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REPORT

Evolution of groundwater recharge as a result of forest development on the east coast of the province of Buenos Aires, Argentina

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Abstract
Changes in groundwater recharge associated with variations in land use were analysed with a focus on the role of afforestation on the east coast of Buenos Aires, Argentina. The growth of the population related to such changes was considered, linking water consumption to variations in recharge. A multi-temporal analysis was carried out using aerial photographs for the years 1957, 1975, 1981 and 2016, differentiating three types of cover: bare soil, forested soil and grassland. Water balances for each type of land use and groundwater recharge were estimated. In the forested soil, a reduction in recharge over time can be observed and it can be appreciated that forest expansion occurs at the expense of the sand-dune area, which offers the greatest possibilities for infiltration. At present, the water consumption, which depends solely on the groundwater reserves, is lower than the recharge, but this relationship is reversed during the tourist season. According to the estimated projections, the drinking water supply would be compromised in the coming decades, reaching a critical point or level of collapse as from 2070. This proves that it is essential for the policies and projects aiming at afforestation for different purposes to take into consideration the role of this change in land use when assessing the sustainability of the associated water resources.

Keywords Land use · Groundwater recharge · Coastal aquifer · Afforestation · Argentina

Introduction

An afforestation scheme usually has numerous origins. For instance, it could be related to the development of the timber industry or to the stabilisation of sand dunes in coastal areas, or to CO_2 sequestration. On the Atlantic coast of the province of Buenos Aires (Argentina) there was a project related to the timber industry to establish pines on coastal dunes (CFI 1966). The scheme, devised for strictly commercial purposes, was never developed, but it serves as a precedent as regards afforestation projects in the region.

Being partially afforested, aquifers occurring in coastal dunes are freshwater reservoirs, often constituting the only water supply sources to meet demand (Carretero and Kruse 2015). The composition of the main freshwater aquifer is characterised by barrier sands underlain by dune sands with two bounding interfaces: towards the continent, an interface with freshwater–brackish water, and towards the sea, with freshwater and saltwater. The main recharge area occurs in the central portion of the sand-dune barrier; as a result of rainfall excess, the groundwater, which only flows along a short section, discharges in two opposite directions: towards the sea and towards the continental plain. Given the characteristics of these limited groundwater reservoirs, the volume of freshwater reserves that may be used by the population is directly linked to the possibilities of annual recharge from rainwater excess. Therefore, an increase in evapotranspiration will entail a decrease in water excess with infiltration capacity and, thus, a decrease in usable water reserves.

Land-use planning guidelines in Argentina, which date from 1977, stipulate that the creation or expansion of urban centres in dune environments should only be undertaken after their stabilisation and afforestation. On the east coast of the province of Buenos Aires, the typical vegetation is grassland,

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but since the mid-twentieth century there are sectors that have been afforested with conifers (Rodrigues Capítulo 2015; Rodrigues Capítulo and Kruse 2011; Rodrigues Capítulo et al. 2017).

There are different scientific contributions on the consequences of afforestation as regards the water cycle and, in particular, groundwater recharge. In accordance with the regulations of the European Union, in 1996 Ireland launched plans to double the area of reforested land by 2035 (Irish Government 1996). The plan ignores the potential environmental impact of forestry, in particular on groundwater and its quality, since recharge in forest areas may be 10% of the one estimated for grasslands (Allen and Chapman 2001).

Fahey and Jackson (1997) analysed the hydrogeological impact of converting native forest into pine plantations in South Island, New Zealand, and conclude that a reduction in recharge occurred. In the Andean highlands of Ecuador, the use of afforestation is related to agriculture, erosion reduction and atmospheric carbon sequestration. Studies show that the afforestation with pines (*Pinus patula*) reduces water reserves by 50% (Buytaert et al. 2007).

In China, there are programs to increase vegetation cover in order to improve the environment in dry areas and to protect the soil from erosion and sand storms. However, water stress and the increase in competition for water use restrict reforestation. In particular, the reduction of water reserves after afforestation has generated a debate on the approach for its management in dry areas (Wang et al. 2008).

Forest establishment is a method used in sand-dune environments for their stabilisation (Doody 1989; Doody 1991). On occasion, the establishment of conifers leads to the disappearance of native species, as has been the case of 8,000 ha (14%) of dunes in Great Britain (UK). Such a process occurred between 1922 and 1952, when 4,000 ha were afforested (Macdonald 1954). Countries such as Libya have implemented dune stabilisation plans since the 1950s to convert barren parts of the desert into productive areas (Commonwealth Forestry Association 1969).

The lack of hydrogeological information and of monitoring networks affects the study, knowledge and understanding of coastal aquifers in South America, and Argentina also suffers from this shortcoming (Bocanegra et al. 2010; Planas et al. 2000). The alterations caused in the water balance—in particular, in the groundwater recharge possibilities—and, consequently, in the variations in freshwater reserves due to conifer afforestation in coastal areas are not fully known.

In the absence of monitoring networks, the use of other tools to estimate recharge variations, and therefore of fluctuations in freshwater reserves, is necessary. The use of historical aerial photography, together with a water balance that takes into consideration the different land-use types, is a method that may fill such a gap. The aim of this work is to assess the alterations in recharge resulting from changes in land use/land cover (LULC) focusing on the role of afforestation in two areas of the coast of the province of Buenos Aires: Punta Médanos and Pinamar. Besides the changes in land use, the evolution of the population, including projections to 2100, were considered, linking it to the projection of water consumption and recharge variations.

Study area

The study area is located in the eastern sector of the province of Buenos Aires, Argentina. From a hydrogeological perspective, it lies within the Región Costera (Coastal Region; González 2005; Fig. 1). It is composed of aeolian sand bodies that define the interaction between the continental and marine processes (Rodrigues Capítulo 2015), comprising a strip of land with an average width of 3 km, running parallel to the coastline and extending over a surface area of 141 km^2 distributed between Pinamar (65.3 km^2) and Punta Médanos (75.5 km^2). These sand accumulations reach topographic elevations between 35 and 40 m asl (metres above sea level) and stand between a continental plain to the west and the Atlantic Ocean to the east. The continental plain (Fig. 1) has a flat relief, with topographic values below 5 m asl and an average elevation of 4.3 m asl. The dominant landscape is prone to flooding, with clayey soils (vertisols; Soil Survey Staff 2014). In the coastal barrier, the soil development depends on the stability of the sand accumulations and, in general, soils are Typic Torripsamments and Quartzipsamments (Soil Survey Staff 2014).

The landscape has undergone successive anthropogenic interventions in the last 100 years. Such activities have caused constant, progressive alterations of the land configuration. In almost the whole area, the natural topography has been deeply modified, whereas in some sectors, only remnants of the original relief can be observed. The more ancient alterations date from the early twentieth century, when the communications routes were established. The progressive stabilisation of sand dunes by means of the introduction of exotic forestry species has been a consistent practice throughout the last 80 years (Copello and Ramos 2015). Other, more recent, alterations are associated with golf courses and polo fields, the impermeabilisation of the surface in urban areas and the encroachment of real estate ventures (REV; Rodrigues Capítulo et al. 2017).

The hydrogeological system reflects the evolution of the coast, associated with transgressive and regressive processes with lateral variations in the sedimentation, both in thickness and in lithological composition. The different aquifer units are in hydraulic continuity, as there are variable connections between them, depending on the occurrence of aquitards and their thickness variations (Rodrigues Capítulo 2015; Rodrigues Capítulo and Kruse 2017).

Fig. 1 Study area: Location and geomorphological map

The climate, according to Thornthwaite's (1948) classification, is humid mesothermal little or no water deficiency ($B_2B'_2ra'$). The mean annual precipitation is of the order of 900 mm. The monthly rainfall distribution is relatively uniform along the year, with an average value of 76 mm/month and a slight increase during the hottest months. The temperature range between the warmest and coldest months is approximately 14 °C, whereas the mean annual temperature is 14.5 °C (Rodrigues Capítulo 2015). The LULC types, which include forests, urban settlements and sand dunes with little or no vegetation, show different infiltration conditions. Recharge occurs exclusively from precipitations and water flows downward from the water table to the underlying aquifer system.

The groundwater flow pattern is represented by equipotential curves parallel to the coast, with a groundwater divide that tends to coincide with the maximum topographic highs and groundwater flow directions towards the east (sea) and west (continent), with hydraulic gradients ranging from 1 to 4 m/km (Rodrigues Capítulo 2015).

The drinking water supply is exclusively collected from groundwater sources. In Pinamar, the population is served by means of a system operated by a sanitation service provider, whereas in Punta Médanos, it is supplied by domestic wells (Carretero et al. 2020). Some of the wells drilled in areas afforested between 1980 and 1990 are out of service as a result of the marked lowering of the water table. Such a condition makes it possible to infer the effect that afforestation has had on the lowering of the groundwater levels, which was a starting point for this work.

Materials and methods

As the development of afforestation dates back to the 1940s, it was necessary to use aerial photography instead of satellite imaging, since these date from the late 1970s. Besides, the resolution that can be achieved with photographs is higher than the one of the Landsat images available for the earlier dates and the first high-resolution satellite products did not include the period of interest. The photographs were mosaicked together and processed using a geographic information system (GIS), subsequently undertaking a supervised classification to differentiate LULC. The areas for each previously defined LULC type were identified and the water balance surplus was assigned as recharge for each case. Water consumption and its future projections were estimated to assess the availability of the water resources.

Aerial photography

Data and classification

Aerial photographs of the Ministerio de Infraestructura y Servicios Públicos de la Provincia de Buenos Aires (Ministry of Infrastructure and Public Works of the Province of Buenos Aires) were compiled (Table 1). The area covered extends from Punta Médanos (36°53′53.76″S, 56°40′54.55″ W) to Pinamar (37°12′33.66″S, 56°56′30.24″W), covering a total surface area of 141 km^2.

In order to analyse the different LULCs, it was necessary to process the photographs beforehand. A graphics software was used to adjust the enhancement, brightness and contrast of each of the images; then, photomosaics for 1957, 1975, 1981 and 2016 were constructed. Finally, a GIS was created, making it possible to georeference and spatially integrate the images based on 40 control points per mosaic, according to a planar map projection system (Gauss-Krüger, zone 6).

A supervised classification was undertaken to differentiate each type of LULC, and the output resulted in a raster image for each case. The land cover classification was based on the spectral characteristics. It should be noted that a large amount of fieldwork data was available, collected in a succession of field trips. In order to validate each class, approximately 260 control points were used.

According to the objectives, and based on images and field surveys, three types of LULC were distinguished: forested soil, bare soil and grassland. The surface area for each type of LULC was calculated. The lLULC changes in the sand dunes were assessed, estimating the surface area of such changes and the variations in percentage for each LULC. The variations were analysed, taking into consideration the entire area and considering Pinamar and Punta Médanos separately.

Classification accuracy assessment

Error matrices were constructed for the four supervised classifications carried out, and the producer's and user's accuracy for each LULC type were calculated.

Table 1 Aerial photographs (Ministerio de Infraestructura y Servicios Públicos de la Provincia de Buenos Aires)

Period	Scale	No. of photos
1957	1:15,000	54
1975	1:20,000	32
1981	1:20,000	32
2016	1:5000	56

Water balance

The water balances were calculated by the Thornthwaite and Mather (1955) method, based on the precipitation data obtained from the weather station of the Servicio Meteorológico Nacional (SMN; National Weather Service) in Villa Gesell. The daily data correspond to the period 1997–2016, which is considered to be representative of the rainfall in the region since the average precipitation, as the only source of supply to the water system, has remained the same over time; therefore, it would not be responsible for the variations in groundwater reserves (Carretero and Kruse 2010; Carretero and Kruse 2012). Interception was assumed to be contributing 100% to evapotranspiration. Due to the fact that the records of the weather stations in the area are not very extensive, in order to verify the variability of the mean annual precipitations, the records of two stations that are not located in the study area were used (Dolores and Punta Indio), as they are subjected to the regional climate patterns. The mean annual precipitation (1925–2008) is 929 mm/year in Dolores and 965 mm/year in Punta Indio. In Fig. 2, the annual series is shown; in both cases a slight positive trend can be observed. According to these conditions, precipitation as a source of supply to the hydrological system has, on average, remained constant or shown a negligible rise. This supports the hypothesis regarding the limited variation in mean annual precipitation in the period analysed.

The mean monthly temperatures have remained relatively constant throughout the decades studied (Fig. 3). Otherwise, an increase in temperature would reduce the potential for groundwater recharge. This possibility has also been rejected as a cause of the decreasing recharge in the study area.

Mean daily reference evapotranspiration ($\mathrm{ET_o}$) values were used. The $\mathrm{ET_o}$ may be estimated using the FAO Penman–Monteith equation (Allen et al. 1998) and, subsequently, the $\mathrm{ET_c}$ may be calculated by means of Eq. (1):

$$\mathrm{ET_c} = \mathrm{ET_o} \times K_\mathrm{c} \tag{1}$$

where $\mathrm{ET_c}$ is the maximum evapotranspiration of the cover; $\mathrm{ET_o}$ is the reference evapotranspiration and K_c is the crop or cover coefficient.

Whenever there was no crop or vegetation cover, a specific K_c value for bare soil was assigned. The mean field capacity (FC) value adopted for this sand-dominated soil was 160 mm/m, following Falasca and Forte Lay (2006) and Forte Lay and Spescha (2001), who set a value between 140 and 180 mm up to a depth of 1 m along the entire coastal sand-dune barrier. Three cases were considered: bare soil (loose sand lacking plants or roots), soil covered by a conifer forest and grassland. In the first case, the effective depth assigned for the water balance was 0.25 m and so a FC of 40 mm was set, since

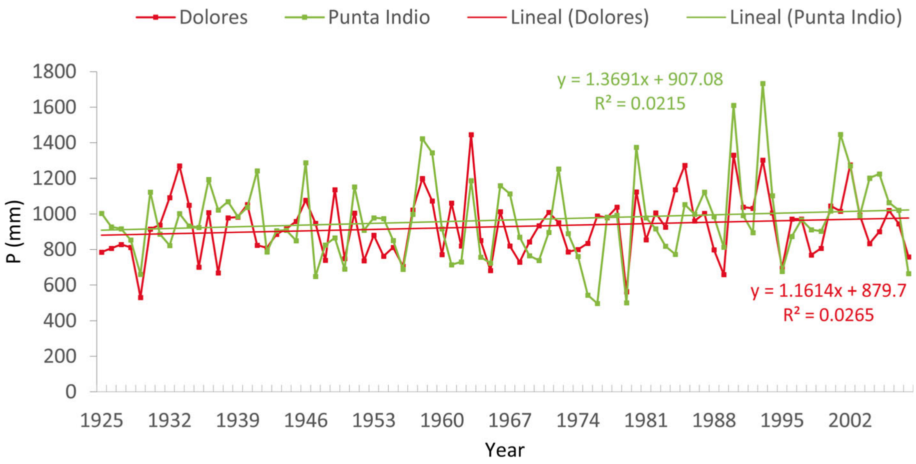


Fig. 2 Historical series of annual precipitation for two weather stations in the region (1925–2008)

the effect of evapotranspiration cannot penetrate any further. As regards the second case, a root exploration of over 1 m deep had to be taken into account, since it is a well-established forest; therefore, in the water balance, a depth of 1.25 m—corresponding to a FC of 200 mm—was considered. In this area, water table is at a depth of over 6 m bgl. (Rodrigues Capítulo 2015) and the forest roots do not reach the groundwater (Sudmeyer et al. 2004). In the third case, which is a grassland, the value adopted for root exploration depth reaches 0.62 m; accordingly, the FC is 100 mm. Water holding capacity for different LULC types is shown in Table 2, and the K_c values for each LULC type in Fig. 2.

The guidelines proposed by FAO (Allen et al. 1998) were used to determine the K_c values. According to this procedure, the relationship between ET_o and K_c is graphically represented for different wetting intervals, making it possible to infer the monthly K_c values along the year. The K_c values applied to the bare soil were obtained from such a graph (Fig. 4). For the soil with a conifer forest cover, a K_c value of 1 throughout the year was assigned, so ET_c and ET_o were similar in this specific case. According to FAO (Allen et al. 1998), "conifers exhibit substantial stomatal control due to reduced aerodynamic resistance. The K_c can easily reduce below the values presented, which represent well-watered conditions for large forests". Because of the climatic conditions of the study area, a K_c equal to 1 is the appropriate value to be used. In the case of the grassland, a K_c of 1 was also adopted, since, according to Falasca and Forte Lay (2006), it is the most advisable option if the objective is to calculate the water balance of a permanent, continuously growing grassland with relatively low grasses in the region.

Due to the characteristics of the soils and the lack of surface runoff, it is considered that the water balance surplus is directly transformed into recharge. The negligible value of the surface runoff can be verified from the lack of a drainage network, riverbeds and water erosion features. Roads in urban areas, which are sandy, are not asphalted. An infiltration rate of 130 mm/h was estimated for Pinamar (INTA 2016), which supports the limited significance of the surface runoff in favour of greater infiltration.

This condition makes it possible to infer that, when precipitation completely saturates the soil field capacity, the surplus rapidly translates into water excess capable of reaching the

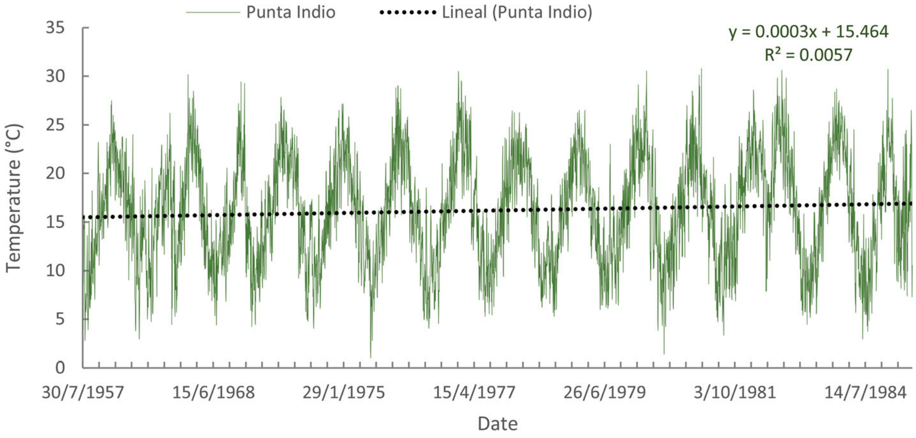


Fig. 3 Historical series of temperature for the Punta Indio station (1957–1991)

Table 2 Water holding capacity for different LULC types

Land Use/land cover	Water holding capacity (mm)			
	Field capacity	Wilting point	Available water capacity	Saturation
Bare soil	40	16	24	80
Grassland	100	40	60	200
Forested	200	80	120	400

water table close to the surface, becoming direct recharge to the aquifer.

The ET_o and K_c values adopted were processed with the AGROAGUA v.5.0 software (Forte Lay et al. 1995). Daily water balances and the continuous monitoring of the soil water storage may be undertaken with this application, using variables such as soil field capacity, daily potential evapotranspiration and daily rainfall.

Population and water consumption

In the study area, the main economic activity is tourism; there are no factories, no cattle farming, agriculture or any other important activities, which is why water use is regarded as being exclusive for human consumption.

The daily water consumption associated with the evolution of the population of Pinamar was calculated according to the results of the INDEC national censuses, 1980, 1991, 2001 and 2010, with 4,977; 7,987; 11,366 and 70,033 inhabitants, respectively (INDEC, 1980, 1991, 2001, 2010). A projection to 2100 was estimated, using a factor of 2.24 to calculate the population growth rate on the basis of the trends observed. It was not possible to obtain population values for 1957 and 1975, as the municipality was created in 1978. In the cases of 1981 and 2016, the water consumption of the tourist influx was added to this calculation, based on data provided by the Secretaría de Turismo, Cultura y Educación, Municipalidad de Pinamar (Department of Tourism, Culture and Education, Town Council of Pinamar 2015). The tourist season extends from December to March and, in order to determine a future trend, the number of visitors was considered as a constant over time.

There are no population data for Punta Médanos; besides, urbanisation is recent and, therefore, in this case, the information in the master plan of the REV was considered (ARBA 2015). A population of 30% of the planned number of inhabitants has been living at the site since 2016, by 2020 it is projected to rise to 50%, and the total number of inhabitants will be reached by 2030.

If the land-use evolution is considered, and taking into account the rest of the area only occupied by sand dunes, the surface area that will be devoted to forests and REV between 2030 and 2100 was estimated, following the development model of the REV. Continuing along this line, a projection was made from 2030 to 2100, using the average population density of the existing REV as a parameter and predicting a proportional increase over the years.

The total water consumption was estimated for the REV based on the population projected and considering an average consumption of 200 L/day (Planas et al. 2000). The irrigation water values were calculated following Domene and Saurí (2006) and Hof and Schmitt (2011). These authors establish that the volume of water for the irrigation of gardens fluctuates between 40 and 50% of the indoor water consumption. In the REV with golf courses, there is an extra consumption of more than 500 m^3/day. A generalisation was made following Durán Valsero et al. (2001) and Lyman (2012), who calculated a mean irrigation value for the standard surface area of an 18-hole golf course. The rate of recharge variation between 1981 and 2016 was chosen to make a projection that would

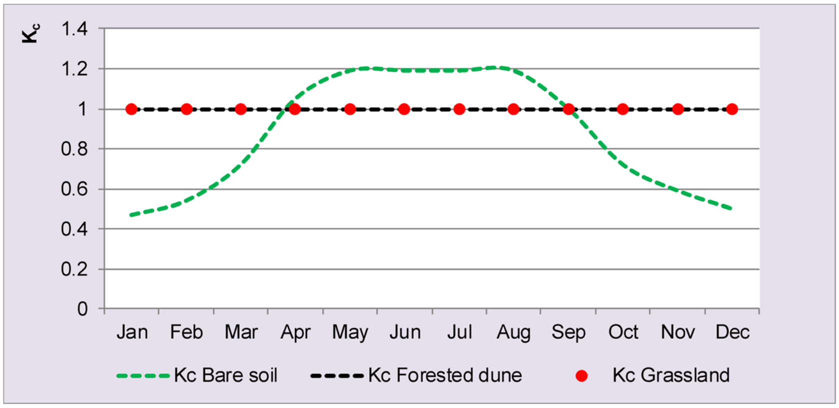


Fig. 4 Crop or cover coefficient (K_c) values for different land use/land cover (LULC) types

accompany the evolution of the population and the water consumption. The value estimated for Pinamar resulted in a reduction of 0.55% a year, whereas in the case of Punta Médanos, of 0.34%.

Results

Land-use types

As stated above, depending on the LULC, three units can be recognised: forested, bare soil and grassland.

The forested sector (Fig. 5a) has conifers of the species *Pinus pinaster*, *P. radiata*, *P. pinea* and, to a lesser extent, *P. halepensis*. The average heights are over 40 m, whereas on the basis of the ages it is possible to distinguish two types of forests, the younger ones of less 30 years and the mature ones of over 50 years, with the latter group being the most widely distributed. There are complementary species of acacias (*Acacia longifolia*) and tamarisks (*Tamarix gallica*).

The grassland sector (Fig. 5b) corresponds to the sand dunes, where the native vegetation has grown; this vegetation is capable of retaining sand. This process of stabilisation represents the natural evolution of the mobile dune towards the fixed dune. This landscape may also be observed in areas in which there is a greater moisture content, for instance, in the interdunes.

The bare soil is composed of transverse dunes, barchans, barchanoid ridges and parabolic dunes (Fig. 5c). The geometry of these bodies is characterised by extended southeast-facing stoss slopes, whereas the lee slopes or slip faces can be identified by their high angle, in certain cases being vertical. In the north, these bodies develop perpendicularly to the coastline. These landforms tend to decrease in height and lose their typical geometry as they approach the sea. In the coastal areas, these sand accumulations appear as stabilised dunes fixed by shrub communities, with *Acacia longifolia, Adesmia incana, T. gallica* and *Myoporum laetum* being the dominant species.

Land-use evolution

According to the accuracy assessment conducted, good results have been obtained (Table 3); therefore, the supervised classification carried out is valid and representative of the LULC defined. The LULC evolution is shown in the maps for the periods 1957, 1975, 1981 and 2016 (Fig. 6).

Figure 7 shows the relationships between LULC changes. There is an overall increase in grassland and forested soil. In 1957, almost one third of the surface area corresponded to bare soil, followed by grassland and forested soil. In 1975

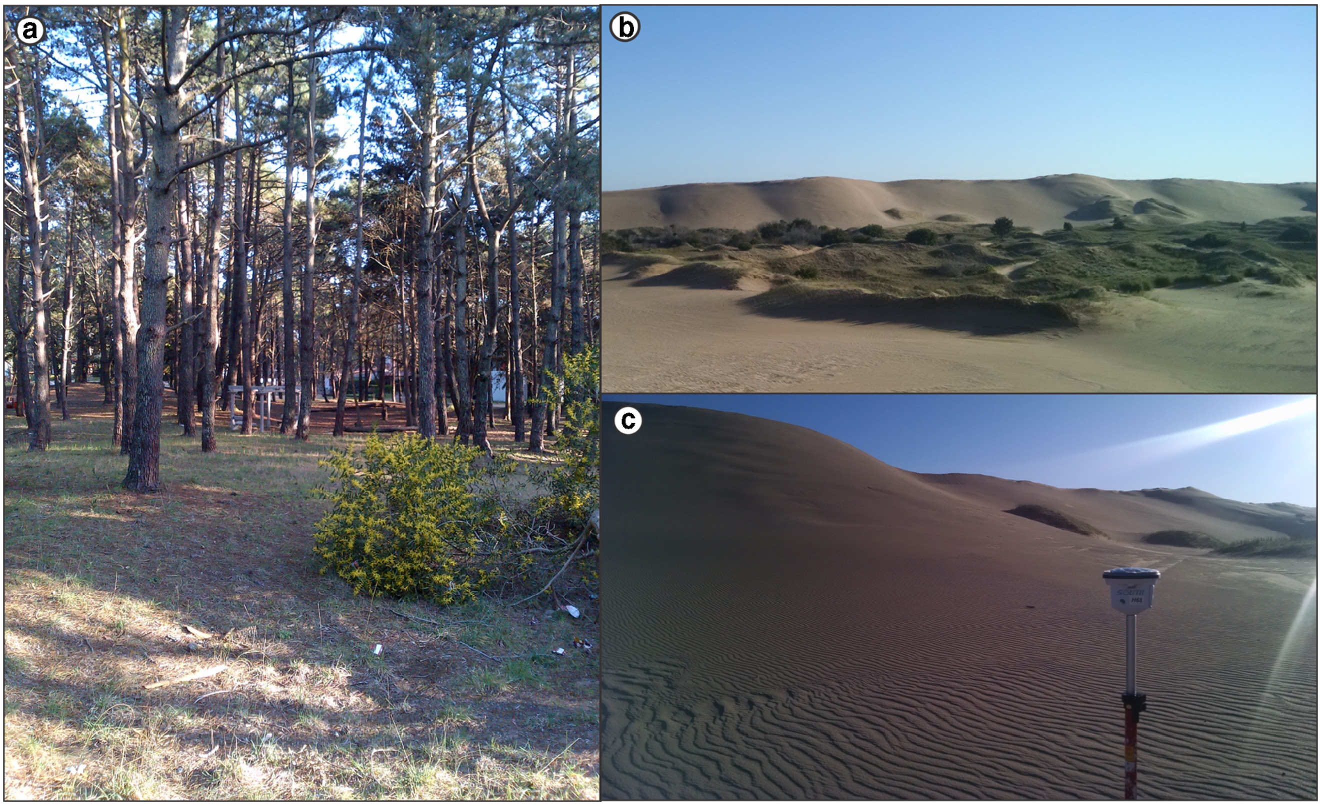


Fig. 5 LULC types: **a** forested soil, **b** grassland, **c** bare soil

Table 3 Producer's and user's accuracy for the supervised classifications carried out

Year	(%)	Bare soil	Grassland	Forested
1957	Producer's accuracy	78	94	96
	User's accuracy	99	81	80
1975	Producer's accuracy	90	99	95
	User's accuracy	93	93	98
1981	Producer's accuracy	84	80	87
	User's accuracy	97	54	92
2016	Producer's accuracy	96	88	88
	User's accuracy	90	81	99

and 1981, there was an increase in forest cover, whereas the grassland remains constant. The distribution for 2016 shows a dominance of forest cover over grassland and bare soil.

There is an increase in forest cover throughout the period analysed (Fig. 7). Between 1975 and 1981, a significant increase from 6 to 12% can be observed, resulting from the emergence of REV in the central sector of Punta Médanos. In 2016, the forest cover was denser, reaching almost 30% of the area and separated by bare soil areas of increasingly smaller extension.

In Pinamar, the increase in forest cover is characterised by a progressive expansion and densification. In the period 1957–1975, the increase is from 6.6 to 18.7%, then it comes to a standstill between 1975 and 1981, and by 2016 more than half of Pinamar (53.3%) is covered by forest. In both sectors, there is no great variability in the evolution of the grassland; therefore, it can be inferred that the increase in the forested area is caused by the decrease in bare soil.

The most recent aerial photographs make it possible to recognise a new LULC connected to the REV, related to the creation of small artificial lakes fed by wells. Such interventions have become common practice in REV for recreational purposes, in accordance with the concept of "environmental amenities".

Water balance and evolution of recharge associated with LULC

A daily time-step water balance was calculated for the different types of LULC. Precipitation and water surpluses for forested soil, grassland and bare soil during the period January 1997–December 2016 are shown in Fig. 8a–c. The mean annual precipitation was 929.4 mm and the mean annual water surpluses were 223.4, 275.1 and 422.3 mm, respectively. These values make it possible to infer the effect that the different LULC types have on water surplus. Evapotranspiration in the forested soil causes a decrease in the water surplus of the order of 34.8% with respect to the grassland and of 47.1% to the bare soil.

Variations in recharge are associated with the changes in LULC (Table 4). In Pinamar, recharge in the sand dune decreased from 19 hm^3 in 1957 to 6 hm^3 in 2016, which represents a reduction of 66%. In the grassland, it has changed from 7 to 5 hm^3, whereas in the forested sector, the recharge volume went from 1 to 8 hm^3. The latter change is only apparent, as it is due to the increase in the surface area for this LULC. Even though it was the sector with greater expansion, it is the one with the lowest values of surpluses becoming recharge. The total recharge for Pinamar from 1957 to 2016 showed a 24% reduction, going from 26 to 20 hm^3 in almost 60 years.

In Punta Médanos, the recharge in the sand dune was 20 hm^3 in 1957, decreasing to 9 hm^3 by 2016, with the reduction being 52%. In the grassland, the recharge has changed from 4 to 6 hm^3. The increase in the surface area of the forests was from 3 to 19 km^2, resulting in an increase in recharge from 1 to 4 hm^3 between 1957 and 2016.

If the two sectors are compared, Pinamar had a greater increase in forest cover than Punta Médanos, as well as a greater reduction of the sand-dune area. This leads to a greater reduction in recharge, i.e., 24 and 19% for the first and second sectors, respectively.

In the entire area, the recharge in the sand dune was reduced by 61%, decreasing from 40 to 16 hm^3 between 1957 and 2016. The greater loss (59%) occurred from 1981 to 2016. The forest cover increased more than 600% and the recharge changed from 2 to 12 hm^3. The changes in the grassland were not evident and the recharge values remained similar (9 and 11 hm^3). It can be observed that the growth of the forest occurs at the expense of the loss of the bare soil area. It was assumed that the entire area is represented by the sand-dune environment. Thus, if a quantification of the recharge was performed, before afforestation and urbanisation, the value would be 58 hm^3 for the total area of 141 km^2. On the other hand, if it were completely occupied by forest cover, it would be 29 hm^3, resulting in a 49% decrease.

Evolution of recharge vs consumption

The population increase is associated with water use and consumption. The changes in LULC detected led to reductions in recharge and, consequently, in freshwater reserves. It is worth recalling that, in this region, groundwater is the only resource available to supply the urban centres. That is why any changes in LULC entail changes in the recharge to the aquifer and in the volume of water available to the population, whether of locals or tourists. Decreases in recharge, together with increases in water use, lead to the disturbance of the water cycle.

The evolution of recharge and water consumption indicate that in Pinamar the recharge in 1981 was 24.6 hm^3/year, whereas the consumption was 4.9 hm^3/year. At present, such

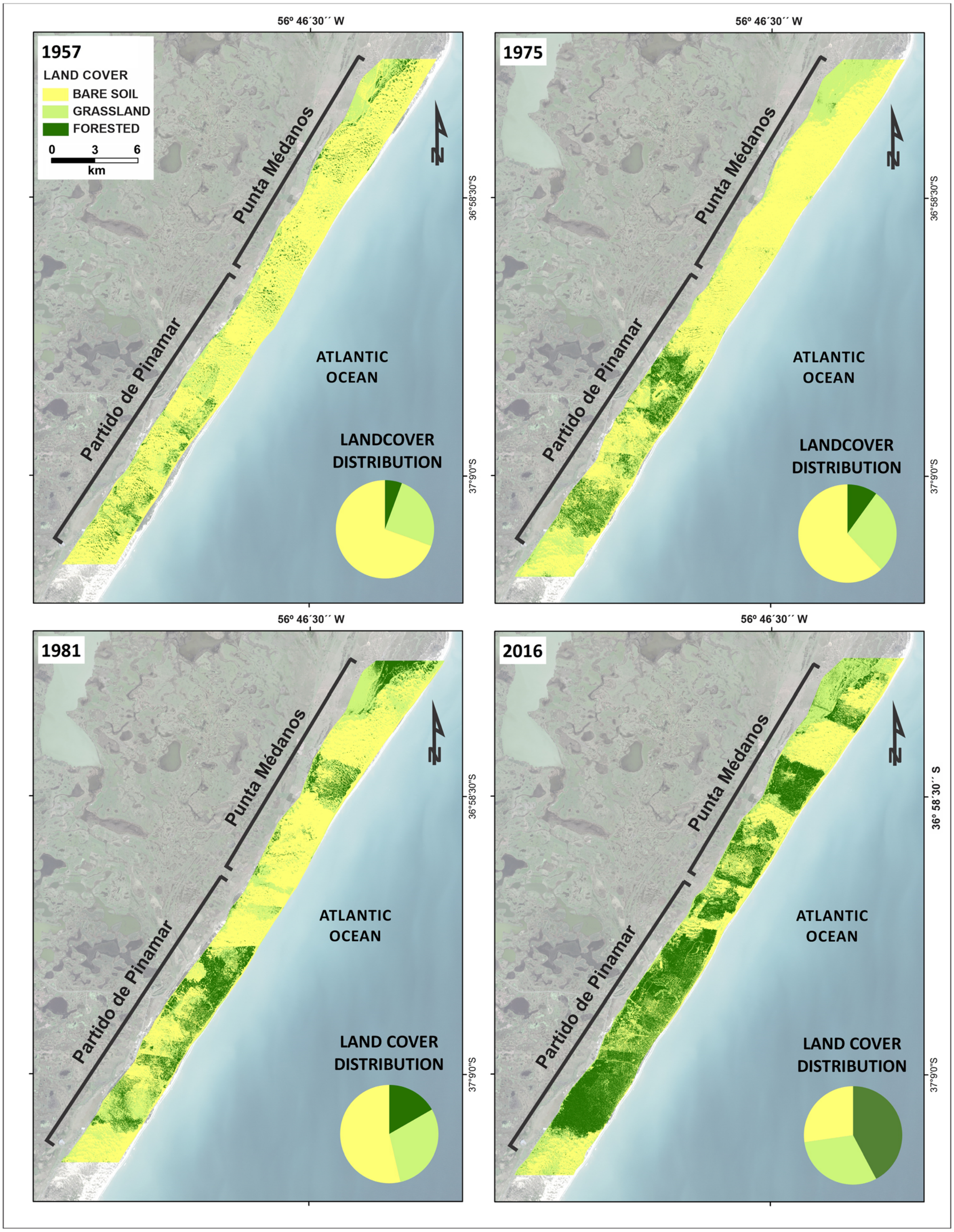


Fig. 6 Temporal evolution of LULC changes: forested soil, grassland and bare soil (1957, 1975, 1981 and 2016)

values are 19.9 and 10.8 hm^3/year, respectively, which represents a reduction in recharge of 19% and an increase in use of more than 200%. A projection to 2100 shows that as from 2070 the consumption would exceed the recharge and from then on the supply to the population would be compromised due to the depletion of the water resources (Fig. 9a). The recharge would decrease around 50%, whereas the consumption would increase 400% in somewhat less than 100 years.

Figure 9b shows the special case constituted by the four months of intensive use of water in the summer season. During the September 2015–August 2016 hydrological year, the consumption exceeded the recharge from December to

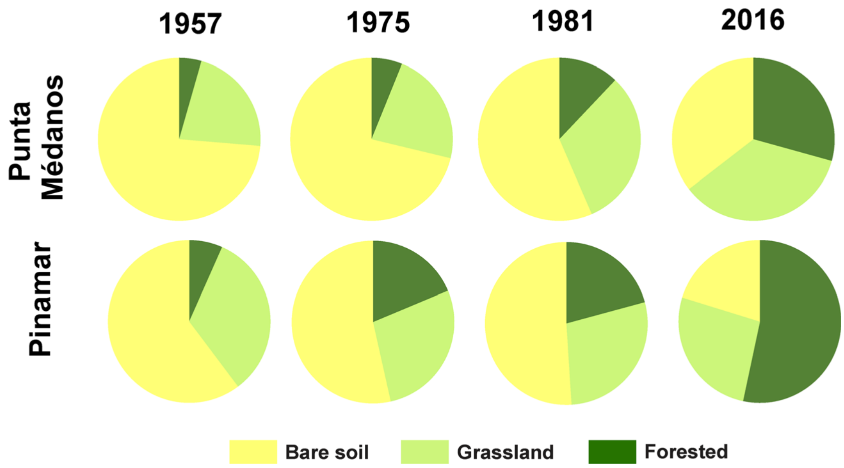


Fig. 7 Evolution of LULC for Pinamar and Punta Médanos

March, with January being the month with the greatest deficit. Even though it may seem that the hydrological system is capable of supplying the current stable population without difficulty, this situation is radically altered by the tourist

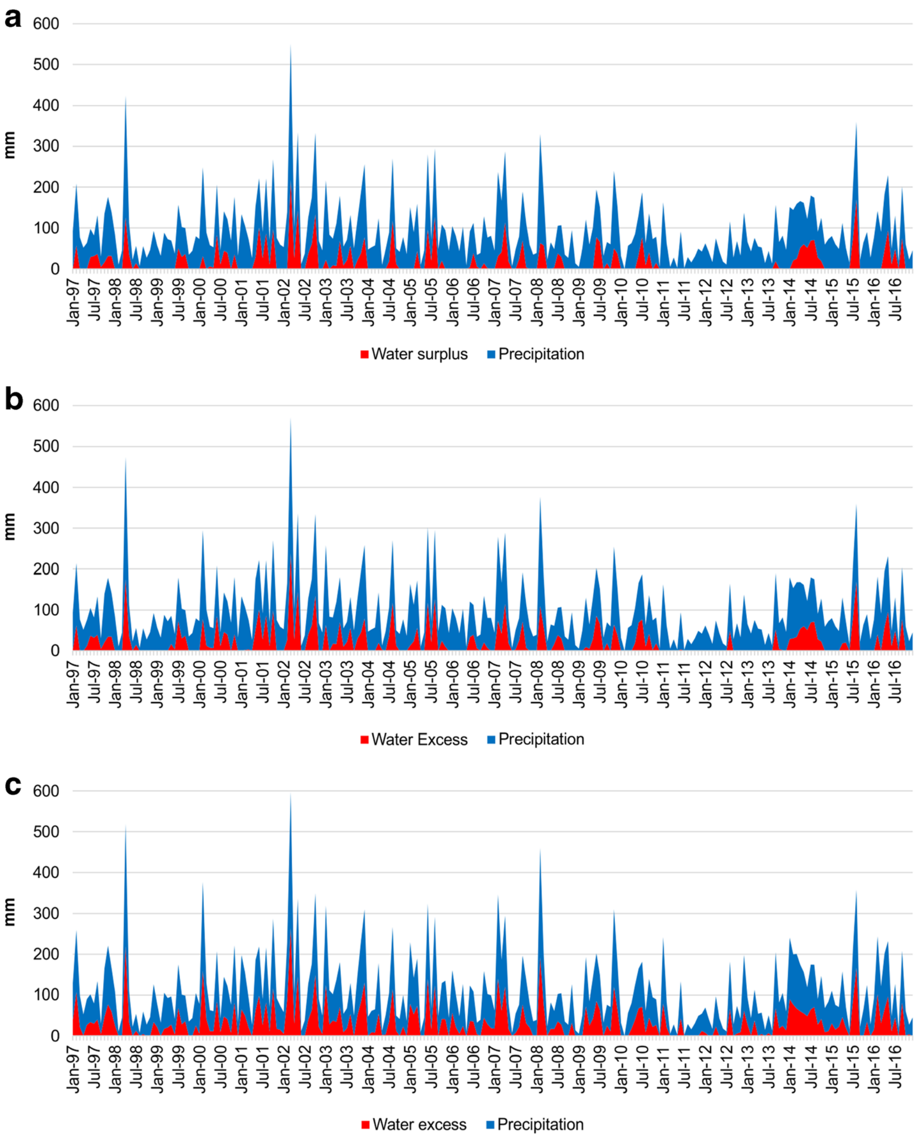


Fig. 8 Monthly water surpluses for **a** forested soil, **b** grassland and **c** bare soil

Table 4 Surface area, recharge and percentage variations for Pinamar, Punta Médanos and the entire study area. The variation in area and recharge are proportional for each LULC; the percentage of variation is the same for both. Totals are in *italic*

Location	LULC	Area (km^2)				Recharge (hm^3)				Variation (%)			
		1957	1975	1981	2016	1957	1975	1981	2016	1957–1975	1975–1981	1981–2016	2016–1957
Pinamar	Forested	5	14	16	40	1	3	3	8	181	11	157	702
	Grassland	25	21	21	20	7	6	6	5	−16	1	−6	−20
	Bare soil	46	40	39	15	19	17	16	6	−11	−5	−60	−66
	Total	*76*	*76*	*76*	*76*	*26*	*25*	*25*	*20*	*−5*	*−1*	*−19*	*−24*
Punta Médanos	Forested	3	4	8	19	1	1	2	4	38	97	143	561
	Grassland	14	15	21	23	4	4	5	6	3	39	12	61
	Bare soil	48	47	37	23	20	19	15	9	−3	−21	−37	−52
	Total	*65*	*65*	*65*	*65*	*24*	*24*	*22*	*19*	*−1*	*−7*	*−12*	*−19*
Total area	Forested	8	14	24	59	2	3	5	12	77	68	152	651
	Grassland	35	40	42	43	9	10	11	11	13	6	3	23
	Bare soil	98	87	76	38	40	36	31	16	−11	−13	−49	−61
	Total	*141*	*141*	*141*	*141*	*51*	*49*	*47*	*39*	*−4*	*−4*	*−16*	*−23*

influx. This scenario coincides, besides, with the lowest recharge values of the year.

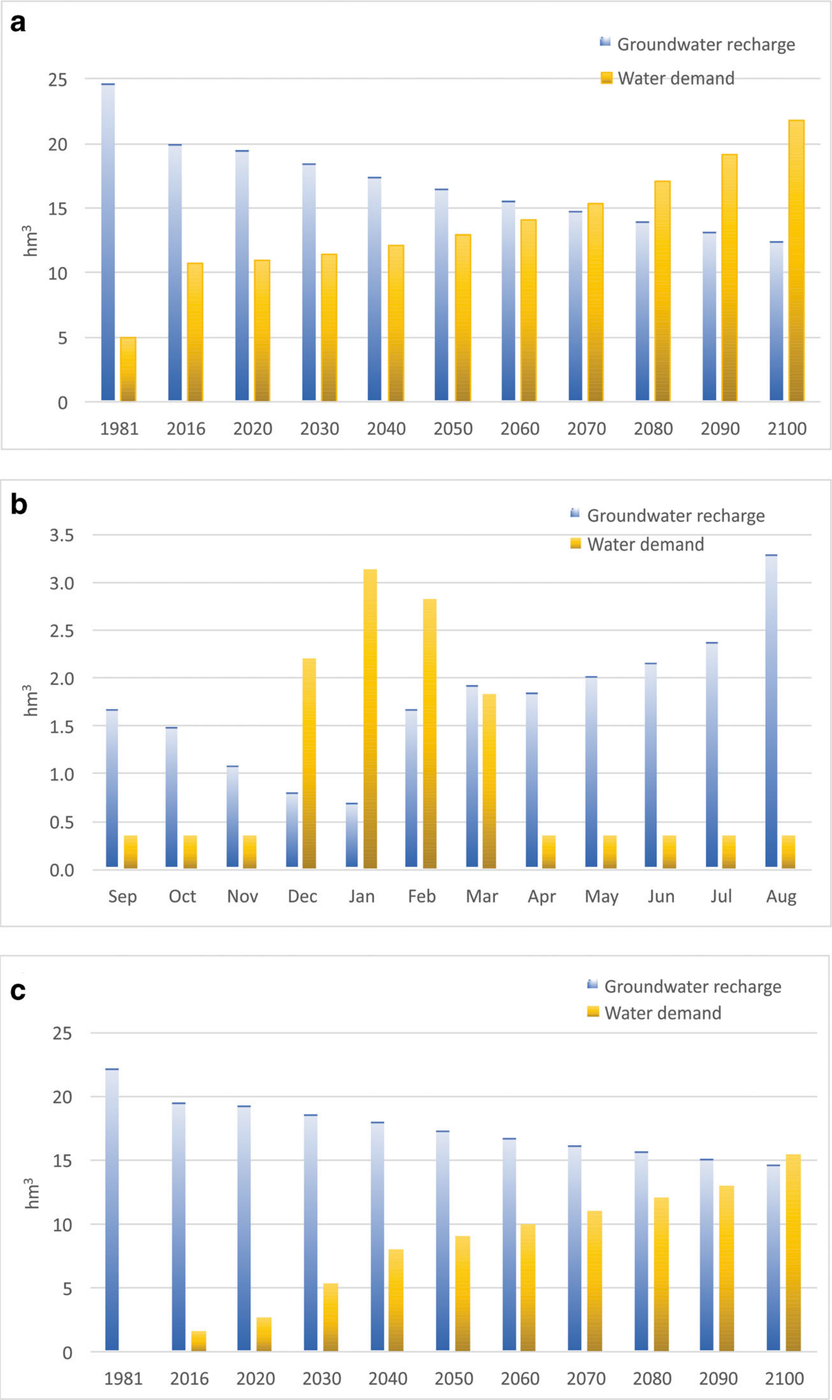
In Punta Médanos (Fig. 9c), the growth of REV occurred after 2000, which is why any prior consumption is considered as zero. The projection to 2030, when the present-day REV is supposed to be at 100% of their capacity to accommodate the population, shows a consumption of 5.3 hm^3/year with a recharge of 18.5 hm^3/year. When the expansion of the urbanisation and afforestation is projected onto the rest of the land characterised by the bare soil, by 2100 the consumption may exceed the recharge.

By 2100, in both sectors, the water consumption exceeds the recharge. This phenomenon could occur earlier if there are periods of lower water surpluses, since a possible increase in the mean temperatures, and therefore of evapotranspiration, would result in lower recharge values and a more premature water stress situation. However, in the projections estimated for the coastal areas and the Argentine Sea in the Tercera Comunicación Nacional de la República Argentina a la Convención Marco de las Naciones Unidas sobre Cambio Climático (Third National Communciation to the United Nations Framework Convention on Climate Change for Argentina) (Secretaría de Ambiente y Desarrollo Sustentable 2015), the changes in air temperature—closely related to the sea surface temperature—are smaller for the Argentine Sea than for the continental mainland for every scenario and time horizon in the twenty-first century, forecasting for the near future (2015–2039) increases of less than 0.5 °C with respect to the period 1981–2005. The changes in precipitation would not be very relevant either, with projections of 10% reductions and increases in annual precipitation. Under these scenarios, the possible changes in the ocean ecosystem would be more related to the local impact of anthropogenic activities than to the effects of climate change.

Discussion

When the recharge phenomenon is studied in urban areas, a controversy arises, since, even though impervious surfaces reduce infiltration, there may be a process of infiltration in surfaces with secondary permeability (i.e. deteriorated road surfaces). Added to this, there may be irrigation of green spaces and losses in the water supply network, which would increase the recharge in urban areas. This phenomenon is frequently described in urban contexts (Hibbs and Sharp 2012; Lerner 2002; Sharp 2010; Sharp et al. 2013; Wiles and Sharp 2008) and also in nearby areas in the province of Buenos Aires (Kruse et al. 2013). These processes have not been observed in urban areas in the north coast of Buenos Aires (Carretero et al. 2014) or in those affected by afforestation (Punta Médanos and Pinamar). It may be the case that such a phenomenon is not present in this area due to the time of settlement of the urban centres. These localities were founded in the mid-1900s, and the significant population growth was only recorded in the 1980s. The sewage systems and drinking water networks, where available, are relatively recent and in general are in good working order, which is why they would not cause water losses to ground and therefore would not cause a rise in the water table.

Fig. 9 Evolution of recharge and water demand: **a** Pinamar, projection to year 2100; **b** Pinamar, September 2015–August 2016 hydrological year; **c** Punta Médanos, projection to year 2100



In a sector situated in the north of the study area in the sandy coast of Buenos Aires (Carretero et al. 2014), the variations in LULC between 1973 and 2010 were analysed using Landsat images and the modifications in recharge to the aquifer as a consequence of urbanisation were assessed. A reduction of 10% in the recharge volume was observed if the total area is considered, whereas in the case analysed—mainly as a consequence of afforestation—the reduction varied between 19% in Punta Médanos and 24% in Pinamar. From the perspective of the main urban areas in the district, the recharge reduction in San Bernardo-Mar de Ajó was approximately 25%, while in San Clemente and Las Toninas-Mar del Tuyú it was about 18%. The variations for the period 1987–2012 were the focus of previous work (Carretero et al. 2013): similar values were found for San Clemente (21%), with the values for Las Toninas-Santa Teresita being slightly higher (30%).

Both studies were undertaken in the same sand-dune barrier. In one case, the decrease in recharge is connected to the encroachment of urbanisation, whereas in the other it is the consequence of the establishment of nonnative forests, which substituted the bare soil. If the value of the decrease in reserves (10%) over the entire surface area of the study in Carretero et al. (2014) is compared to the ones in the present work (19 and 24%), it would seem that the effect of afforestation on the water cycle is much greater than the one caused by urban growth. However, if the focus is placed on the reduction in recharge values in urban areas (18–30%), the effect of urbanisation (imperviousness) would be higher than the one of afforestation.

Nevertheless, the decrease in recharge due to afforestation is not insignificant; in studies carried out in other regions, even higher values have been obtained than the ones presented for the coast of Buenos Aires (19 and 24%). Such would be the case for Ecuador, which reaches 50% (Buytaert et al. 2007) and New Zealand, with 27% (Fahey and Jackson 1997), whereas in Ireland such a value would be 10% (Allen and Chapman 2001). In such cases, the studies were conducted in areas that had undergone reforestation and in environments different from the one in the coastal area. However, in Marina Romea, Ravenna, Italy, Mollema et al. (2013) calculated the transpiration rate of pine trees (*P. pinea*); the resulting tree transpiration is much greater than precipitation. According to these calculations, there would not be much water available to recharge the freshwater lenses that compose the coastal aquifer in that region.

The projection to 2100, following the current trends, indicates that the water consumption would exceed the recharge 1.6 times in the aforementioned northern sector (Carretero et al. 2014). In the cases studied here, this relationship would be 1.1 in Punta Médanos and 1.8 in Pinamar, indicating that in the latter locality the water supply may be more deeply affected.

Population growth is associated with the use and consumption of water. It is a priority to protect the coastal dunes and to manage the water resources stored in them in a sustainable manner. Cases of groundwater overexploitation have been studied, for example, in China, the Middle East, northern Africa, Saudi Arabia and the US, where important decreases in the water table could be observed (Backman et al. 2007; Hoque et al. 2007; Howard and Gelo 2002). Obviously, in coastal areas, the depletion of reserves entails a greater risk, such as saltwater intrusion—a process that has already been detected in the aquifer of the coast of Buenos Aires (Perdomo et al. 2013).

In order to be able to undertake a detailed quantification of the decrease in groundwater reserves, it is necessary to set up a monitoring network covering the study area. Besides, developing a land management plan with the aim of protecting the areas unaffected by urbanisation and with preserved natural conditions is critical; for instance, such is the case of the natural areas surrounding the urban centres, which may constitute reserves to eventually supply water to the population. Similarly, these land management plans should seek not to increase the surfaces covered by forests.

Conclusions

The usefulness of serial aerial photographs, both old and new, was verified in a coastal area with progressive afforestation to analyse the land-use changes and their association with the groundwater reserves and the possibilities for drinking water supply. It constitutes an alternative when lacking historical data to understand the evolution of groundwater recharge variations.

As a consequence of afforestation, the groundwater recharge between 1957 and 2016 decreased at a rate of almost 85,000 m/km^2, which is equivalent to the drinking water supply of approximately 1,000 inhabitants per year. The projection of recharge and water consumption for 2100 made it possible to verify the lack of sustainability of the groundwater system and a situation of progressive depletion, which entails a high risk in the water supply to the population. If such recharge and consumption were compared to the present-day values in Pinamar and Punta Médanos, the risk is clearly irrefutable: a 38% decrease in recharge and 102% increase in consumption occurred in Pinamar, whereas in Punta Médanos the results indicate a 32% decrease and a 200% increase, respectively.

In coastal areas such as the ones under study, where groundwater is the only source of supply to the population, the stabilisation of sand dunes by means of forests with nonnative species should be planned considering how it affects recharge. For the sustainable use of the groundwater resources, the establishment of native species as an alternative is required. Forests constitute "environmental amenities", which is why efforts should be made to achieve a delicate balance between the change in LULC to forested areas and the factors that attract visitors to engage in outdoor leisure activities in these coastal areas. Even though forests are highly regarded worldwide, as they offer scenic views, privacy and aesthetically pleasing locations to participate in tourism activities, their influence on the water cycle should not be disregarded.

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