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ORIGINAL ARTICLE

Impact of afforestation on coastal aquifer recharge. Case study: eastern coast of the Province of Buenos Aires, Argentina

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Abstract
The effects of afforestation on groundwater recharge—which is the only source of drinking water supply in the Pinamar District (Partido de Pinamar), located on the eastern coast of the Province of Buenos Aires, Argentina—are analysed. The study area is characterised by a sand-dune barrier parallel to the coast, where freshwater lenses accumulate. These are bounded to the west by the brackish water of the continental plain and to the east by the seawater. Soil texture makes it possible to infer the infiltration capacity. Methods associated with groundwater table fluctuations, hydrodynamics, hydrochemistry and the characteristics of stable isotopes (^{2}H and ^{18}O) in groundwater were used. In order to confirm the results, daily water balances were carried out. Recharge variations were quantified based on periodic groundwater table records and water balances. A decrease in recharge was verified in forested areas with respect to non-forested areas (bare soil). The groundwater flow (hydraulic gradients), the electrical conductivity of groundwater and the fractionation of stable isotopes indicate that the higher evapotranspiration in areas with tree cover leads to a decrease in water surplus and in the possibilities for groundwater table recharge. The effects of afforestation on recharge and, therefore, on good-quality shallow groundwater reserves constitute a key element in planning the sustainable use of the water resources.

Keywords Water surplus · Groundwater recharge · Forested areas · Freshwater reserves

Introduction

The importance of forests for recreational purposes is recognised worldwide. They offer scenic views, privacy and aesthetically pleasing locations to carry out such activities (Van Berkel and Verburg 2012; Van Berkel et al. 2014).

On the Mediterranean coast of Turkey, forests constitute a defence against dune erosion and tree cover degradation, as well as being a tourist attraction (Kuvan 2005). Afforestation is regarded as a land use that induces changes in the water cycle and, particularly, in the water balance. In certain cases, forest establishment may increase groundwater recharge and decrease surface run-off, due to an increase in infiltration capacity (van Dijk and Keenan 2007). Even though afforestation may not reduce large-scale floods or landslides, it may do so on a local scale. Its influence may affect the precipitation patterns on a local or regional scale, changing the surface–atmosphere transfer of heat and moisture (van Dijk and Keenan 2007).

In arid areas of China, the increase in vegetation cover is essential to improve the ecosystem, especially to protect the soil against erosion and sandstorms (Huang et al. 2017). However, water stress and the increase in competition for the use of freshwater restrict reforestation. In particular, the reduction in water reserves after afforestation generates debate about forest management in dry areas. The transformation of grasslands into forests decreases the annual water reserves by 50–100 mm. In certain periods, plantations on gentle slopes consume the entire surface run-off originating upstream (Wang et al. 2008). The same effect is described by Farley et al. (2005), who—based on record collection and the measurement of surface run-off in pilot areas—claim

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that in regions where surface run-off is less than 10%, it may lead to a total loss due to the presence of vegetation. If the natural surface run-off is 30% of the precipitation, it would be reduced to half or even less when trees are planted.

In Marina Romea, Ravenna, Italy, Mollema et al. (2013) calculated the transpiration rate of pines (*Pinus pinea*). Results show that transpiration is much greater than precipitation. According to these results, there would be no water available for the recharge of freshwater lenses.

In New Zealand, since the mid-1970s, the changes in recharge, groundwater flow and base flow due to the replacement of native species and grasses by conifers have been studied. The effects of afforestation on the annual water reserves were not detected until 7 years had passed. After 9 years of tree growth, the difference between the annual water reserves in areas with herbaceous cover and the one in the forested area was 200 mm, with a 27% reduction. The response to surface run-off was more immediate, reducing the peak flows by 55–65% and the quickflow, by 45–55% (Fahey and Jackson 1997).

On the Gambier Plain, southern Australia, Allison and Hughes (1972) assessed recharge variations in areas under pasture and forest using environmental isotopes (tritium). The results of the tritium concentrations suggest that there may not be recharge to the aquifer in the environment under forest cover, in this case, related to the age of the water.

Based on the water balance and flow duration curves, Buytaert et al. (2007) show that in Ecuador (Andean highlands) the use of afforestation for economic purposes reduces the recharge. This practice, when using pines (*Pinus patula*), leads to a 50% decrease in recharge (242 mm/year), whereas in cultivated areas, the recharge is very similar to the one of the natural environment.

Using the groundwater table fluctuations, Hibbert (1965) analyses the effect of forests on the groundwater reserves in a review of 39 cases. These studies show that a decrease in afforestation increases the reserves and that reforestation leads to their decrease. An annual recharge increase of 4.5 mm can be estimated for each percentage point of vegetation cover reduction. The reduction in the reserves after afforestation seems to be proportional to the growth rate of the seedlings, whereas the increase appears to be proportional after felling, according to the 94 cases reviewed by Bosh and Hewlett (1982). Related to this, Sun et al. (2000), by means of weekly measurements of the groundwater table, detected a rise after the felling of cypresses (conifers) in the Florida flatwoods.

Sahin and Hall (1996) collected information from 145 cases, whose available data included annual mean rainfall, groundwater mean elevation above sea level, catchment area extension, percentage of catchment area with modified cover and mean annual potential evaporation. By means of fuzzy linear regression analysis of the data obtained, these authors showed that the reduction in vegetation cover increases the recharge volume. A 10% reduction in vegetation cover in a conifer forest increases recharge by 20–25 mm, while in a *Eucalyptus* forest, the increase is only 6 mm. Moreover, in Ireland, Allen and Chapman (2001), who applied the water balance method, indicate that reforestation would lead to a run-off reduction by up to 20%. Recharge rates in forest areas could be reduced to 10% of the rates estimated for grass or heathland.

On the eastern coast of the Province of Buenos Aires, the typical vegetation is the grassland, but since the mid-twentieth century there are sectors that have been afforested with conifers, constituting a tourist attraction (Rodrigues Capítulo 2015; Rodrigues Capítulo and Kruse 2011; Rodrigues Capítulo et al. 2017). In this work, the effects of afforestation on groundwater recharge are analysed in a region in which the supply of drinking water to the population depends exclusively on the groundwater reserves of a shallow aquifer. Water availability is directly linked to the possibility of infiltration of the water surplus from precipitation.

Study area

The Pinamar District is located on the eastern edge of the Province of Buenos Aires, Argentina (Fig. 1). It covers an area of 66.2 km^2, including the localities of Monte carlo, Pinamar, Ostende, Valeria del Mar and Cariló (Fig. 1).

This sector is located between the continental plain and the Atlantic Ocean, in a landform known as sand-dune barrier, which has a NE–SW orientation. The predominant composition is highly permeable fine- to medium-grained sands, with no distinguishable traces of water erosion. It is composed of sand bodies of aeolian origin that determine the interaction between the continental and marine processes. This landform has an approximate maximum width of 3.5 km, with well defined lateral boundaries. To the west, it is bounded by the plain, contrasting with low-permeability, high-salinity sediments. To the east, the groundwater system is in hydraulic equilibrium with sea water due to a freshwater–saltwater interface. Natural recharge is in situ from precipitation, with lateral discharge to the sea, as well as to the continental area located to the west.

The hydrogeological system consists of five hydrofacies, three of which are aquifer units (hydrofacies A, C and E), whereas the other two are aquitard units (hydrofacies B and D) occurring in between the former. The groundwater table is located within hydrofacies A (fine sands with shell fragments), which extends with different thicknesses all along the sand-dune barrier, whereas hydrofacies C and E represent deeper aquifer units. The thicknesses of hydrofacies A range from 2 to 15 m. Mean transmissivity (T) and hydraulic conductivity (K) values are 174 and 20 m/d, respectively,

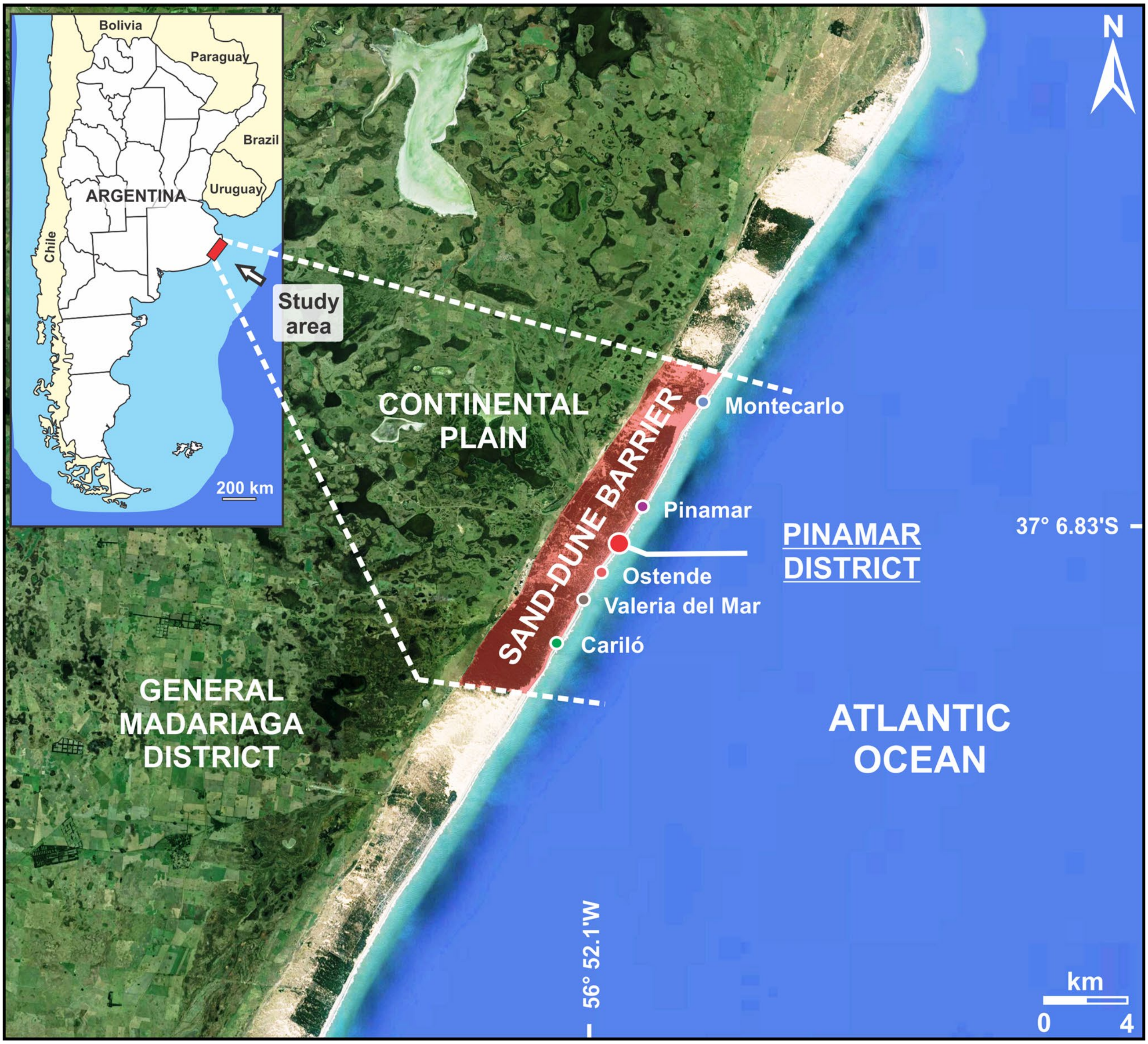

Fig. 1 Study area. Landsat-7 TM image (Path/Row: 223/086) of the sand-dune field in the north of the Partido de Pinamar (Pinamar District) taken on 25 March 2015

whereas the storage coefficient (*S*) is 0.10. Among the deeper systems, hydrofacies C (medium-grained sands) shows thicknesses that reach 12 m in the central sector. *T* values range from 45 to 70 m^2/d and *K* values, from 10 to 20 m/d, while *S* varies between 1×10^{-3} and 1×10^{-4}. Hydrofacies E is an aquifer unit occurring as lenses up to 20 m thick within hydrofacies D. *T* and *K* values are from 15 to 150 m^2/d and from 4 to 40 m/d, respectively, whereas *S* ranges from 1×10^{-3} to 1×10^{-4} (Rodrigues Capítulo 2015).

According to the classification by Thornthwaite (1948), the climate is $B_2B'_2ra'$, where B_2 is moderately humid, B'_2 is cool temperate mesothermal, *r* stands for little or no water deficiency, and *a′* a summer concentration of the thermal efficiency of less than 48%. The mean annual precipitation is 902 mm, with a relatively uniform monthly distribution and a slight increase in the warmer months.

The typical soils are entisols (Fig. 2), characterised by a limited degree of pedological development, with a thickness of less than 40 cm and a histic A horizon in which the woody remains originate from the exotic tree vegetation (conifers).

The original parent material of the soils is sands, and their development depends on the stability of the sand accumulations (INTA 1989). The soils can be divided into Typic Quartzipsamments and Torripsamments, located in the most active parts of the dune, devoid of vegetation. In turn, in the

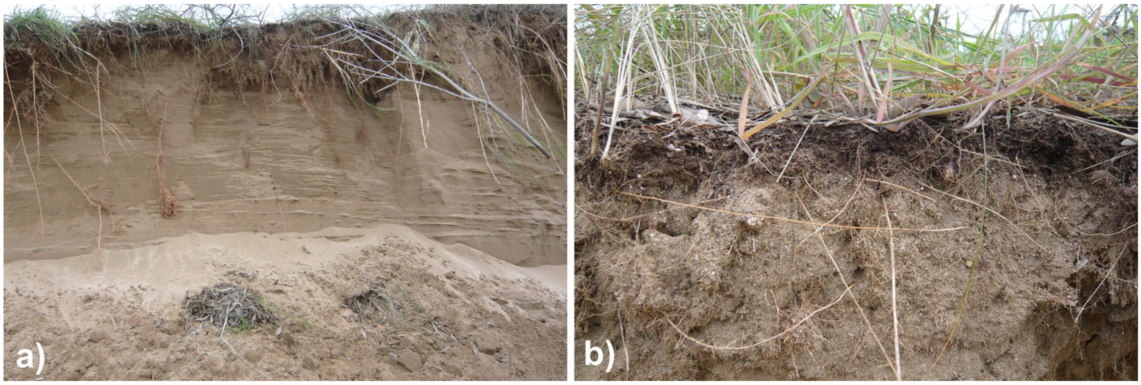

Fig. 2 **a** Cross section and **b** detail of soil in the sand-dune barrier

flatter sectors with greater vegetation cover, Entic and Aridic Haplustolls, as well as Entic Hapludolls, predominate.

The landscape has undergone successive anthropogenic interventions in the last 100 years. Some of the transformations date back to the early twentieth century, when alterations were necessary to build roads to allow access by land. Afforestation has been a constant practice in the last 80 years, associated with the progressive stabilisation of sand dunes.

Materials and methods

In order to analyse the effect of afforestation on the groundwater system, land use surveys were conducted. The hydrodynamic and hydrochemical behaviour was assessed, and stable isotopes (^{2}H and ^{18}O) were determined in groundwater. The verification of the results obtained was undertaken on the basis of daily water balances.

Land uses

In order to integrate the geographic information system, Landsat 7 TM images (bands 1, 2, 3, 4, 5 and 7; path/row 223/086) were used; these had a 30-m spatial resolution and had been acquired on 27 February, 2015.

The band combination 3–2–1 was used to generate an RGB true-colour image, so as to differentiate the main geological and geomorphological features. For the purpose of obtaining a better rendition of the waterbodies and landforms, false-colour images were created by combining the bands of the visual spectrum and the infrared ones, with the combinations 4–3–2, 4–5–3 and 7–4–2 being of particular interest.

With the aim of producing land cover maps, supervised classifications were carried out using a geographic information system with the 4–3–2 and 4–5–3 image combinations. The criterion used for the selection of such combinations is based on the properties given by the infrared field, which gives images a clearer contrast in the areas with vegetation cover.

Groundwater hydrology

The analysis of the hydrodynamic evolution was carried out based on monthly groundwater table measurements in a monitoring network composed of 65 wells, whose depths are between 10 and 25 m bgs (metres below ground surface). The period analysed spans from September 2011 to March 2015. Besides, in order to evaluate the influence of afforestation on the behaviour of the groundwater table, groundwater contour maps were made for September 2014 and March 2015, corresponding to the months with the highest and lowest groundwater table levels, respectively, for the abovementioned hydrological year. Finally, the behaviour of the groundwater table was assessed, taking into consideration whether the wells analysed occurred under forest cover or in bare soil.

A hydrochemical and isotopic characterisation of groundwater was undertaken by means of two sampling campaigns carried out in March 2012 and November 2014. The objective was to assess the effect of trees on the shallow groundwater table.

The isotopic analysis (^{2}H and ^{18}O) was performed by laser spectroscopy, using an off-axis integrated cavity output spectrometer (OA-ICOS, Los Gatos Research Inc.) (Lis et al. 2008) at the Stable Isotope Laboratory of the Instituto de Geocronología y Geología Isotópica (Institute of Geochronology and Isotopic Geology [INGEIS], CONICET-UBA, Buenos Aires, Argentina). The isotopic results were expressed as δ, defined as:

$$\delta = \frac{1000\left(R_s - R_p\right)}{R_p} ‰ \quad (1)$$

where δ ‰ is the isotopic deviation in ‰; s: sample; p: international reference; R: isotope ratio (^{2}H/^{1}H, ^{18}O/^{16}O).

The reference used is the Vienna Standard Mean Ocean Water (VSMOW) (Gonfiantini and Araguás 1988), with uncertainties of ± 0.3‰ for δ ‰^{18}O and ± 1.0‰ for δ ‰^{2}H. By definition, the value of δ VSMOW is 0‰. Therefore, a positive δ indicates a higher concentration of the heavy isotopes ^{18}O or ^{2}H than the reference.

Chemical determinations included major cations and anions. The pH and electrical conductivity values were measured in situ with a multiparameter water quality meter (Solinst TLC) and a conductivity meter, respectively. Gravimetric determination of the total dissolved solids was performed according to SM-2540 B. The analysis of major cations was undertaken by means of the following methods: calcium by EDTA titrimetric SM-3500-Ca B, sodium by flame emission photometric method SM-3500-Na B, potassium by flame emission photometric method SM-3500-K B and magnesium by calculation method SM-3500-Mg B. Major anions were determined by the following methods: bicarbonate by titrimetric SM-2320 B, sulphate by nephelometric SM-4500-SO_4-E and chloride by Mohr SM-4500-Cl. The nitrogen compounds were detected as follows: nitrate by ion-selective electrode SM-4500-NO_3^- D, nitrite by Ilosvay von llosva SM-4500 NO_2^- adaptation and ammonia by ion-selective electrode SM-4500-NH_3-D. The SM-3500-Fe B colorimetric method was used to determine total iron and the SM-3500-Mn and B persulphate methods in the case of manganese (APHA 2005).

Water balance

A daily water balance was performed, on the basis of which the water surplus values were obtained. The data correspond to the daily precipitation series for the period 1997–2015. The daily mean reference evapotranspiration (ET_o) data, as defined by FAO (Food and Agriculture Organization of the United Nations), were derived from Falasca and Forte Lay (2006), who calculated the ET_o for Argentina according to the Penman–Monteith method (Allen et al. 1998) using 118 weather stations (period 1961–1990). Based on this information, they constructed ET_o monthly maps, which were represented by curves with similar ET_o values. The maps obtained for each month made it possible to interpolate the monthly ET_o values for those localities that lack the necessary information to calculate them.

All of the values—such as K_c, ET_o and precipitation—are included in the AGROAGUA v.5.0 application (Forte Lay et al. 1995), which was used to calculate the water balance. This software makes it possible to carry out daily water balances and continuously monitor the soil water storage, using the daily rainfall, daily potential evapotranspiration and soil field capacity variables.

The water balance was established on the basis of three components: the water supply, which is precipitation, the potential atmospheric demand or maximum water demand for a certain soil cover (ET_c) and the water reserves, which is the soil water storage.

As the soil and the vegetation that covers it do not always release to the atmosphere all of the water that is demanded of them, the concept of actual evapotranspiration (ET_a) is defined. It is the evapotranspiration that actually occurs given a specific ET_c and initial storage; it is always similar to or lower than ET_c.

Equation (2), which combines the basic elements of the balance, is as follows:

$$P - ET_a - \Delta S - Q = 0 \tag{2}$$

where P is the precipitation for the period; ET_a is the actual evapotranspiration; ΔS is the variation in soil water storage and Q is the soil water surplus, defined as the sum of the surface run-off and infiltrated water. As there is no surface run-off in the study area, Q is equal to the infiltrated water.

The relationship between ET_a and ET_c depends in turn on the soil water content. Thornthwaite and Mather (1955) propose a relationship according to specific retention tables for each field capacity (FC), which is linear for short time periods (1 day). This condition responds to a simple scheme in which the ET_a value is similar to the ET_c value only in FC; the ET_a value is reduced by half when the soil contains half of its storage capacity, and it is null when the soil moisture is exhausted. This is the scheme adopted in this work, which uses a daily time-step water balance method.

Besides, according to the above-mentioned definitions, the maximum value of ET_c derives from ET_o, defined as the rate of evapotranspiration from “a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s/m and an albedo of 0.23”. This value may be estimated by means of the FAO Penman–Monteith equation (Allen et al. 1998), based on temperature, humidity, wind and solar radiation. Once obtained, ET_c may be determined by means of Eq. (3):

$$ET_c = ET_o \times K_c \tag{3}$$

where ET_c is the maximum evapotranspiration of the cover; ET_o is the reference evapotranspiration; and K_c is the crop or cover coefficient.

In those cases in which there is no crop or vegetation cover, a specific K_c for bare soil is defined. In this work, the FC of this soil, which is mainly composed of sand, was obtained from Falasca and Forte Lay (2006), who assigned a value between 140 and 180 mm up to a depth of 1 m along the whole coastal sand-dune barrier; therefore, the mean value adopted was 160 mm/m. Two cases were analysed: one consists of bare soil (loose sand with no plants or roots) and the other of soil covered by a conifer forest. In the former case, an effective depth of 0.25 m was assigned for the water balance and, therefore, a FC of 40 mm, as the effect of evapotranspiration, cannot reach further down. On the other hand, in the latter case, as it is a well-established forest, a root exploration of over 1 m deep had to be considered, establishing an effective depth of 1.25 m for the balance, which proportionally corresponds to a FC of 200 mm. In order to define the root zone, a container where the water content may fluctuate can be used, expressing the water content as root zone depletion. This makes it more direct to add and subtract the losses and gains, since the different soil water balance parameters are generally expressed as water depth. As a result of irrigation, rainfall and the capillary rise of groundwater towards the root zone, the root zone gains water, whereas the root zone depletion decreases. Conversely, water is removed from the root zone due to crop transpiration, soil evaporation and percolation losses, while the depletion increases. The difference between the water content at field capacity and the wilting point equals to the total available water in the root zone. This is so because the water content above field capacity cannot be held against the forces of gravity and will drain, and because the water content below wilting point cannot be absorbed by the roots. The volume of water that a crop can extract from its root zone is referred to as the total available water, whose magnitude is determined by the type of soil and the rooting depth. As regards conifer trees, the latter varies between 1 and 1.5 m (Allen et al. 1998); therefore, the average value of 1.25 m was chosen for this case study. The K_c values adopted were set according to the guidelines proposed by FAO (Allen et al. 1998). According to FAO (Allen et al. 1998), in the case of soils with limited or no vegetation cover, K_c depends on several factors, such as the time interval between wetting events (irrigation or rain), the evaporation power of the atmosphere (ET_o) and the magnitude of the wetting event. As regards the first factor, in frequently wet soils, the surface wetted leads to a very high evaporation value, which at times may even exceed a value of 1. (In such a case, the value of the ET_c—only evaporation—may slightly exceed the ET_o value, as there is no transpiration.) Conversely, when the surface is dry, the K_c value decreases rapidly and, therefore, ET_c will be much lower than ET_o. Concerning the evaporation power of the atmosphere, the higher it is, the quicker the surface dries between wetting events and so the time-averaged K_c for the period will decrease. Finally, regarding the magnitude of the wetting event (in this case, rains), when heavier rainfall events occur, K_c increases, as the surface is wet for a longer period of time. Therefore, in this case, variations in K_c were introduced so that it was higher in winter (lower ET_o) and lower in summer (higher ET_o).

Following Allen et al. (1998), where the relationship between ET_o and K_c was graphically represented for different wetting intervals, the monthly K_c values along the year could be inferred. A 4-day wetting interval was chosen, as it is approximately a frequency of 7–8 rainfall events per month, a reasonable value for the region. The K_c values applied to the bare sand-dune soil are represented in Fig. 3. In the case of soil with a conifer forest cover, the K_c value adopted was 1 throughout the year, which is why in this case ET_c was similar to ET_o. Allen et al. (1998) give a K_c value equals to 1 for conifers saying that "Conifers exhibit substantial stomatal control due to reduced aerodynamic resistance. This K_c represents well-watered conditions for large forests". Therefore, because of the climatic conditions of the study area, a K_c equals to 1 is the appropriated value to be used.

Due to the characteristics of the soil, no surface run-off processes can be observed, and it is considered that the water balance surpluses are transformed directly into effective recharge to the aquifer.

Results

Land cover

The processing of satellite images indicates that 55.6% of the surface is forested and 44.4% corresponds to sand dunes with no vegetation (bare soil or non-forested area) (Fig. 4a).

The forested area (Fig. 4b) is characterised by the presence of conifers, with species such as *Pinus pinaster*, *Pinus radiata*, *P. pinea* and, in smaller numbers, *Pinus halepensis*. The average heights are slightly over 40 m; it is possible to differentiate two types of forests depending on the ages: young forests of less than 30 years and mature ones of over 50 years, with the latter being the most widely distributed ones.

There are complementary plantations of acacias (*Acacia longifolia*) and French tamarisks (*Tamarix gallica*).

The bare soil cover is composed of transverse dunes, barchans, barchanoid ridges and parabolic dunes (Fig. 4d). The geometry of these bodies is characterised by extended windward faces oriented to the south-east, while the leeward faces show a high angle, in certain cases being almost vertical. In the north, these bodies occur perpendicular to

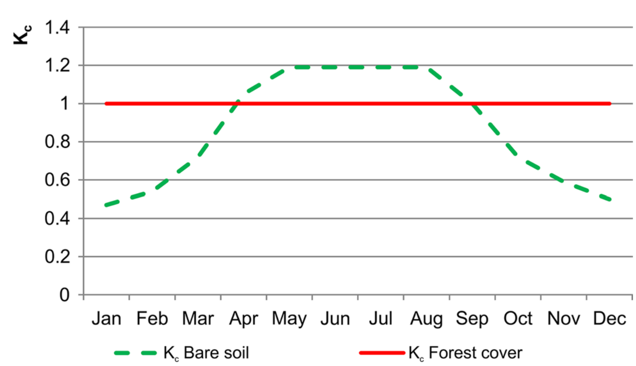

Fig. 3 K_c values used for the determination of ET_c

the coastline, making it possible to infer that the prevailing winds are from the south-west–north-east.

These landforms tend to lose their typical geomorphological characteristics as they approach the sea, with a decrease in height and in their distinctive shape, together with a deviation in the direction of the axes of the sand dunes that compose the barrier, shifting from a west–east to a north-west–south-east direction.

In the coastal areas, these sand accumulations occur as dunes stabilised by shrub communities, mainly *Acacia longifolia*, *Adesmia incana*, *T. gallica* and *Myoporum laetum* (Fig. 4c).

Groundwater flow and groundwater table fluctuations

Groundwater contour maps (Fig. 5a, b) allow the identification of a radial phreatic morphology with equipotential curves oriented parallel to the coast, indicating a groundwater flow direction to the sea and another one to the continent. In general, the subsurface watershed coincides with the maximum topographic heights, following an imaginary line oriented in a south-west–north-east direction. This watershed shows a slight displacement to the west with respect to the geographical centre of the sand-dune barrier, in particular in Ostende, Valeria del Mar and Cariló.

In March 2015, a generalised lowering of the groundwater table can be observed, and it is more marked in the sectors with denser tree cover (Cariló and Valeria del Mar). Such a condition is made evident by a displacement to the north-west of the 3 and 4 m a.s.l. (metres above sea level) contour lines and the retraction of the 5 m a.s.l. contour line to the north (Fig. 5b). In the dune area in the north of the district, this phenomenon is made evident by a slight lowering of the groundwater table as a result of the water surpluses occurring even in the season with the highest evapotranspiration.

In September 2014, in the northern sector (bare soil), the hydraulic gradient reached a mean value of 3.12 m/km, whereas in March 2015, it was 3.05 m/km. By contrast, in the forested area (Cariló and Valeria del Mar), the average hydraulic gradient was 1.8 m/km in September 2014 and 1.16 m/km in March 2015. This condition suggests the regulating effect of forests, as a result of a higher evapotranspiration in the warm months (March 2015). Cross sections of the sand-dune barrier (Fig. 6) make it possible to assess the variations in groundwater flow lines between the non-forested areas in the north (Fig. 6a) and the forested ones in the south (Fig. 6b). The maximum hydraulic gradient corresponds to cross section **a** and the minimum one to cross section **b**.

The effects of afforestation may also be observed and estimated based on the individual behaviour of the groundwater table (Fig. 5c) for the period September 2014–March 2015 in monitoring wells located in a forested area and a non-forested area. In both cases, a groundwater table rise occurred in September 2014, reaching 4.82 and 8.10 m a.s.l., respectively (equivalent to 5.77 for the forested soil and 4.05 m bgs for the bare soil). In March 2015, the deepening of the groundwater table observed reached elevations of 3.7 and 7.35 m a.s.l., respectively (depths of 7.6 and 4.7 m bgs), indicating a difference of 1.12 m in the forested soil and of 0.75 m in the bare soil. This represents 33% less deepening of the groundwater table in the bare soil, which is equivalent to a 37-mm-thick sheet of water considering a 10% porosity.

Hydrochemical and isotopic characteristics

The hydrochemical characterisation of groundwater made it possible to observe the predominance of sodium bicarbonate type water over the chloride type, whereas the evolution shows the typical behaviour of recently infiltrated water. An increase can be recognised in the electrical conductivity of water in both flow directions, together with an increase in ion concentrations, in particular of HCO_3^-, Na^+ and Cl^-. Slightly elevated concentrations of total Fe and Mn^{++} have been identified; these are the result of the mineralogy of the sands that compose the aquifer.

The delta-value range obtained during the isotope sampling carried out in March 2012 (Fig. 7a) for the forested soil were from − 24 to − 27 for ^{2}H ‰ and from − 4.4 to − 5 for ^{18}O ‰. Similar values were found in November 2014 (Fig. 7b), where the interval was from − 22 to − 26 for ^{2}H ‰ and from − 4.1 to − 4.7 for ^{18}O ‰.

In the case of the bare soil (Fig. 7a), the data for 2012 ranged from − 28 to − 37 for ^{2}H ‰ and from − 5.1 to − 6.2 for ^{18}O ‰, whereas for 2014 (Fig. 7b), the values were between − 26 and − 32 for ^{2}H ‰ and between − 4.8 and − 5.5 for ^{18}O ‰.

Such values made it possible to propose a series of hypotheses about the effects of afforestation on the processes that foster isotope fractionation. On analysing Fig. 7, two groups can be distinguished. The first group (G1 and G3, bare soil) has values below − 26 and − 4.8 for ^{2}H ‰ and ^{18}O ‰, respectively, whereas in the case of forested soil (G2 and G4), such contents are over − 28 for ^{2}H ‰ and − 5.1 for ^{18}O ‰. According to these values, together with the water balance and the groundwater contour maps made, it is possible to infer a greater degree of fractionation (enrichment) in sectors with tree cover, which would be the result of an increase in evapotranspiration.

This condition is also accompanied by an increase in electrical conductivity values in the forested areas, in which the mean value for groups G2 and G4 reaches 1100 µS/cm, unlike groups G1 and G3, which have mean conductivity values of 540 µS/cm. This situation could be explained on the basis of an increase in the ion concentrations resulting in a higher evapotranspiration in the forested areas.

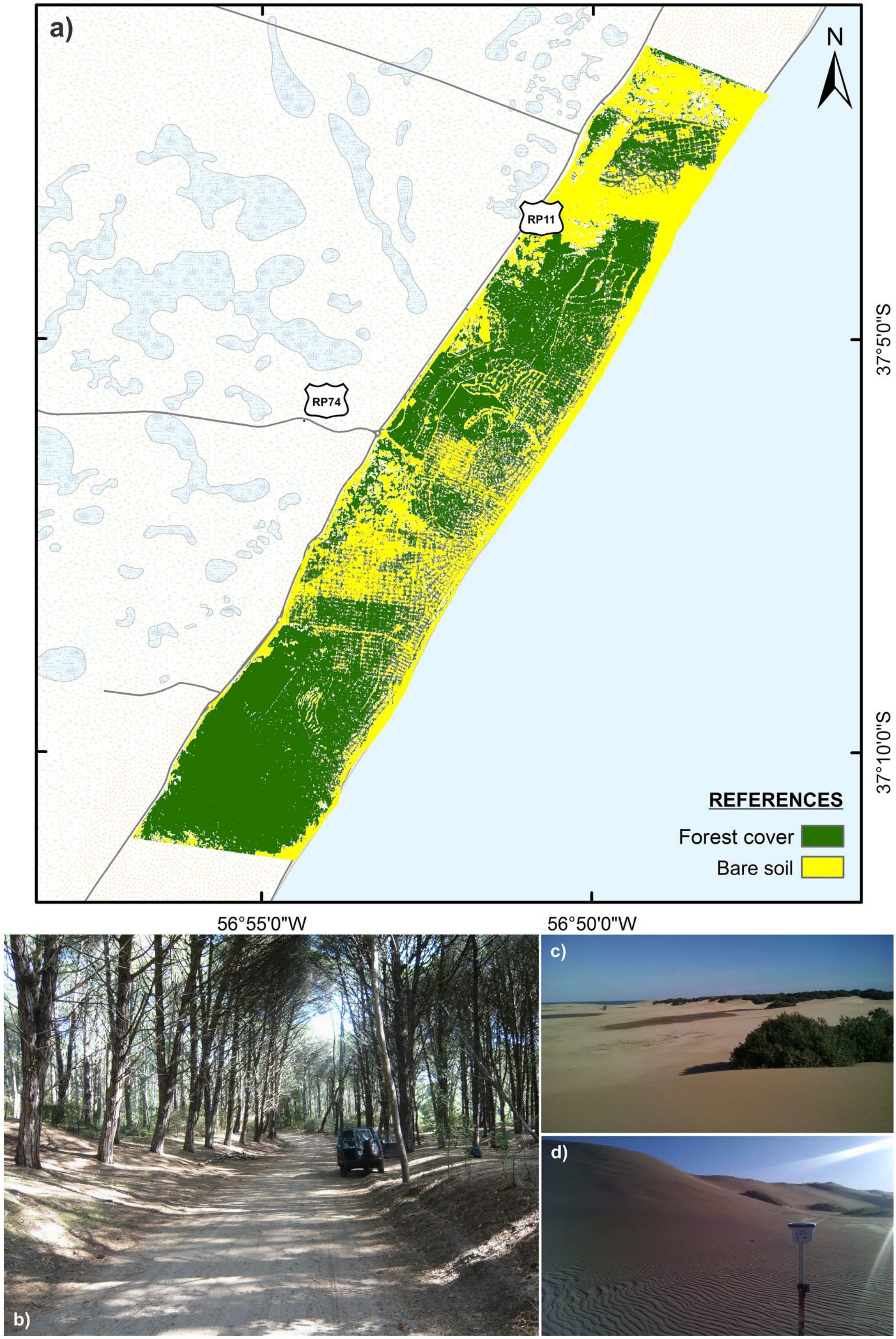

Fig. 4 **a** Cover map made on the basis of supervised classification, **b** sector afforested with conifers, **c** bare soil with shrubs for stabilisation, **d** bare soil with transverse dunes

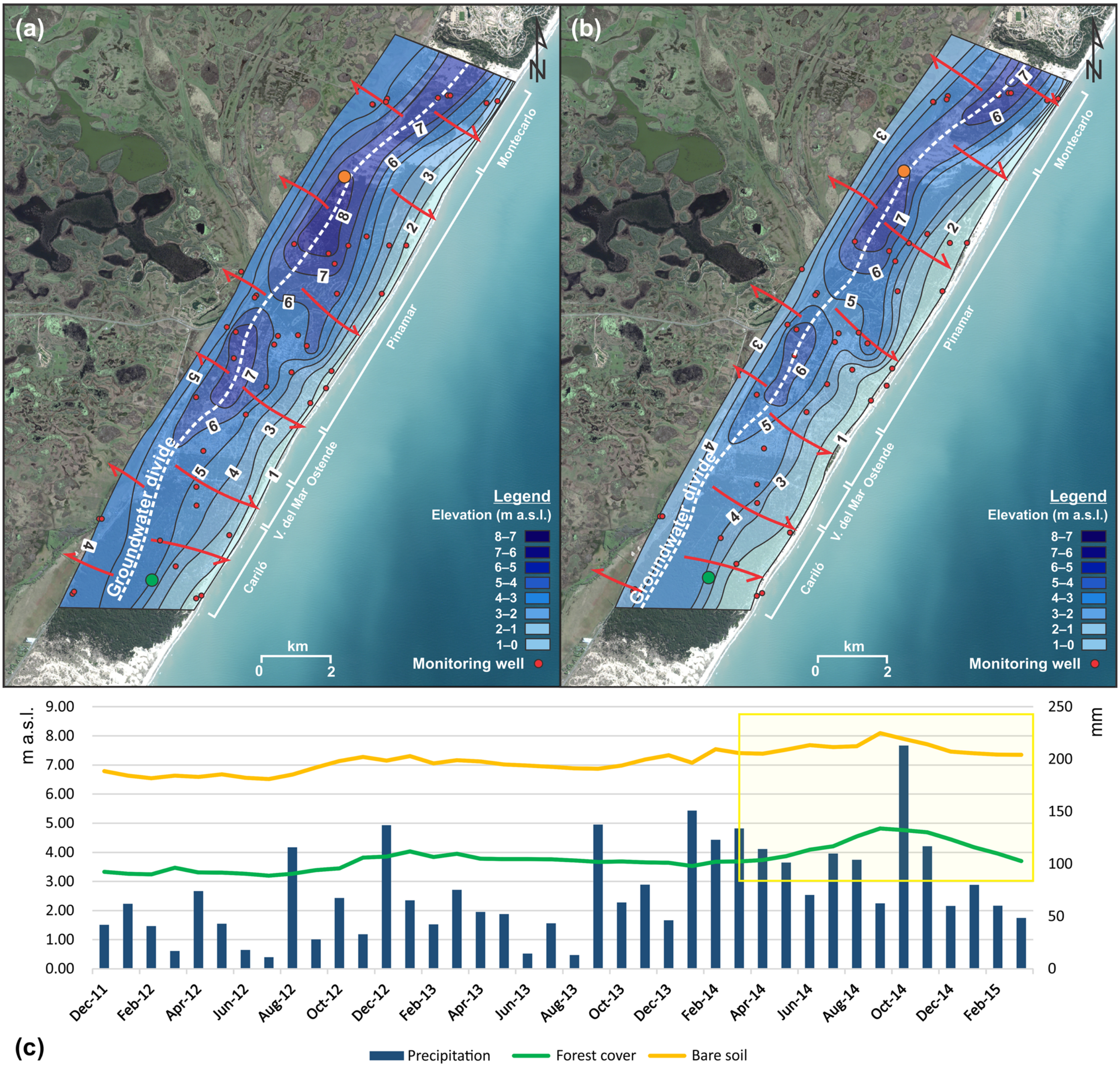

Fig. 5 Groundwater contour maps for the months of **a** September 2014, **b** March 2015, **c** temporal evolution of groundwater table levels and precipitation. The yellow box shows the time frame considered for the hydrological year studied

Relationship between water surpluses and hydrodynamic evolution

The groundwater table fluctuations in both cover types (Fig. 5), as well as the evolution of the groundwater contour maps for September 2014 and March 2015, were related to the water surpluses obtained on the basis of the daily water balance. Such periods correspond to the maximum and minimum groundwater table elevations, respectively (Fig. 5a, b).

The daily water balance was estimated for both situations: bare soil and forested soil. In Fig. 8, the values of water surpluses and precipitation for the period January 1997–January 2015 are plotted.

Greater water surpluses are registered in bare soil with respect to forested soil. This is due to the lower field capacity in the former case, which causes the soil to rapidly reach its maximum storage capacity during a given rain event. Besides, the remaining water occurs as surpluses, which—due to the lack of surface run-off—will recharge the groundwater table. The opposite occurs in the second case, in which FC is higher. The decrease in water surpluses in the forested soil takes place in the summer, because in this high ET_o

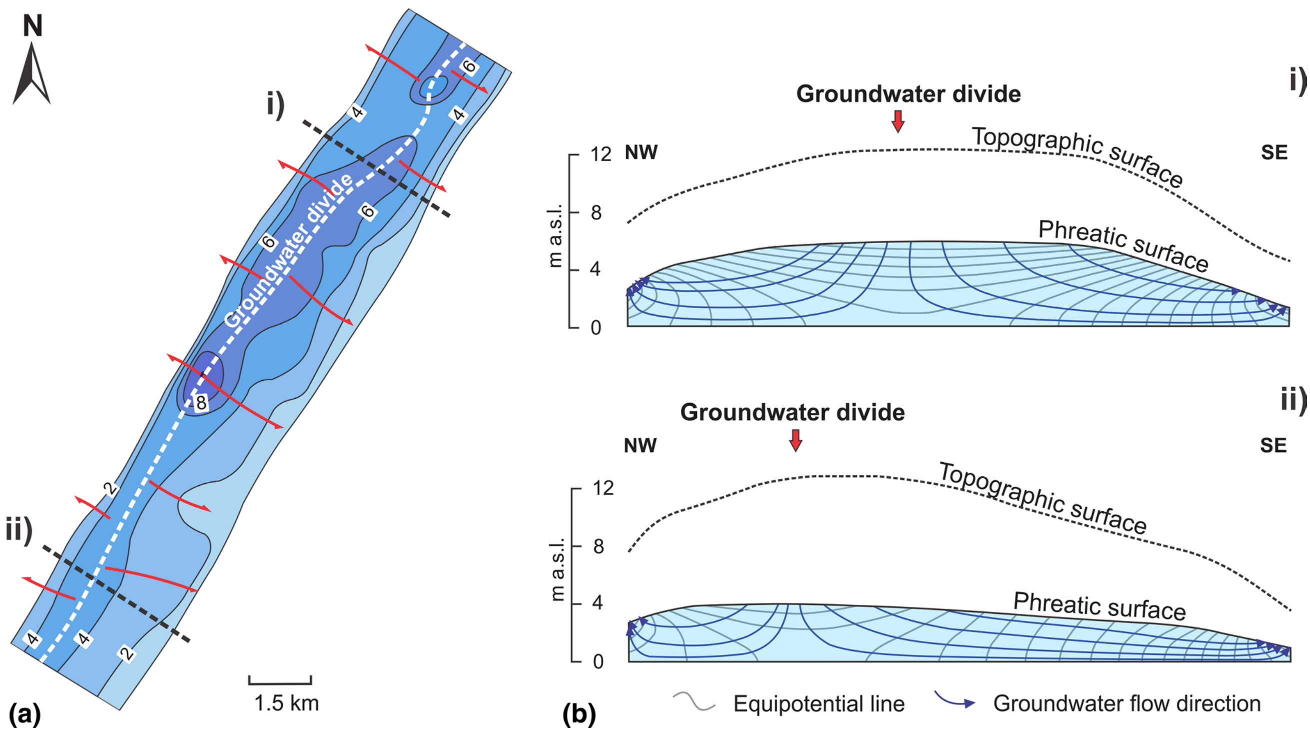

Fig. 6 **a** Groundwater contour map (Date: May 2014), the arrows indicate groundwater flow direction. **b** Simplified cross sections (*i*) for bare soil in the northern sector and (*ii*) for forested soil in the southern sector

season, the forested soil retains a K_c of 1 as it does the rest of the year. In the case of bare soil, in the summer K_c decreases (Fig. 3) and, therefore, ET_c decreases with respect to ET_o. Thus, given a similar precipitation, its transformation into water surpluses occurs more rapidly; this does not happen in the forested area, where the high ET_o during the summer determines the same ET_c value, and consequently in that season the water surpluses decrease.

On the other hand, the proportion between the water surpluses of both soil types decreases in winter (Fig. 9a), owing to the fact that—in this season with moister soils—the K_c of the bare soil slightly exceeds a value of 1; therefore, ET_c is slightly higher than ET_o, leading to less water surplus (195 mm). This does not occur in the soil under forest, where K_c remains at a value of 1 and ET_c remains the same as ET_o, and so it does not affect the value of the water surplus (148.6 mm).

In Fig. 9b and c, it can be observed that given a similar amount of precipitation, the percentage of water surpluses for the annual period is higher in the bare soil (420.5 mm/year) than in the soil under forest (219.3 mm/year).

This relationship may also be recognised in the values obtained from the daily water balance calculated for September 2014 and March 2015, in which the water surpluses reach 93.1 and 92.7 mm for bare and forested soils, respectively (Fig. 10). In turn, in March 2015, water surpluses were only obtained in bare soil, with a value of 28.5 mm, which makes it possible to rule out aquifer recharge processes in the soil under forest.

Discussion

Forest establishment may reduce groundwater recharge, which is particularly important in water-limited environments (Lubczynsky 2009).

Different methodologies have been used to verify such recharge variations. In this work, concurring evidence was analysed, including groundwater table fluctuations, the hydrodynamic, hydrochemical and isotopic characteristics of groundwater, and the verification by means of a daily water balance. It was demonstrated that a greater rise (33%) occurs in the groundwater table associated with the water surpluses from precipitation in bare soil areas than in the forested area. Groundwater contour maps confirm that, in forested areas, a deeper groundwater table is registered and the groundwater table surface shows less pronounced hydraulic gradients than in non-forested areas. This condition is made evident by a 3% relative variation of the hydraulic gradients in bare soil with respect to soil with forest cover, in which it reaches 66%.

Besides, a ^{2}H and ^{18}O isotopes enrichment in the sectors with forest cover may be the result of a higher evapotranspiration. Such a characteristic is also verified by the lower

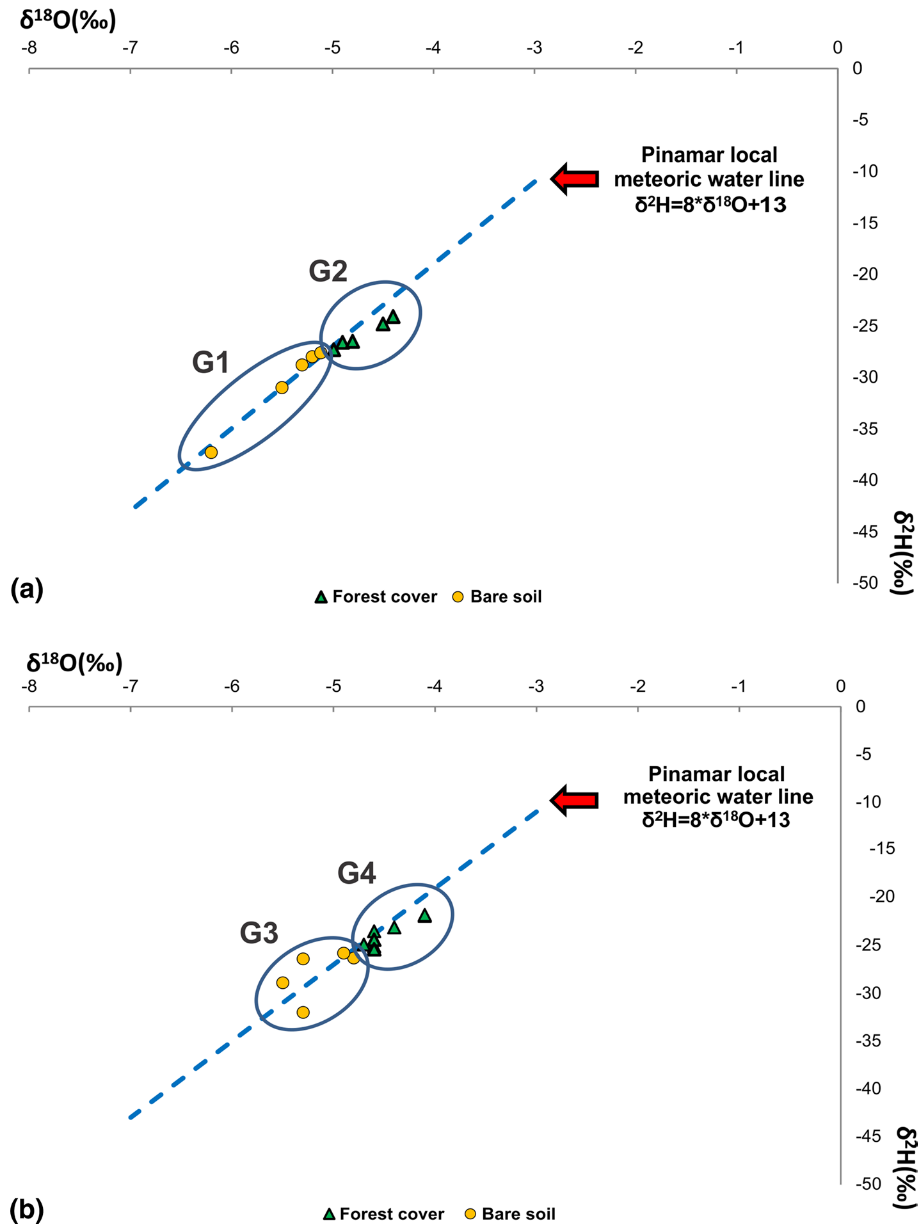

Fig. 7 δ^2H versus δ^{18}O diagram of groundwater samples taken in **a** March 2012 and **b** November 2014. LMWT taken from Dapeña (2007)

values of electrical conductivity of water in the bare soil area.

The daily water balance made it possible to verify that, for the period 1997–2015, the water surpluses from precipitation were 52% lower in the forested area, a consequence of the higher evapotranspiration, and therefore, a smaller amount of water may have been available for groundwater table recharge.

These results are consistent with the ones obtained in other regions using a variety of assessment methods. A combination of study methods, such as the measurement of the groundwater table in the field, of moisture in a laboratory setting and water balances, were used in Western Australia by Carbon et al. (1982). Such studies indicate that the infiltration at depths of more than 6 m was much less in soils with pine plantations (240 mm), whereas it was greater (400 mm). in areas with native vegetation (*Bromus mollis*, *Eragrostis curvula*, *Hyparrhenia hirta*, *Medicago sativa*, *Trifolium subterraneum*). This suggests a decrease in reserves in shallow groundwater under established forest. The data from the annual water balance for the pine forest show surpluses of 11% with 89% of evapotranspiration, whereas for the native vegetation, the surpluses are 34% with 66% of evapotranspiration. The infiltration values reported by these authors are similar to the ones obtained in this work, i.e. 219 mm/year in the forested area and 420 mm/year in the non-forested one. In the case of Australia, the surpluses in the forested soil were 36% lower than in the soil with native vegetation, whereas on the coast of Buenos Aires

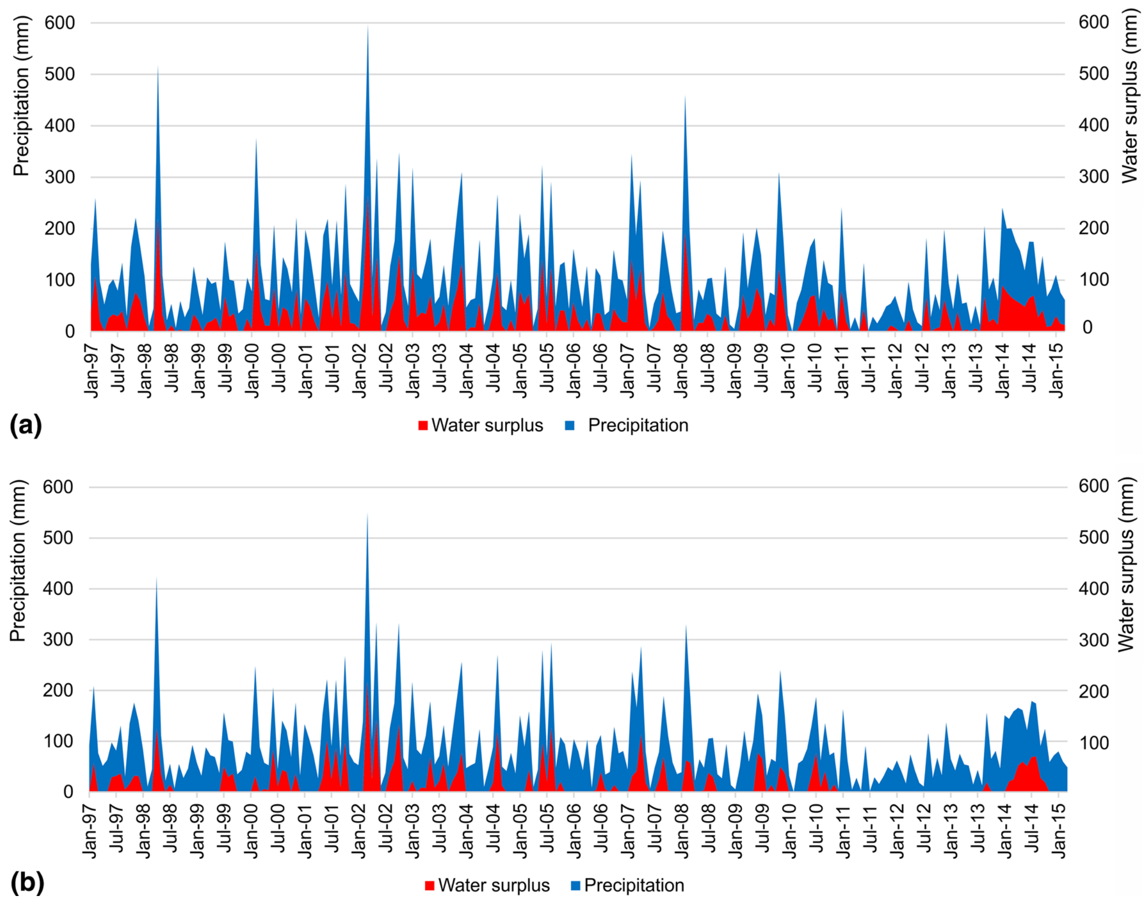

Fig. 8 Monthly water surpluses and precipitation (mm) for **a** forested soil and **b** bare soil

such a value is 48% lower. It can be observed that the surplus variation values and the consequent infiltration are within the ranges obtained in other cases with soils afforested with conifers.

Conclusions

Concurring evidence was used to assess the effects of afforestation on recharge. Methods such as the measurement of groundwater table fluctuations and the water balance are frequently used for this type of assessment. The combination of the results obtained from the evaluation of the hydrodynamic, hydrochemical and stable isotope (^{2}H and ^{18}O) conditions is not so frequent in the literature.

A greater rise in the groundwater table associated with water surpluses from precipitation was observed in areas with bare soil with respect to forested areas. This was confirmed on the basis of data collected in September 2014 (shallowest groundwater table in the hydrological year) and March 2015 (deepest groundwater table). The differences recognised indicate that recharge is 37 mm greater in the bare soil area. This is verified by the daily water balance, as on those same dates a water surplus of 29 mm can be observed.

The groundwater contour maps confirm that deeper groundwater table is registered in the forested areas (7.6 m, forested; 4.7 m, bare soil) and the hydraulic gradients are less pronounced than in the non-forested areas (1.16 m/km, forested; 3.05 m/km, bare soil).

Stable isotope fractionation (^{2}H and ^{18}O) made it possible to recognise two groups. One group corresponds to the forested area, where a higher degree of fractionation (enrichment) can be observed, possibly related to a higher evapotranspiration due to tree cover. The other group, associated with the bare soil, has the opposite characteristics, that is, an isotopic depletion.

The electrical conductivity of water—directly associated with the total water salinity—in the forested area has a mean value of 1100 µS/cm, whereas in the non-forested area, such a value is 540 µS/cm. An increase in salinity in the forested area can be inferred.

The daily water balance for the period 1997–2015 showed a value of water surplus from precipitation of 219 mm/year

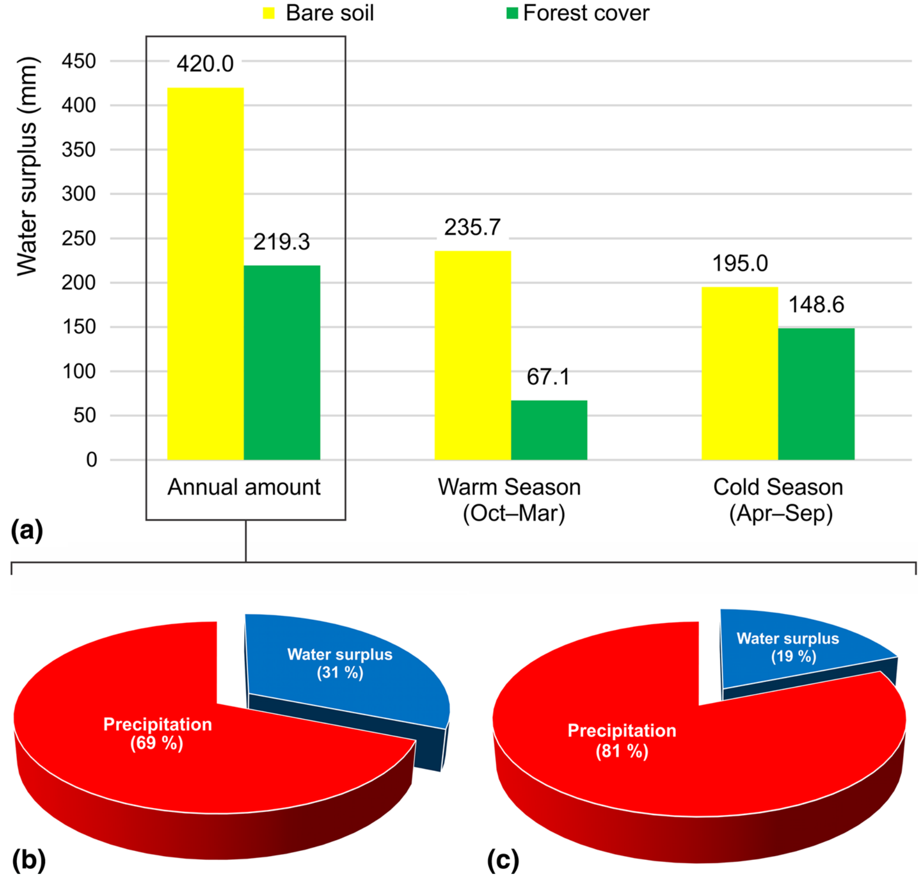

Fig. 9 **a** Annual and 6-monthly mean water surpluses (mm) in the study area, **b** annual relationship between precipitation vs water surpluses for bare soil, and **c** forest cover

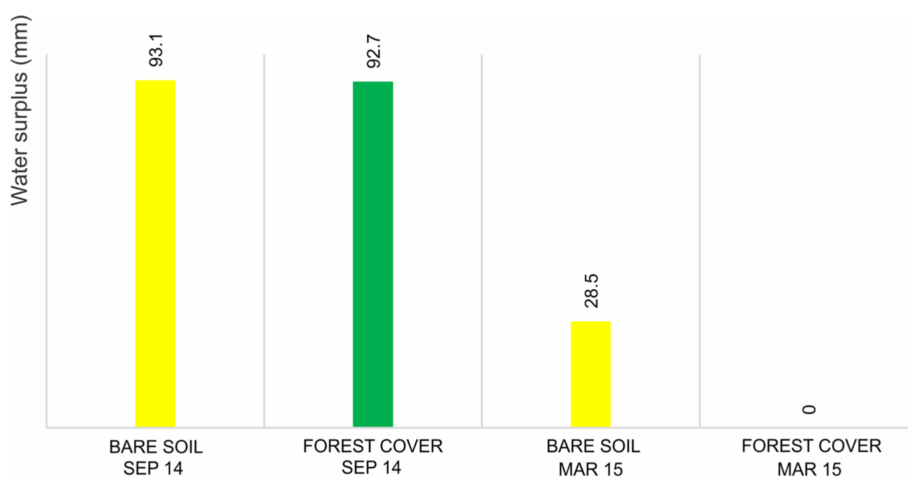

Fig. 10 Water surpluses obtained for the months of September 2014 and March 2015

in the forested area and of 420 mm/year in the non-forested one. These values are equivalent to 24 and 46% of the annual precipitation, respectively.

The groundwater flow conditions and the groundwater table fluctuations indicate that recharge in the non-forested area may be 33% higher than the value registered in the forested area. The hydrochemical conditions, and in particular the isotopic ones, qualitatively confirm such conditions.

On the other hand, the daily water balance indicates that the water surpluses that infiltrate and recharge the groundwater system may be of the order of 200 mm/year higher than in bare soil.

Results show a direct effect of afforestation on the groundwater reserves, given the differences observed in the recharge. It should be taken into consideration that this recharge feeds the only source of drinking water supply. In certain coastal areas in Argentina, such as the one analysed, it would be necessary to assess future forest establishment and its effects on groundwater recharge. According to the analysis carried out, land use management should consider the effects of afforestation on the water cycle and the availability of groundwater reserves. Consequently, it is important to include the modifications that occur in soils under forest among the water resource management guidelines.

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