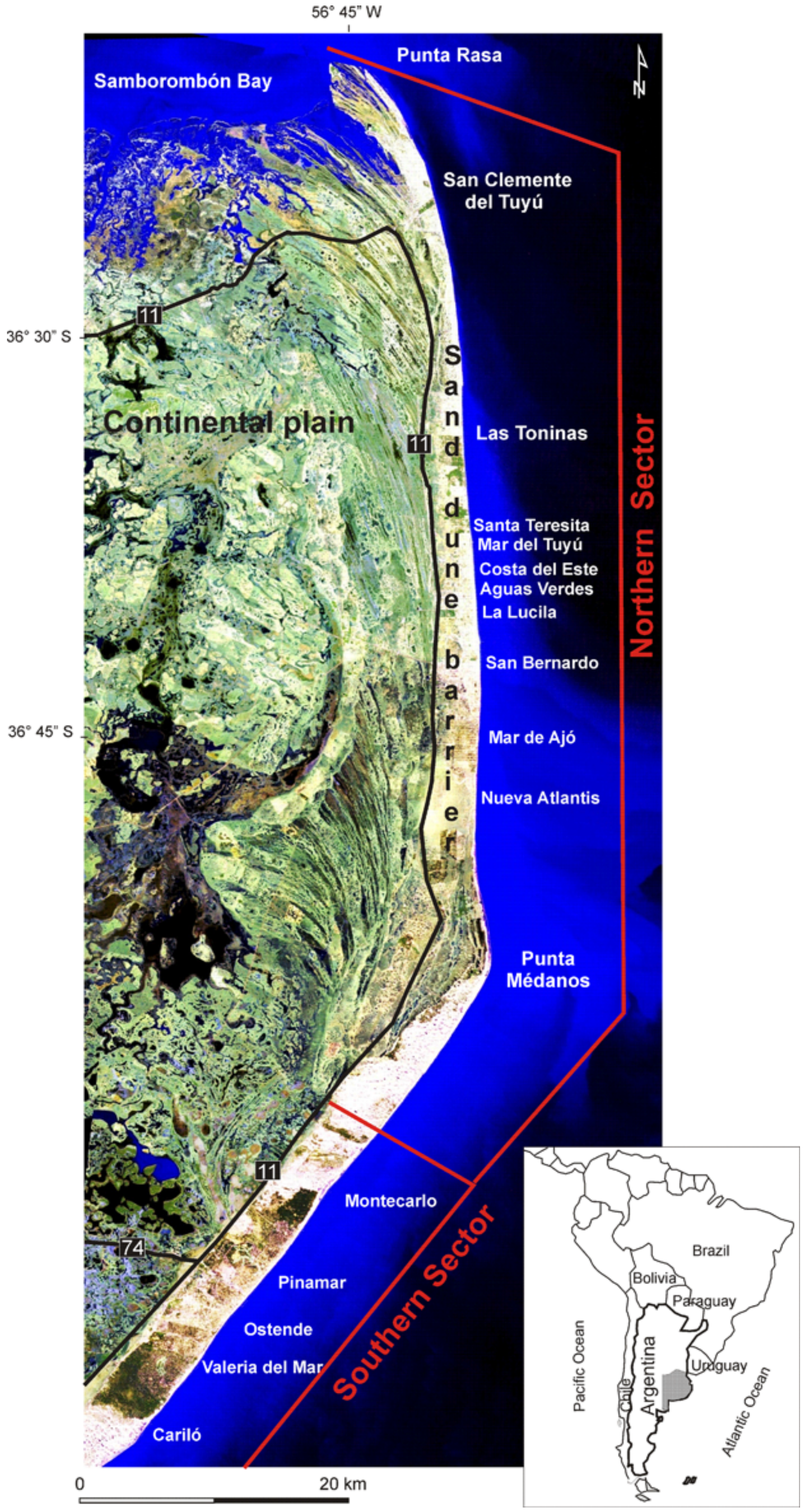

Fig. 1. Landsat image of the study area in Argentina; 11 and 74 are provincial routes.

It is one of the most important tourist destinations in the country. The dominant economic activity is tourism; there are no industries, livestock farming, agriculture or other activities, with water use being almost exclusively for human consumption and recreational use. The population, which depends on the coastal aquifer for water supply, increases considerably during the summer.

Tourism in the summer season, especially in January and February, leads to a ten-fold increase in the baseline population. In the northern sector, there may be over 2 700 000 tourists in its 249 km^2 area, whereas in the southern sector, 1 000 000 visitors concentrate in 66 km^2 (Rodrigues Capítulo *et al.* 2016).

The climate is humid temperate, with less precipitation in the cold months (April–September) and more precipitation in the warm ones (October–March). The mean annual precipitation ranges between 900 and 1000 mm, with 60% occurring in the months with higher evapotranspiration (warm months), which is why a higher groundwater recharge occurs during the cold season (Carretero & Kruse 2012). Such recharge derives from the precipitation excess.

The water table, whose morphology is radial with equipotential curves parallel to the coastline, has two groundwater flow directions, one towards the sea and the other towards the continent, with a hydraulic gradient that ranges from 1.5 to 4 m km^{-1}. Depending on the vegetation cover, higher recharge occurs in bare ground (470 mm a^{-1}) than in forested ground (261 mm a^{-1}), indicating a higher evapotranspiration in the case of tree cover (Rodrigues Capítulo *et al.* 2016). Generally speaking, the groundwater divide coincides with the maximum topographic elevation heights, following an imaginary line running in a SW–NE direction. In the northern sector, the thickness of the aquifer ranges between 10 and 15 m, with water table depths of 1–3 m b.g.l. (metres below ground level); on the other hand, in the southern sector, the water table is at a depth of over 6 m b.g.l., occurring in an aquifer with a thickness between 20 and 40 m.

From a hydrochemical point of view, both sectors have low-salinity water, with a predominance of a sodium–calcium–bicarbonate type water, corresponding to recently infiltrated water. In the northern sector, the thickness of the aquifer is limited by a chemical zonation and a vertical gradient of the electrical conductivity, which increases abruptly at a depth of 5–7 m. This phenomenon cannot be observed in the aquifer system of the southern sector, which has a greater thickness of good quality water.

One of the problems in both sectors (northern and southern) is the high concentration of total Fe and Mn, whose origin is related to the mineralogical composition of the aquifer (Carretero *et al.* 2013; Carretero & Kruse 2015). Also, isolated occurrences of salinization processes can be recognized, both in the northern sector (Santa Teresita) and in the southern sector (Pinamar, Valeria del Mar and Cariló). These processes are connected with the intensive extraction of the resources, which favours the advance of a saline front, which can be verified by the major increase in electrical conductivity values in wells close to the coast.

Materials and methods

The groundwater extraction systems were analysed in both of the study areas. The water tables were measured in groundwater monitoring networks. Extraction yield data were analysed and groundwater flow maps for different dates were constructed to show the fluctuation of the water tables during seasons of high or low water extraction.

Based on the analysis of the constraints to define the optimal groundwater extraction system, a DT was designed to allow decision-makers to choose the most effective system.

DTs are constructed on the basis of top-down, divide-and-conquer strategies, splitting collections of objects into smaller groups as the tree grows (Quinlan 1990). Structurally, DTs are composed of series of tree nodes and branches (Gao & Alexander 2008).

The variables selected were water table depth, aquifer thickness, surface area required to install the well and distance between wells. To apply the DT in other areas, these variables may be modified according to the specific values of the medium.

Because of the location of the freshwater–saltwater interface, and as a safety measure, a buffer of 50 m from the coastline was established.

The variables considered were as follows.

(1) Water table depth. A value of 3.5 m b.g.l. was defined as the limit. This value is related to the fact that the centrifugal pumps in wellpoint systems are a constraint for their use and may overcome a vacuum column and extract water from a maximum depth of 7.6 m. Some pumps do not exceed 4.5 m (Edward E. Johnson 1966); as regards the pumps used in the case study, the value did not exceed 3.5 m. This variable is the first one to be evaluated and the one from which the first decision of the DT stems.

(2) Thickness. Once water table depth has been assessed, the thickness of the aquifer is considered. In the case under study, a minimum aquifer thickness value of 20 m has been set to choose a vertical well. In this case, the choice is based on theoretical grounds determining that, to establish the length of a well, it is advisable to reach the impermeable base of the aquifer, unless the expected yields, the economic constraints of the well or the excessive depth of such a base make it acceptable to adopt a partially penetrating well as a solution (Custodio & Llamas 1996). A field test was carried out in the aquifer of the northern sector (15 m thick), where low-flow pumping of a vertical well was undertaken with a submersible pump. As a result, the well was depleted a few minutes after the pumping had started. Also, as previously mentioned, one of the conditions for the siting of a wellpoint system is that the aquifer should be between 6 and 15 m thick (Edward E. Johnson Inc. 1966). Therefore, in an aquifer with a thickness of less than 20 m, it would be possible to install wellpoint systems only if the rest of the variables allow it.

(3) Surface area required (SAR). This parameter represents the land surface area required to install a well. It is a conditioning factor, particularly for the installation of wellpoints. The area needed to install a wellpoint system is a circle of 300 m^2, whereas in the case of a vertical well, it is fairly small, no larger than 2–3 m^2 (Fig. 2a).

(4) Distance between wells (DBW). The distance between wells was defined depending on the radius of influence estimated for each well type.

The theoretical radius of influence was estimated for each water extraction system, following the method proposed by Theis (1935) and considering the average hydraulic parameters of the aquifer system, transmissivity (T) and specific yield (S), according to equations (1) and (2),

$$s = \frac{Q}{4\pi T} W(u) \tag{1}$$

$$u = \frac{r^2}{4Tt} S \tag{2}$$

where S is specific yield, r is distance between wells, T is transmissivity, t is time (in days); Q is discharge, s is drawdown in the borehole, u and $W(u)$ are well function.

It was verified that this approach can be applied to the unconfined aquifer under study, as the drawdown caused by the extraction systems proposed is small with respect to the saturated thickness

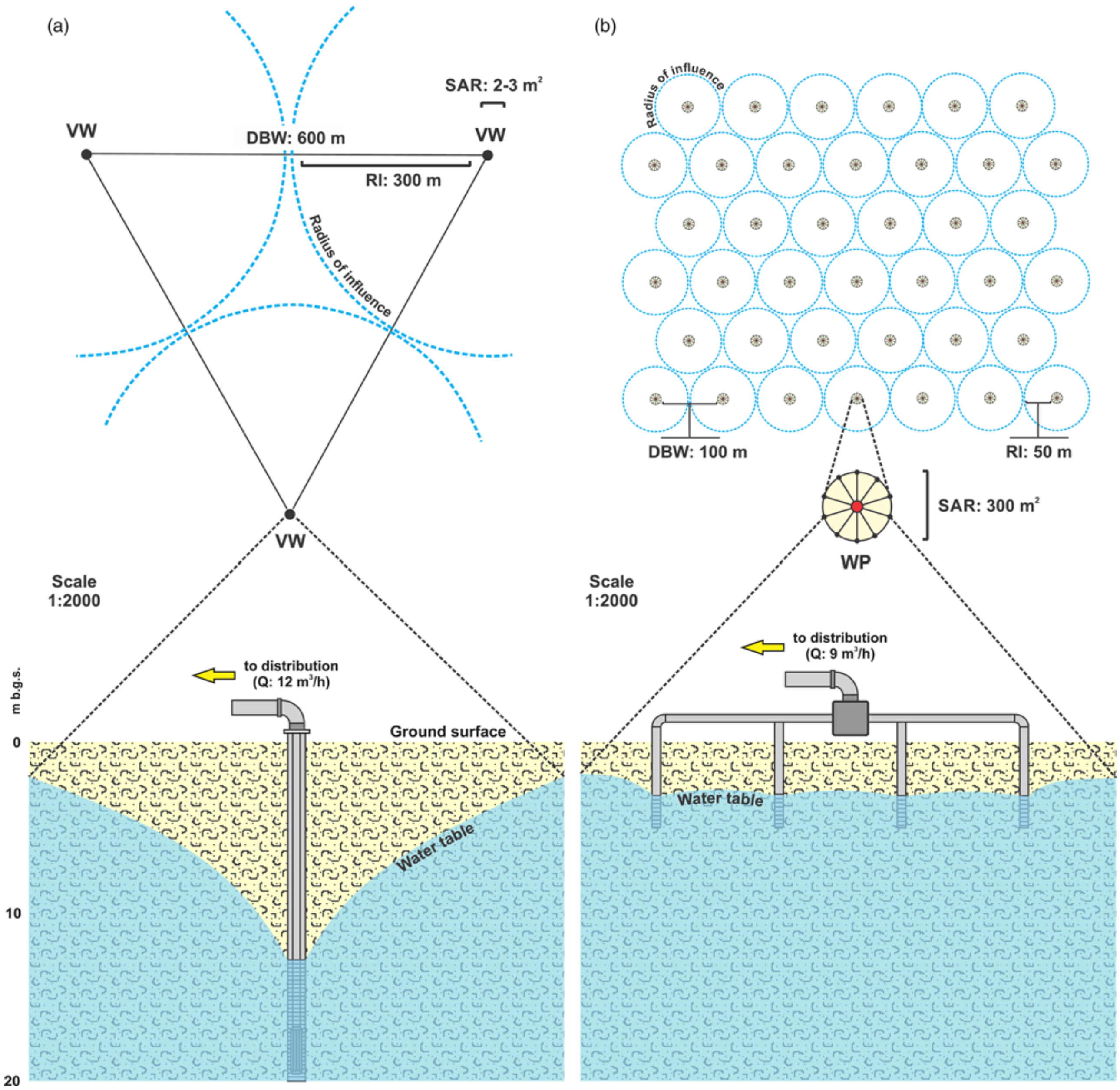

Fig. 2. Spatial distribution for (**a**) vertical well (VW) and (**b**) wellpoint (WP). DBW, distance between wells, SAR, surface area required; RI, radius of influence.

(Todd & Mays 2004). The correction of the drawdowns induced by the pumping proposed by Kruseman & de Ridder (1994) according to equation (3) yields differences of a few centimetres when compared with equation (1); such differences are negligible when the radius of influence is estimated. Equation (3) is as follows:

$$s' = s - \frac{s^2}{2b} \tag{3}$$

where s' is corrected drawdown, s is observed drawdown and b is saturated aquifer thickness.

In the case of the wellpoint system, the value considered is 50 m, whereas in a vertical well, it reaches 300 m. The radii of influence were determined depending on the extraction yields of the cases under study (wellpoints, 9 m^3 h^{-1}; vertical wells, 12 m^3 h^{-1}; Fig. 2b).

Finally, the DT method was applied in a locality of the southern sector whose aquifer has the necessary characteristics to use this tool (sandy aquifer, limited by a freshwater–saltwater interface, and variable aquifer and unsaturated zone thicknesses). The theoretical demand was also calculated, taking into consideration a value of 200 l d^{-1} per person (Planas *et al.* 2000). The production yields of the vertical wells and wellpoints were estimated, considering an operating period of 12 h d^{-1}.

Results

To evaluate by means of DTs the possible groundwater extraction methods to be used, the extraction systems present in the study area are described, as well as the modifications they introduced into the aquifer system.

Extraction system in the northern sector (San Clemente del Tuyú)

The drinking water supply originates in a pumping field located to the south of the locality, outside the urbanized area. Extraction is undertaken by means of a Ranney well system and wellpoint systems located in the coastal barrier, with a morphological expression ranging between 0.5 and 3.5 m a.s.l.

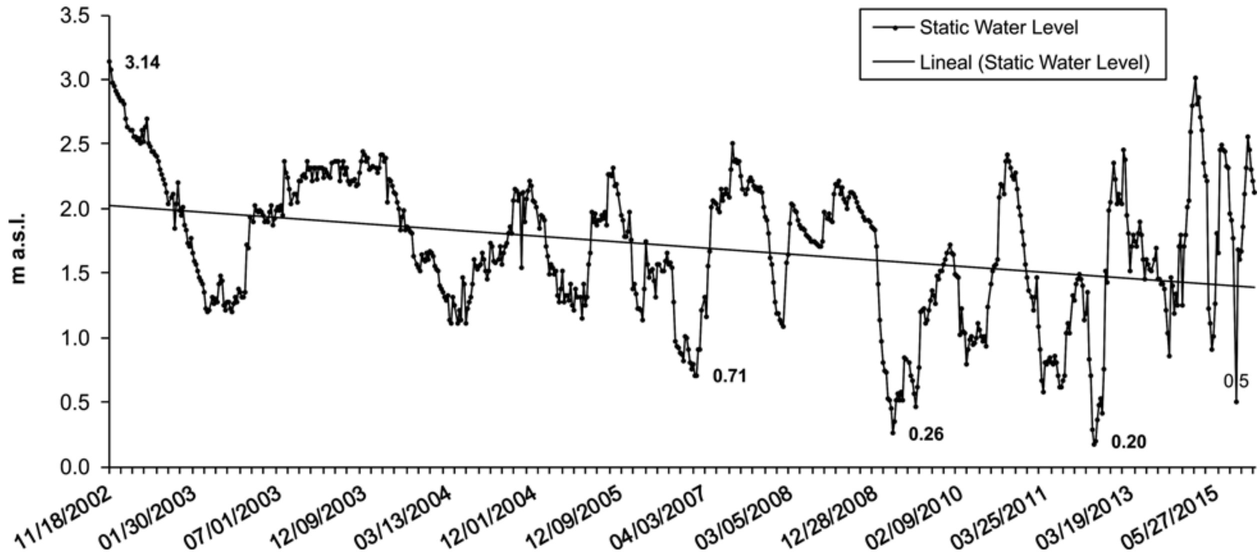

Fig. 3. Water-table fluctuation for a monitoring well in the pumping field, San Clemente del Tuyú.

The seven wells with horizontal or Ranney-type collectors (yield 7 m^3 h^{-1}) were installed in the early 1980s, and because of the high cost and complexity of their installation, when expanding the area of water extraction, it was decided to set up wellpoint systems. These consist of 21 pumping stations, each of them composed of 10 vertical wells arranged in a radial manner (yield 9 m^3 h^{-1}). The depth of extraction ranges between 4 and 6 m b.g.l. For a drawdown of 0 m, it has been estimated that the radius of influence between wells is 100 m. With a radius of influence of 50 m, the calculated drawdown was 3 cm, a negligible value in the face of the possibility of installing more wellpoints and taking into account the surface area they cover. For a wellpoint system, the circular surface area affected to avoid such an interference is considered to be 0.01 km^2. The actual distance between wells is 25 m; to avoid interference phenomena, they are operated in an alternating manner, although in the summer this regime is not usually respected because of the increase in demand.

The average production for December and March is 800 m^3 d^{-1}, whereas in January and February it is 1500 m^3 d^{-1}, in certain years exceeding 1800 m^3 d^{-1}. Outside the summer months, the average is about 500 m^3 d^{-1}, which indicates that in the high season extraction is tripled.

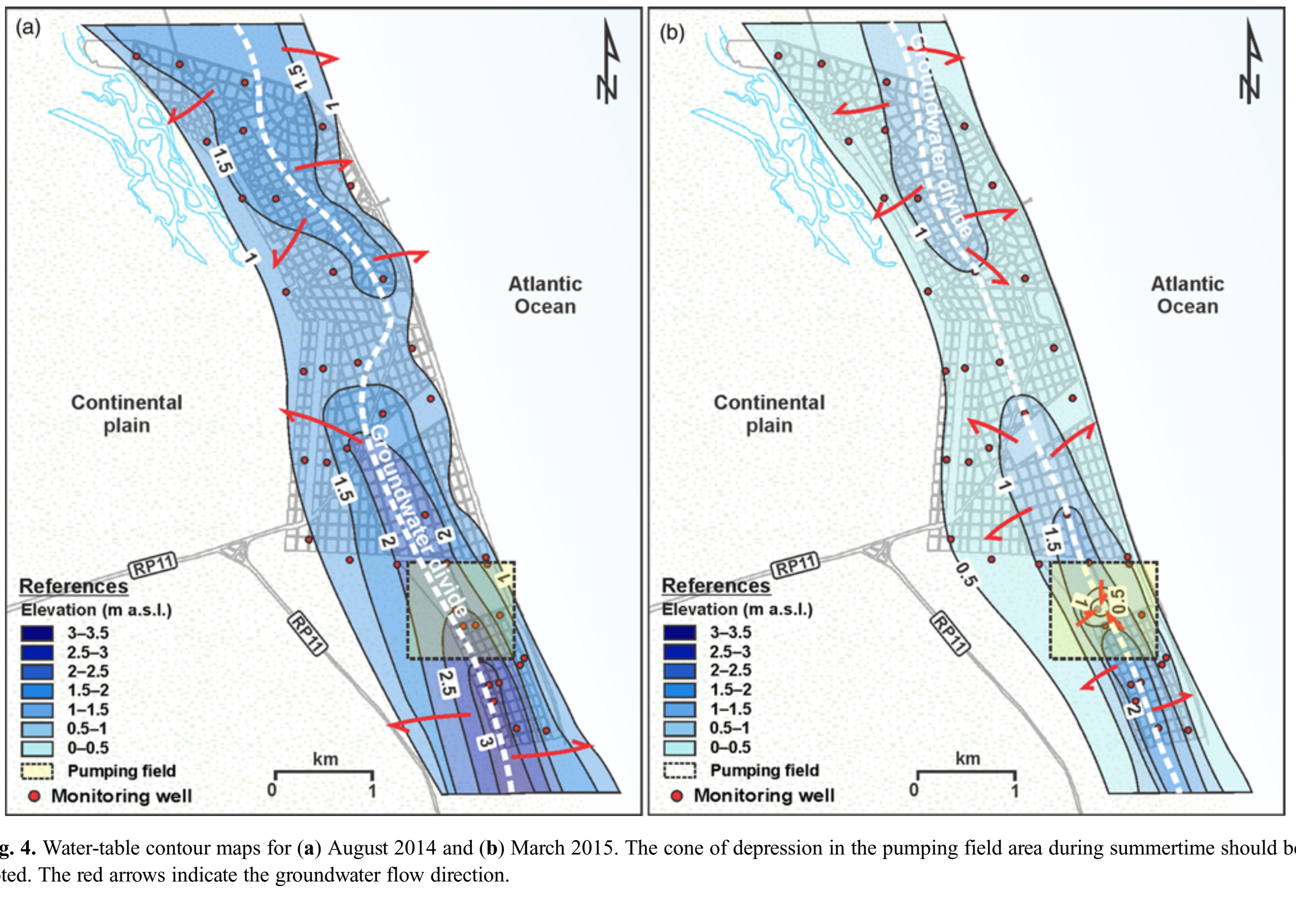

Fig. 4. Water-table contour maps for (**a**) August 2014 and (**b**) March 2015. The cone of depression in the pumping field area during summertime should be noted. The red arrows indicate the groundwater flow direction.

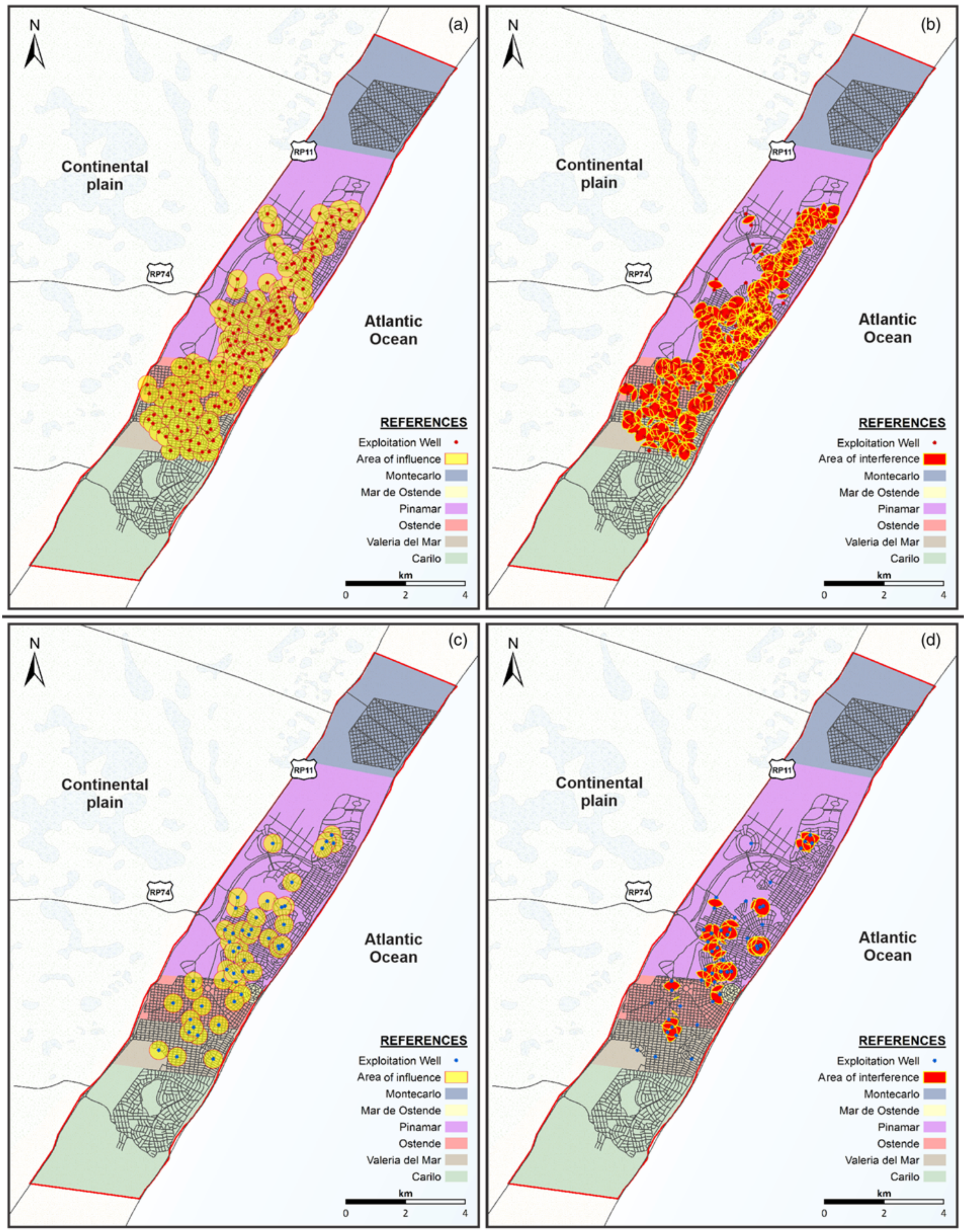

Fig. 5. Area of influence: (**a**) in summer; (**c**) in winter. Area of interference: (**b**) in summer, (**d**) in winter.

The annual precipitation shows a downward trend from 2002 to the present, whereas production behaves in the opposite manner. The consequence of this management can be recognized in Figure 3, as the water table shows a downward trend from 2002 to the present.

The hydrological situation can be observed in the maps (Fig. 4). Two contrasting situations are shown, with the highest groundwater levels measured in August 2014 (Fig. 4a) decreasing to March 2015 (Fig. 4b), after the intensive extraction in the summer. In March 2015, a cone of depression becomes evident in the pumping area.

Extraction system in the southern sector (Partido de Pinamar)

The drinking water supply in the Partido de Pinamar is derived from a multilayer aquifer of Late Pleistocene–Holocene age, whose composition ranges from fine to very fine clean sands to greyish plastic clays.

Extraction is carried out by means of a system composed of vertical wells that reach an average depth of 24 m b.g.l., with the abstraction area occurring between 20 and 25 m b.g.l.

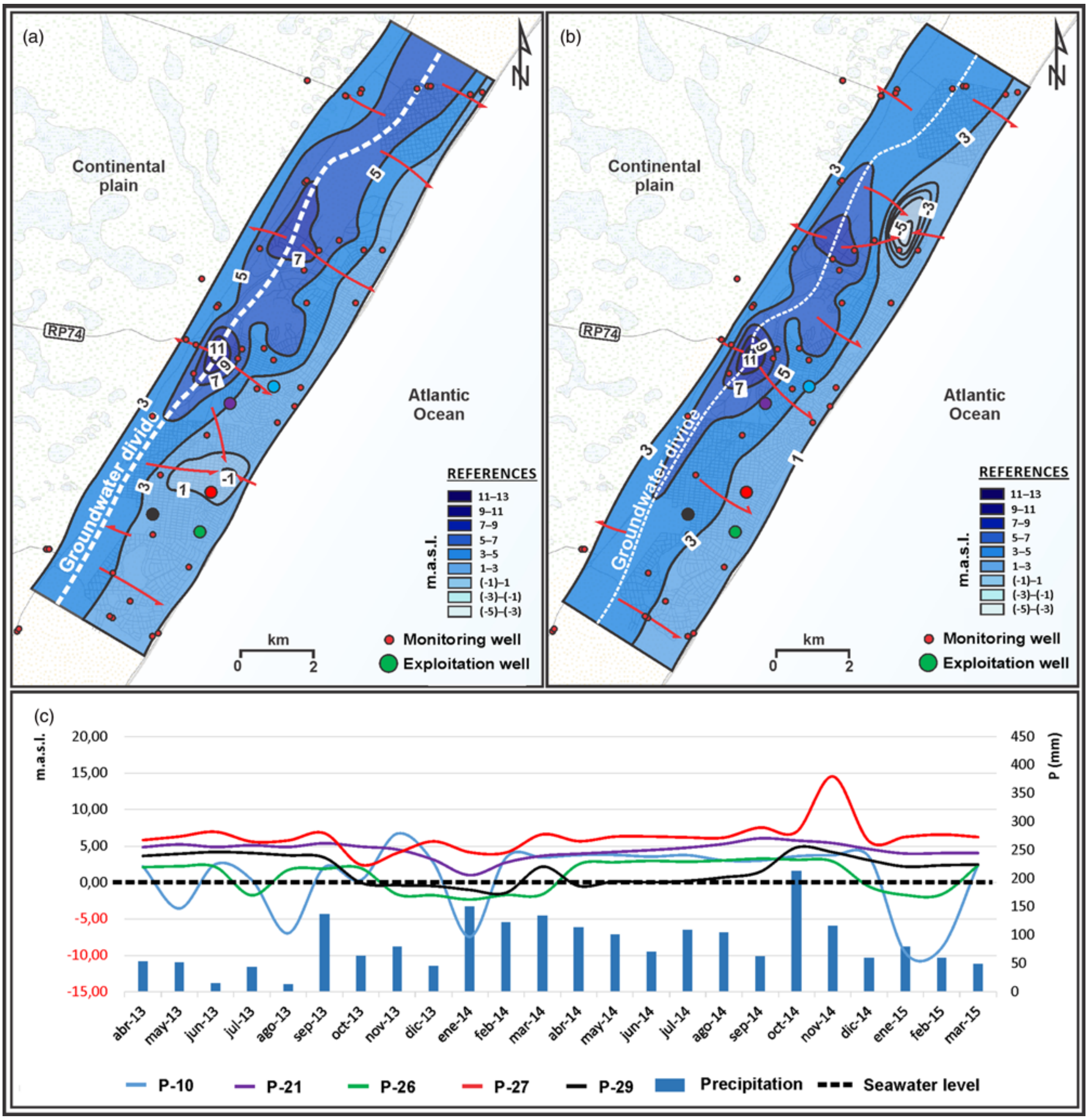

Fig. 6. Water-table contour maps for (**a**) February 2014 and (**b**) February 2015; (**c**) water-table fluctuation for extraction wells in Pinamar.

For groundwater extraction, submersible pumps are used (Rodrigues Capítulo 2015) and mean extraction rates of 12 m^3 h^{-1}. The extraction scheme contemplates putting into operation 151 pumps during the summer (Fig. 5a), which are started manually in a gradual manner depending on the water demand. The distribution is the result of the direction of population growth, not of management criteria. In winter, the operational wells decrease to a third (48 extraction wells; Fig. 5a).

A theoretical radius of influence of 309 m was estimated, which means that the area of influence of each well is 0.3 km^2. In Figure 5a and c, the theoretical areas of influence of extraction during the summer and winter are shown. This indicates that the areas affected by extraction reach 48 and 15.2 km^2, respectively. In Figure 5b and d, the areas generated as a result of the overlapping of the cones of depression in each extraction well can be observed. This explains the decrease in groundwater levels observed locally (8–10 m) (Fig. 6a–c), in certain cases causing the water table to occur below sea level and the inversion of the hydraulic gradient.

Interferences between wells lead to inefficient extraction, not only from a hydrogeological point of view, but also from an economic one, owing to pumping equipment cavitation or the increase in energy costs.

Decision tree

Design

The procedure outlined integrates a logical sequence in the decision-making, which makes it possible to determine an efficient, sustainable use of groundwater so as to avoid the depletion of the reserves and prevent salinization processes.

This DT allows the exploration of the different alternatives according to a reduced number of hydrogeological factors, giving the option of using vertical wells or wellpoint systems in a shallow coastal aquifer. There are also combinations of the variables that do not create the necessary conditions for the sustainable use of the resource (Fig. 7).

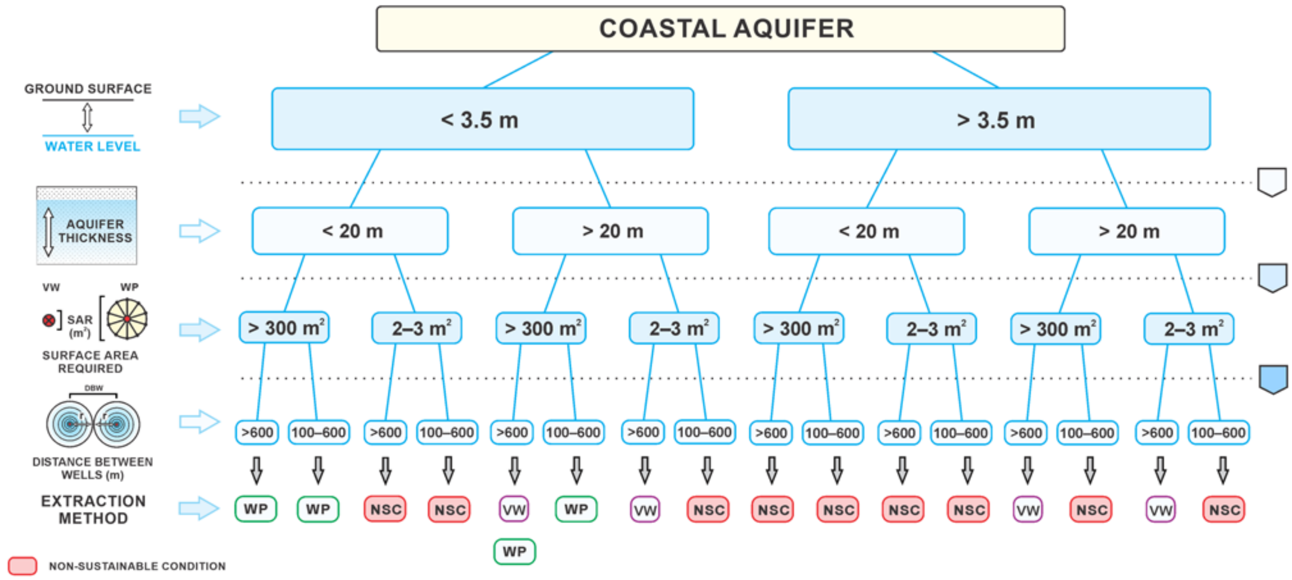

Fig. 7. DT to choose between extraction methods in a coastal aquifer. WP, wellpoint system; VW, vertical well; NSC, non-sustainable condition.

The diagram shows how, through the knowledge of the depth of the water table, the freshwater thickness in the aquifer, the surface area required and the distance between wells, it is possible to determine the most appropriate systems for groundwater extraction.

The first decision to be taken is based on the determination of the water table in an unexploited area. Depending on whether the depth of the water table is higher or lower than 3.5 m b.g.l., the following decision to be made is determined by whether the freshwater saturated aquifer thickness is greater or less than 20 m. On this basis, alternatives arise as regards the surface area required, with the alternative of either over 300 m^2 or between 2 and 3 m^2. Finally, based on the distance between wells, a final decision is made.

Therefore, several hydrogeological factors are included, and the most appropriate extraction system is suggested for the site where the extraction will be undertaken.

In three of its branches, the DT allows the use of a wellpoint, and in three others, a vertical well. There is an option in which it would be valid to install either of the systems, but it is recommended that a vertical well be chosen, as a better use of the thickness of the saturated aquifer would be made.

There are also cases in which it is considered that water extraction is not recommended. Three of these options occur within the branch of the tree with a water table depth of less than 3.5 m b.g.l., in which case installing wellpoint systems in a non-circular arrangement could be considered. Even though their efficiency is not optimal, they represent an alternative option should the need arise to extract water in a sector with these characteristics. Be that as it may, these cases should be studied in detail. This possibility is simply presented as an alternative in case of extreme necessity.

It should also be noted that the main constraint of wellpoints is the depth of the water table, followed by the large expanse of land needed to install them. In turn, although vertical wells do not require such a large land surface area, their greatest disadvantage lies in the radius of influence and the drawdown in groundwater levels.

Application to a case study

The locality of Cariló (Fig. 1) has no drinking water supply service, and it is divided into a populated sector and another one in which it is planned to extend the urban area. The planning of the use of water resources will be solely for domestic purposes. No hotels, spas, golf courses or any use requiring greater water consumption are allowed to be built.

The DT is applied in the sector that still remains unpopulated and in which the local water administration board intends to design a sustainable groundwater extraction system on the basis of the hydrogeological characteristics that would be capable of meeting the drinking water supply needs. The extraction systems will be located within the future urban grid. The application of the DT led to the planning of a mixed extraction system composed of wellpoints and vertical wells.

The location of the vertical wells was determined. These are the ones that contribute the greatest volumes, following the DT branch that includes a water table depth of over 3.5 m, a freshwater thickness of more than 20 m, a minimum required surface area of 2–3 m^2 and a distance between wells to avoid interference between them greater than 300 m (Fig. 8). This set of wells makes it possible to extract a yield of 2300 m^3 d^{-1}. In Figure 8, the sector that lies between the wells and the coastline would become unfit for a vertical well, because of either the lack of enough distance between wells or aquifer thicknesses of less than 20 m. A similar condition can be observed to the west, near the freshwater–saltwater interface.

According to the constraints recognized in the DT branch in which the water table is lower than 3.5 m and the freshwater thickness is less than 20 m, it is possible to locate six wellpoints towards the coast, considering the 300 m^2 necessary for their installation and the distance between them (Fig. 8). These same conditions, but in the western sector, make it possible to plan the setting up of four more wellpoints. This configuration allows the extraction of 1080 m^3 d^{-1} of water.

Depending on the maximum yields estimated for each system, the arrangement of the vertical wells, together with the wellpoints, allows the extraction of a total of 3380 m^3 d^{-1}. This would make it possible to supply a theoretical peak demand of 1690 inhabitants, which is consistent with the estimated population projection for this area.

The implementation proposal for the DT in the locality of Cariló is a case of a mixed extraction system composed of wellpoints and traditional wells. The implementation of this technique will make it possible to avoid, or at least mitigate, the problems of saline intrusion already identified in other sectors of the district. These are the result of the lack of an adequate hydrogeological criterion for extraction in recent decades, which has caused a progressive decrease in the freshwater reserves available for the entire population of the region.

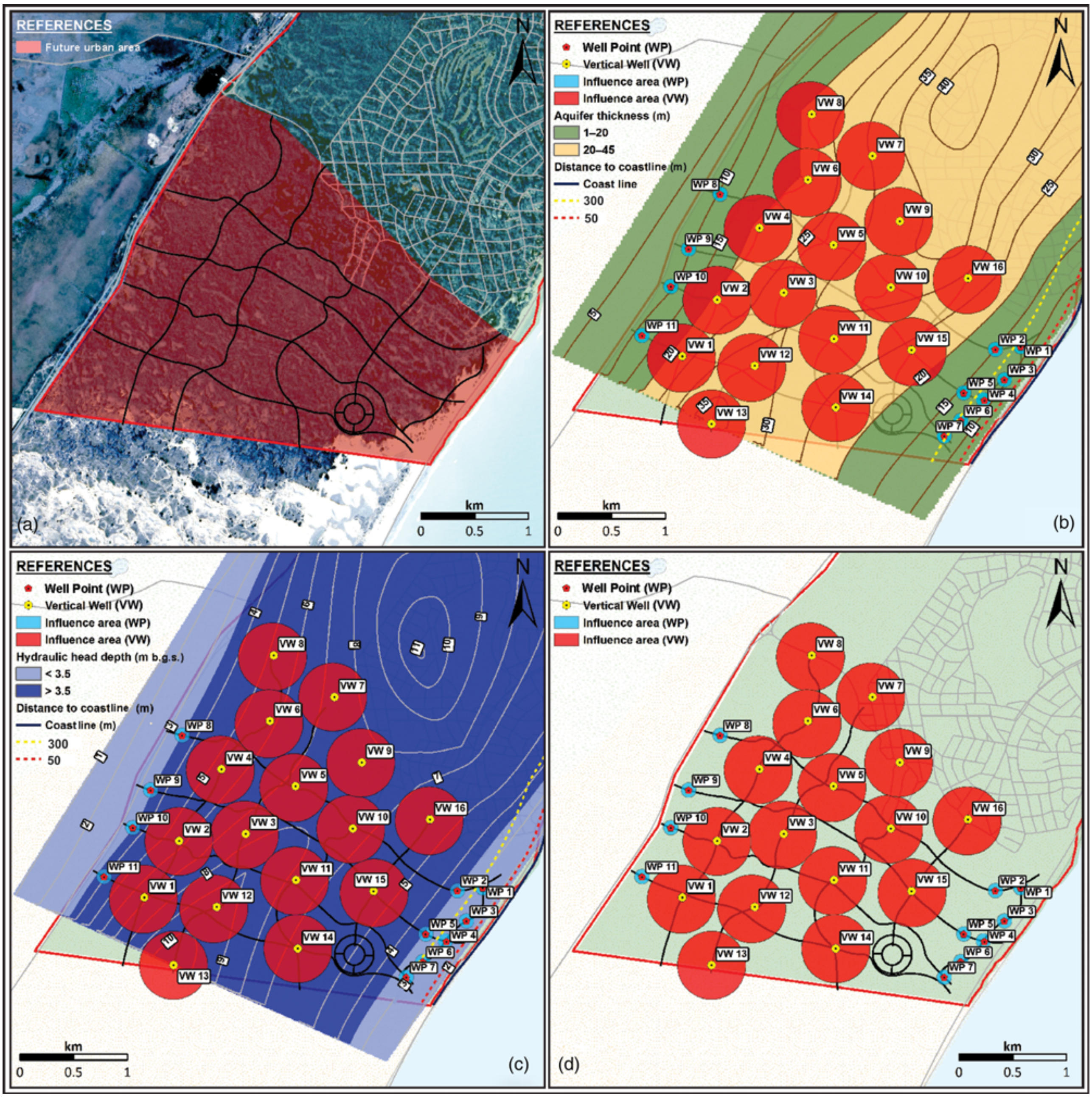

Fig. 8. Maps of the application of the case study in Cariló. (**a**) Future urban area; (**b**) aquifer thickness; (**c**) groundwater depth; (**d**) final arrangement of extraction wells.

Conclusions

To assess the possibilities of extraction of the groundwater occurring in shallow aquifers associated with coastal dunes, two sectors from the eastern coast of the Province of Buenos Aires, Argentina, were analysed. This is the only supply source of drinking water in this region, where a sustainable management of the resources is required to avoid the depletion of the reserves and the degradation of the chemical quality.

At present, in the southern sector, where the freshwater thickness is greater (>20 m), extraction is undertaken by means of vertical wells, whereas in the northern sector, where the thickness is more limited (10 m), wellpoint systems are mainly used. In the former case, the intensive extraction by vertical wells has led to the excessive drawdown of the groundwater levels (over 10 m) with interference between wells. In certain cases, these levels are below sea level, causing the inversion of the hydraulic gradients and salinization processes. In the case of the northern sector, the extraction by means of wellpoint systems has become a feasible option, given that the hydrogeological characteristics do not allow the installation of vertical wells. It is suggested that those areas of the coastal aquifer that are apparently unproductive owing to their limited thickness could be reassessed and the wellpoint system could be used as a method of water extraction.

The results obtained allowed the development of a simple, practical and useful tool for the management of coastal aquifers of limited thickness. A DT is proposed to choose the most adequate extraction system (vertical wells or wellpoints) that would avoid the negative effects of a decrease in reserves and the deterioration of the chemical quality of the water. Such a procedure allows the integration of hydrogeological parameters (water table depth, freshwater thickness, surface area required and distance between wells). This scheme may be of use for decision-makers in less developed countries who are not specialists in hydrogeology, lack sound hydrogeological knowledge and the simulation tools available, and yet must take urgent decisions concerning the supply of water to small localities. This DT may provide them with a basis that would lead to the sustainable management of groundwater.

It is concluded that it is not necessary to commit to a single extraction method, but that the possibility of using mixed extraction systems in the same area must be assessed. In turn, this procedure could be extrapolated to aquifers in coastal dunes with similar geomorphological and hydrogeological conditions.

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