Linking geomorphology and hydrodynamics: a case study from Península Valdés, Patagonia, Argentina

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Abstract A case study is presented to assess the relevance of geomorphology in hydrogeological phenomena in an arid coastal area in the Argentinean extra-Andean Patagonia (Península Valdés) with an average rainfall of 232mm/year and a soil moisture deficit of about 472mm/year. Various geomorphic units were identified by interpreting Landsat 7 satellite images processed with ER Mapper software and then surveyed in the field, as well as by geological characterization. The hydrodynamic analysis was based on a survey of 89 wells, the construction of equipotential maps, and the interpretation of pumping-test results by a non-equilibrium method. The hydrochemical characterization was based on chemical tests analyzed with the Easy_Quim 6.0 application. The combination of geomorphological, geological, hydrodynamic and hydrochemical elements allowed the definition of hydromorphological units that are typical of recharge, circulation and discharge areas, the latter both for coastal and inland areas in wetlands (salt pans) with elevations to −40m relative to sea level. These units and the criteria used for their definition allow immediate recognition of hydrogeological phenomena in arid regions such as the extra-Andean Patagonia, with low information density but with near-optimal satellite imaging of landforms due to the lack of vegetation cover.

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Introduction

As is well known, geomorphology, geology, and climate are first-order determinants of hydrogeological phenomena, not just hydrodynamic but also hydrochemical ones. Unfortunately, there are no relevant works of reference on the relationship between geomorphology and hydrodynamic phenomena in arid regions with low population density, which has motivated the authors to disseminate this work.

The purpose of this research was to demonstrate the usefulness of surveying and interpreting geomorphological data particularly for arid regions, where there is a closer correspondence between hydrogeological units and the geoforms containing them, which was considered from the beginning to be the working hypothesis. These landforms can easily be observed due to the lack of vegetation cover and the high contrast between materials, all of which helps when processing and interpreting satellite images.

This allows the identification and delimitation of hydromorphological units, which according to the above-mentioned hypothesis are highly useful in the prospection and analysis of groundwater dynamics and their hydrogeochemical correlation. This methodology can be applied to a large area of the extra-Andean Patagonia in Argentina, which has an extension of 700,000 km^2, and to similar environments in other countries.

The prevailing features that characterize this work are, among others, the extremely low population density—0.15 capita/km^2—, and consequently the information deficit. Moreover, another characteristic that is of particular interest in the light of this working hypothesis is that Península Valdés lacks allochthonous contributions from surface or groundwater due to the narrowness of the isthmus that connects the peninsula to the continent.

Methodology

In order to avoid unnecessary repetition, the description of the methodology used to deal with the different aspects of

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this study has been grouped together in a single section preceding their discussion.

For the climatological characterization of the region, local rainfall information was organized in monthly series to observe intra-annual rainfall variations, and in annual series to assess historical trends, with records dating more than 80 years at La Adela Farm (Fig. 1) between 1912 and 2007. Temperature data were provided by the neighboring station of the Centro Nacional Patagónico (Patagonian National Center - CENPAT), belonging to the Consejo Nacional de Investigaciones Científicas y Técnicas (National Council on Scientific and Technical Research - CONICET) located in Puerto Madryn (Fig. 1), organized in monthly series to observe seasonal trends.

Based on these data and on field capacity—between 25 and 50 mm (Rostagno 1981)—, two water balances were done using the Thornthwaite-Mather method (Thornthwaite and Mather 1957), which, even though it is not the best method for extreme climates, allows for determination of the intra-annual distribution of soil moisture deficit and definition of the climate type of the region.

The choice of this method over others that could be more appropriate—e.g., Penman-Monteith (Monteith 1965)—stems from the limited, as well as easily available, input data required. The equation estimates potential evapotranspiration monthly by considering the mean monthly temperature and adjusting it depending on daily insolation. Then, by means of a chart weighing the relationship between rainfall, potential evapotranspiration, and the available water reserve in the soil, real evapotranspiration is obtained.

The geomorphological description was based on the interpretation of satellite images and the analysis of aerial photos with a mirror stereoscope. The images (Landsat 7) were processed with the ER Mapper software, and a mosaic covering the entire area was generated. Features of interest were highlighted by combining bands. Based on this mosaic, and with the support of aerial photographs and field corroboration, geomorphic units were mapped.

For the hydrogeological characterization, the main outcropping geological units were identified and classified as aquitards, aquicludes, or aquifers (there are no outcropping aquifuges) based on the hydrolithological and stratigraphic characteristics emerging from the basic geological map and the field observations of the authors; for the subsoil, previous lithologic profiles were used. On the basis of this information, the physical component of the hydrogeological system was identified.

The recognition of the surveyed wells was carried out on a field trip in November 2005, focusing on a total of 89 wells. At each site, water depth was measured and converted to hydrostatic heights in meters above mean sea level (m a.s.l.), using the topographic altitude of the well mouth, and drawing the equipotential map of the phreatic aquifer to reproduce its dynamics using geomorphic units to define the environment.

Eighty-nine groundwater samples were also taken, using the ASTM D 4448-85a (2001) Standard Guide For Sampling Groundwater Monitoring Wells, which establishes the sampling, conservation, and transportation procedures. The physical properties were measured in situ (pH, electrical conductivity, and temperature) and sent to the laboratory for physicochemical testing (calcium, magnesium, sodium, potassium, bicarbonate, carbonate, sulfate, chloride, and nitrate ions) as determined by Standard Methods (American Public Health Association 1998). The results obtained were processed with the Easy_Quim 6.0 application (Vàzquez Suñé 2002), which allowed for classification according to the Piper system.

The final task consisted of combining the results obtained from observing the geomorphology, hydrogeology, underground hydrodynamics, and hydrochemistry in order to define, characterize, and conceptually explain

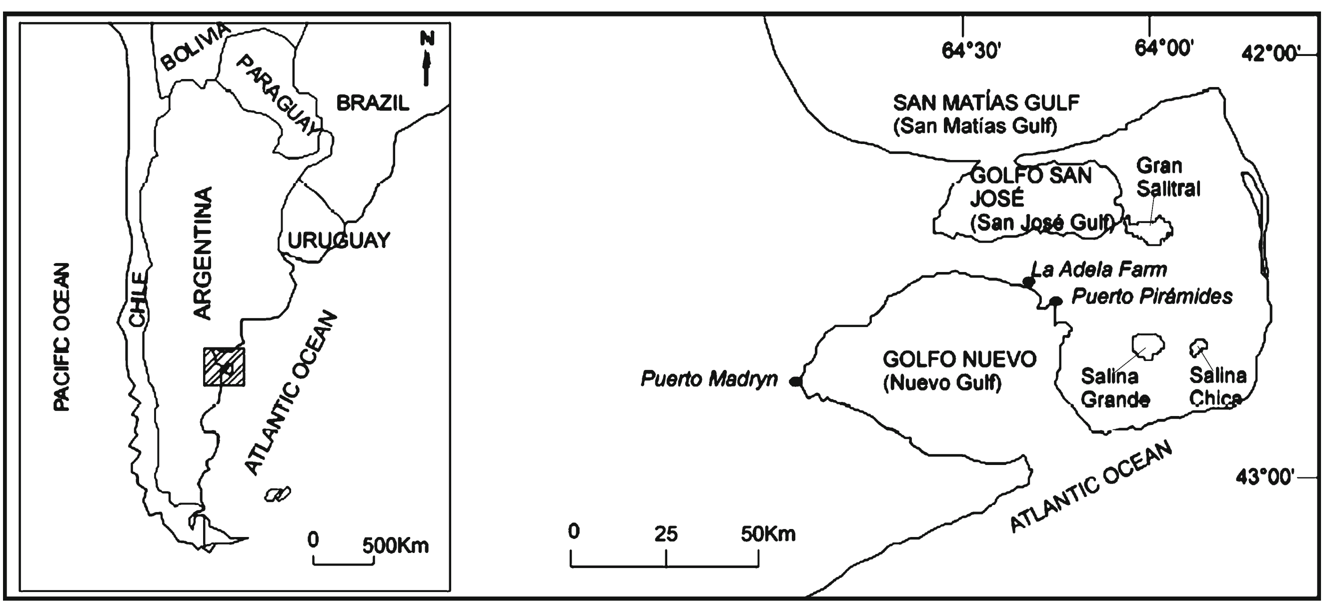

Fig. 1 Location of Península Valdés, Patagonia, Argentina

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hydromorphological units, with a methodological criticism that will be explained towards the end of this report. All the maps were constructed using the MapInfo Professional 8.0 software.

General characteristics

Location

Península Valdés (Fig. 1) is located on the coast of the Argentinean Patagonia, between parallels 42°05′ and 42° 53′S and meridians 63°05′ and 64°37′W. It covers an area of 3,600 km^2, and its limits are the Golfo San Matías (San Matías Gulf) to the north, the Atlantic Ocean to the east and south, and the Golfo Nuevo (Nuevo Gulf) and Golfo San José (San José Gulf) to the west. Its central part is joined to the continent by the Istmo Florentino Ameghino (Florentino Ameghino Isthmus).

Socio-economic environment

Península Valdés is an almost unpopulated region, except for the presence of small, isolated cattle farms, and the tourist location of Puerto Pirámides (Fig. 1) on the shore of Golfo Nuevo. This small town, with no more than 500 permanent inhabitants, receives around 150,000 tourists each year due to the attractive proximity to whale-sighting spots. Clearly, one of the most serious limitations to maintaining quality services for tourism is the lack of sufficient freshwater resources.

Historically, water demand has been associated with livestock activities (cattle and sheep), the supply to salt-production workers connected to the exploitation of the Salina Grande and Salina Chica salt pans (Fig. 1) and, more recently, with the increasing water demands of Puerto Pirámides, for the reasons mentioned above.

Climate

The climate is typical of the northeast region of the extra-Andean Patagonia (Labraga et al. 2008), locally modified by the interaction between the atmosphere and the oceanic mass. The mean annual temperature is 13.4°C, with a minimum of 6.4°C in July and a maximum of 20.4°C in January. Winds blow mainly from the western quadrant with an average annual velocity of 25 km/h. (Barros and Rodríguez Seró 1981).

For rainfall data, the records from La Adela Farm (1912–1999) were used, which showed an annual mean of 232 mm, with a rainy quarter between May and July (81 mm in total) and a drier quarter between November and January, with 40 mm (Fig. 2a). This winter rainy season is typical of the Pacific regime (trade winds that precipitate to the west of the Andes, in Chilean territory), with relatively high interannual variability as is usual in arid climates (Fig. 2b), and reduced special cause variation due to the limited amount of rain.

The water balance of the region, following the Thornthwaite and Mather method for field capacities of 50 and 25 mm, shows the existence of a soil moisture deficit for all months but June and July (Fig. 2a). The difference between rainfall and potential evapotranspiration (704 mm/year) determines a soil moisture deficit of 472 mm/year.

According to the Thornthwaite classification, the climate is arid, mesothermal with no water excess and summer concentration of thermal efficiency <48%.

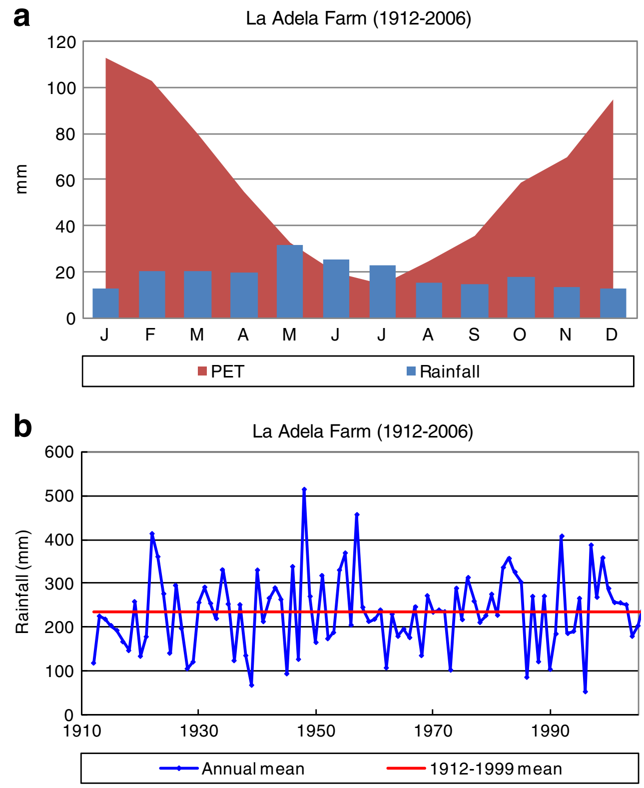

Fig. 2 **a** Monthly rainfall and evapotranspiration distribution records. **b** Annual mean rainfall records

Physiographic characteristics

Península Valdés is characterized by a relatively flat landscape (Fig. 3), with altitudes that do not exceed 120 m a.s.l. Three large endorheic depressions stand out (the Salina Grande, Salina Chica, and Gran Salitral salt pans), in which appear ephemeral hypersaline lakes. Other outstanding characteristics are the Caleta Valdés (Valdés Cove) and all the cliffs that characterize the perimeter of the peninsula (Beltramone 1983).

Concerning the hydrographic features, and consistently with the arid characteristics of the region, no permanent watercourses can be found and, due to the narrow isthmus connecting the peninsula to the continent, allochthonous courses cannot gain access. In this manner, the superficial hydrology is only represented by the three large lakes mentioned above and by ephemeral bodies of water fed by small ephemeral courses during storms (Fig. 3).

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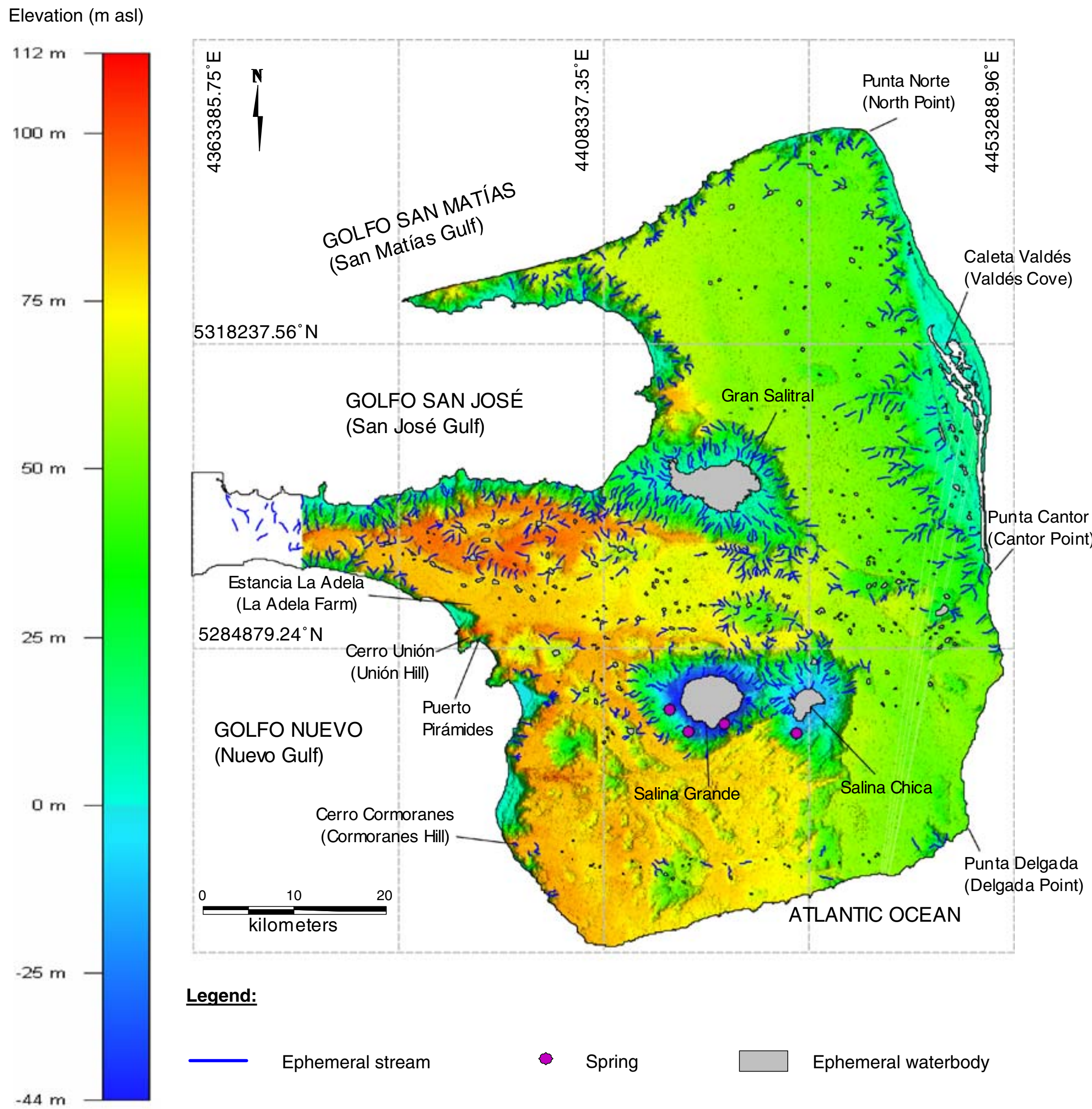

Fig. 3 Topography and drainage map, Península Valdés

Geology

The geology described is represented by Tertiary (Gaiman and Puerto Madryn formations) and Quaternary sediments (Haller et al. 2001) (Fig. 4).

The Gaiman Formation is formed by silts and clays with abundant volcanic ash (cinerites), generally light in color and of solid structure, although normal or lenticular layering can be observed in some banks. It presents fine interlayered sandy levels. Bio-disruption is frequent, with abundant marks of drilling organisms. The base of this formation does not crop out in the area.

Above it is the Puerto Madryn Formation (Haller et al. 2001), composed, from bottom to top, of cineritic mudstone covered by fine-grained, light-grey polymictic sandstone. Among these, there are numerous Ostrea-bearing coquinoid layers whose thickness reaches 0.30 m. Towards the top, there are friable bluish-grey cineritic sandstones, fine-grained and not very thick, as well as calcareous interstratifications. In the roof strata, there are organogenic banks up to 0.20 m thick, with abundant *Ostrea madryna* and scarce individuals of *Ostrea alvarezi*. The thickness of this formation is extremely variable, reaching in its type locality 150 m (Haller 1979).

Scasso and del Río (1988) define a single marine sedimentary cycle that includes the beds known as "Patagoniense" (Gaiman Formation), and "Entrerriense" and "Rionegrense" (both in the Puerto Madryn Formation).

Above this sequence there is a discordant deposit of Quaternary sediments, represented by deposits of glacifluvial origin, which are referred to as Rodados Patagónicos (as described by Fidalgo and Riggi (1970)), as well as others of aeolian, coastal (Caleta Valdés and San Miguel formations), alluvial, and colluvial origin.

The Rodados Patagónicos are polymictic conglomerates with a sand-clay-silt matrix partly cemented with calcium carbonate, which are found on the highest plateau-like surfaces. These deposits reach up to 3 m in thickness (Haller et al. 2001).

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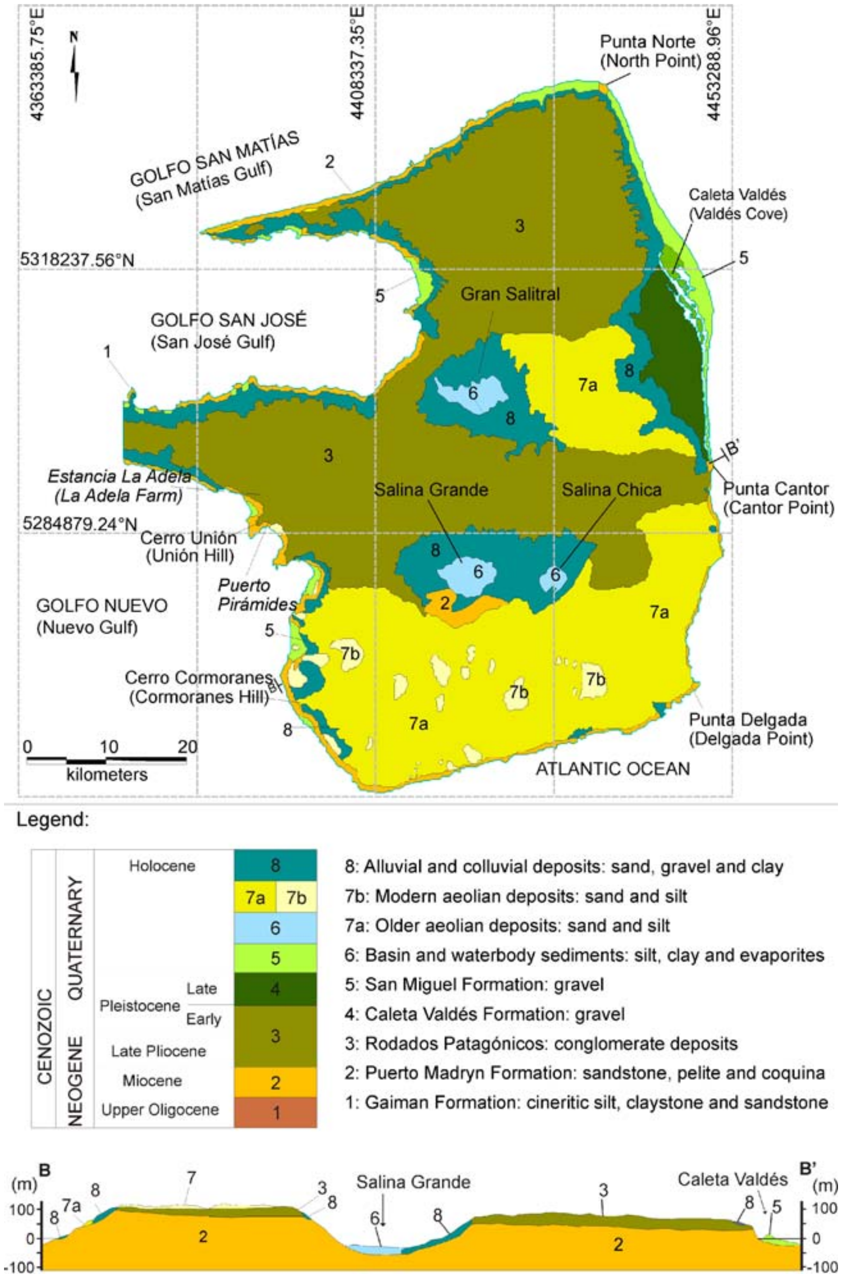

Fig. 4 Geological map (modified from Haller et al. 2001)

The Caleta Valdés Formation (Rovereto 1921) is made up of deposits of marine accretion consisting of well-rounded, medium- to large-sized gravels in a matrix of coarse sand, and remains of marine mollusks such as *Pitar lahillei*, *P. rostrata*, *Ameghinomya antigua*, *Panopea abreviatta*, and *Samarangia exalbida* (Codignotto 1983; Fasano et al. 1984). This formation reaches a thickness of 25 m.

The San Miguel Formation (Haller 1981) is constituted by beach and coastal chain deposits located in the margins of Península Valdés, Golfo Nuevo, Golfo San José and Golfo San Matías. They are made up of gravel and sand with abundant remains of mollusk valves. The thickness of these deposits is from 4–5 m (Weiler 2000).

The sediments of endorheic basins are represented by very fine silt, clayey silt, and clay. The greater basins (Salina Grande, Salina Chica, and Gran Salitral) are characterized by the presence of a saline crust (evaporites) mainly composed of sodium chloride. The thickness of the interlayered beds of salt and silt varies between 1 and 6 m (Brodtkorb 1999).

Among the aeolian deposits, there are some which are slightly older, with a thickness of less than a meter, colonized by vegetation and subjected to erosion by subaerial agents, and on which there are active sand dunes whose thickness may exceed 10 m. Lithologically, it is medium-sized to fine quartz-feldspar sand with a pelitic fraction and very scarce gravel-size fraction.

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The alluvial and colluvial deposits cover areas scattered throughout the region. They are constituted by unconsolidated deposits whose grain size corresponds to fine to medium-sized sand, mixed with varying proportions of silt, clay, and some dispersed gravel. The deposit accumulations are relatively thin and they originated in the material eroded from the different outcropping geological units in the area (Haller et al. 2001).

Tectonics

Different authors have pointed out that Patagonian coasts have been subjected to an intense tectonic activity throughout their geological history (Ameghino 1906; Rovereto 1921; Windhausen 1921; Feruglio 1949/50; Haller et al. 2001; Kostadinoff 1993, among others).

Regarding Península Valdés, Rovereto (1921) pointed out that the Golfo San José and Golfo Nuevo were formed by tectonic activity, as well as the Salina Grande, Salina Chica and Gran Salitral salt pans, and the basin containing the Caleta Valdés.

Kostadinoff (1993) confirms by means of geophysical and geomagnetic explorations what was suggested by Roveretto, and adds that such movements may have been pre-Quaternary as they did not affect the Quaternary deposits.

Soils and vegetation

In general, the soils of the area correspond to the Aridisol and Entisol orders (Fig. 5) (Rostagno 1981).

The first type of soils is typical of arid zones and is characterized by a limited organic horizon above a calcic or natric horizon. These soils occur in the area over the deposits of the Rodados Patagónicos and the older aeolian deposits (see Fig. 4).

Entisols are soils that do not show horizon development and are mainly composed of their parental material. Within Península Valdés they can be found above the present alluvial and colluvial sand dune deposits and the Caleta Valdés and San Miguel formations.

As regards vegetation, the predominant physiognomy corresponds to a bushy steppe mainly featuring *Chuquiraga avellanedae* ('quilembai') accompanied by a grass cover that presents greater or lesser cover between bushes, depending on soil conditions. In the southern area, in

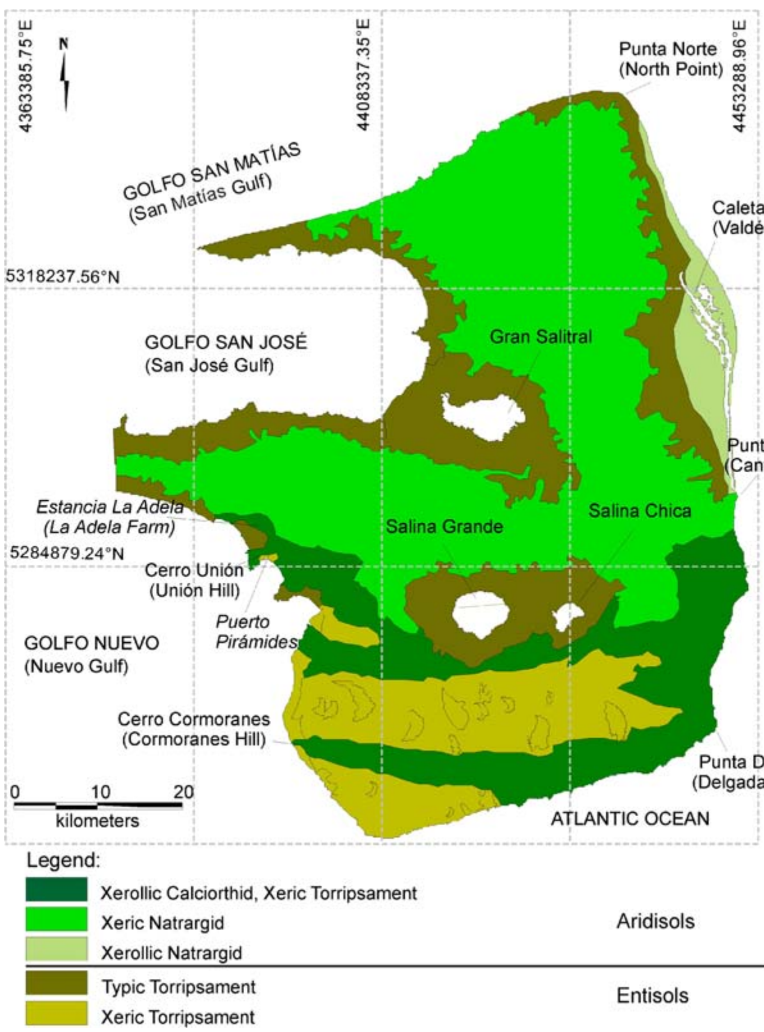

Fig. 5 Soil map (modified from Rostagno 1981)

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which aeolian deposits occur, this bushy steppe yields to a herbaceous steppe of *Sporobolus rigens*, *Stipa tenuis*, and others that cover the soil in its entirety. In the areas where deposits are more recent, a steppe of *Hyalis argentea* ('olivillo') can be found.

Geomorphology

The geomorphological characterization includes both the analysis of present and older landforms. The purpose of this analysis is to have a morphodynamic view that clarifies the relationship between environmental dynamics and the response of landscape to said impulse. The forms analyzed were grouped into four major units (Súnico 1996) (Fig. 6).

Terrace-like plains. Geomorphological unit Tp

This is the predominant feature of the area and it mainly covers the central and northern regions. It is a concave landscape of mild slopes that vary between 1 and 2%. These are characterized by the amount of endorheic basins that occur there (Fig. 3), which display in their interior small waterbodies of the ephemeral type due to the climatic characteristics of the region.

They are carved on the marine sediments of the Puerto Madryn Formation and mostly covered by the Quaternary deposits of the Rodados Patagónicos, except for the highest points in the area such as Cerro Unión (Unión Hill, 109 m a.s.l.) or Cerro Cormoranes (Cormoranes Hill, 106 m a.s.l.).

It is probable that its origin is connected to the Andean orogeny, and topographically it is at a lower level than that of the great plateaus of the extra-Andean Patagonia. From an altitudinal point of view, there are three terrace levels, as can be observed in Figs. 3 and 6: Terrace level I (between 80 and 90 m a.s.l.), Terrace level II (between 70 and 80 m a.s.l.), and Terrace level III (between 50 and 70 m a.s.l.).

Endorheic depressions. Geomorphological unit Ed

These are depressions with no exit or endorheic in origin that are regarded as having an initial tectonic origin and then having been carved by erosion (aeolian, pluvial, mass removal).

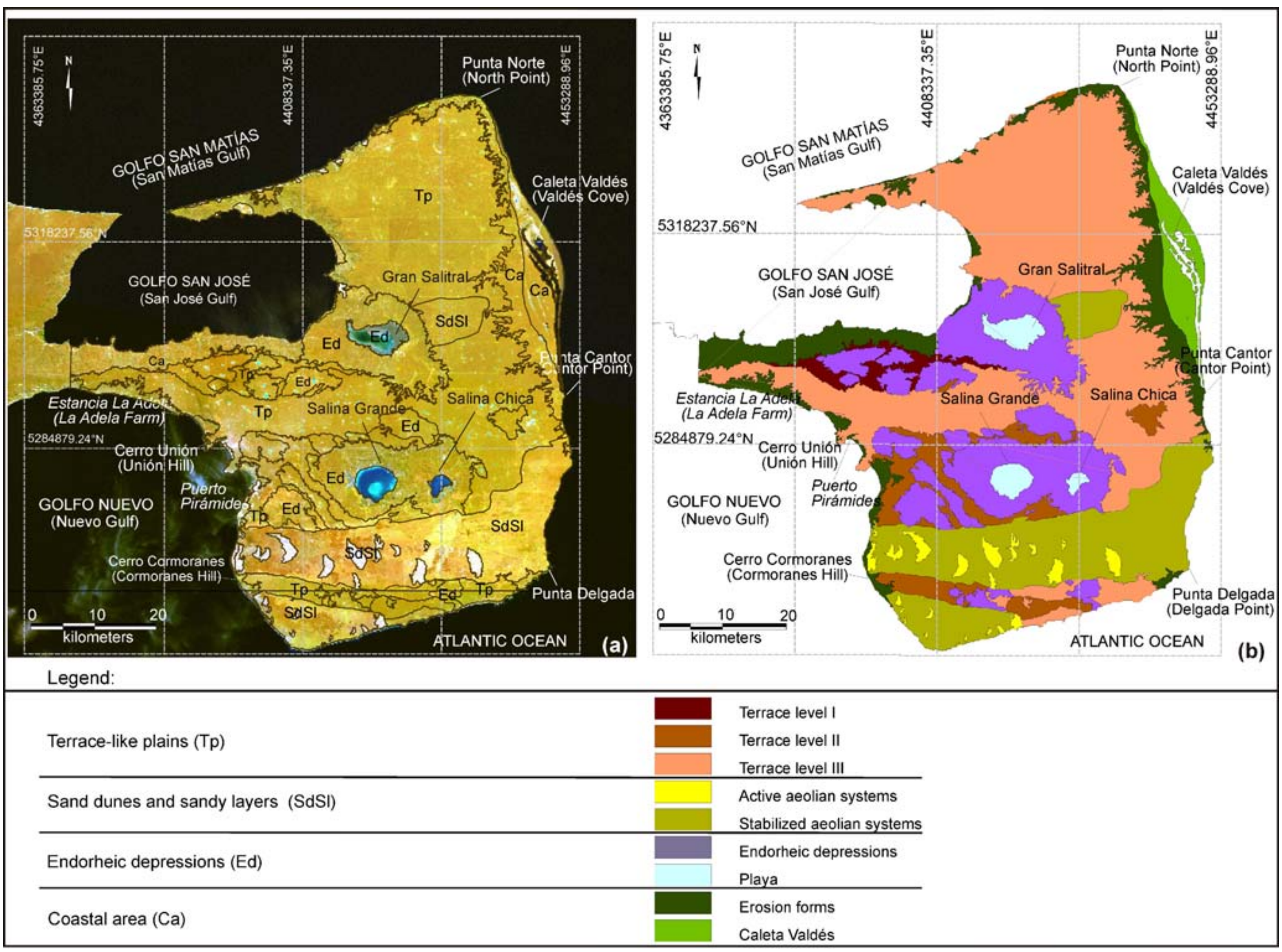

Fig. 6 Geomorphological maps. **a** Satellite image of Península Valdés showing main geomorphological units. **b** Geomorphological subunits

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Carved at the different terrace levels, they are developed from the erosion of the Rodados Patagónicos and part of the Tertiary sediments. Their slopes are smooth and have a centripetal drainage pattern with small, transient water-bodies inside. There are three larger depressions that are different as they have large salt pans inside and reach topographic heights below sea level. These are the basins of the Salina Grande, Salina Chica and Gran Salitral salt pans.

The basins that contain the Salina Grande and Salina Chica salt pans are part of a large elongated depression that runs in an east–west direction, and are separated from each other by a dividing line formed by Tertiary sediments and Rodados Patagónicos. They are two independent endorheic basins, with drainage networks that are typically centripetal and formed by numerous ephemeral courses of different orders (Fig. 3).

The topographic height of the Salina Grande basin is 42 m below mean sea level (–42 m a.s.l.), and that of the Salina Chica is −12 m a.s.l. The edge of the depression that encompasses them is at about 70 m a.s.l., and a difference in level of 112 m between the edge and the bottom is thus created.

The depression where the Gran Salitral is located is 12 km to the north of the basin containing the previously described salt pans. From above, it has a semi-rectangular shape elongated in the west northwest–east southeast direction. The minimum height is −4 m a.s.l. and the edge is at 55 m a.s.l. on its northern end and at 90 m a.s.l. on the south margin, which results in differences in level of approximately 59 and 94 m, respectively. Drainage is centripetal, although in certain sectors there are some courses that are typically parallel. Taking into consideration that the lithology is homogeneous, this change of pattern would support the hypothesis of the tectonic origin of these depressions.

The main geomorphological units observed in these larger depressions are convergent pediments, bajadas and playas (Alvarez et al. 2006), the first two not being mappable at the scale of this work.

Convergent pediments are the erosional surfaces originated by mass-wasting and pluvial activity on the Tertiary and Quaternary sediments that form the slopes of the three largest basins. There is more than one pediment level, which reflects a reactivation of the erosion produced by variations at the base level, whose origin may be due both to climatic and tectonic causes.

The lithologic structure of lowland slopes facilitates the accumulation of alluvial detrital material (sand, gravel, silt), which is deposited at the foot of the pediment surfaces, thus forming *bajadas*. The distribution of these landforms is not uniform around the edges of the salt bodies; there are many sectors where they are highly reduced or they appear in patches.

Playas are the most depressed areas, where water bodies with high salt contents are formed owing to the fact that surface and groundwater runoff flow through Tertiary marine sediments and are then subject to evaporation and concentration in situ. They are temporary lakes covered by a thin salt layer of variable thickness under which an anoxic mud-dominated environment has developed (Brodtkorb 1999).

Sand dunes and sandy layers. Geomorphological unit SdSl

The geomorphological unit SdSl (sand dunes and sandy layers) appears mainly to the south of the depressions of the Salina Grande and Salina Chica salt pans, covering two major strips in the east–west direction in the southern sector. The greatest sand dune strip (385 km^2) begins to the north of the Cerro Cormoranes and spreads to Punta Delgada. The smallest one (93 km^2) begins to the south of the hill and runs towards the southern central area (Fig. 6). Both strips are located to the east of Golfo Nuevo because dominant winds from the west have transported beach sand from there, possibly in periods with low sea levels, coinciding with glaciations.

The height in meters above mean sea level of this geoform is highly variable (Fig. 3) owing to the fact that in its development it covers the existing topography (Tp and endorheic basins). This unit has two different types of aeolian fields: stabilized and active.

Stabilized aeolian systems

These systems are mainly formed by parabolic and linear sand dunes and stabilized by vegetation cover largely composed of *Hyalis argentea* (‘olivillo’) and *Sporobolus rigens* (‘junquillo’). Linear sand dunes appear as parallel or sub-parallel ridges with an approximate east–west direction and most of them are generated by the successive anchoring of parabolic sand dune arms as these advance. Thus, they create a pattern caused by environmental conditions that governed in the past and represent the oldest Quaternary stratigraphic unit of aeolian origin in the area (Súnico 1996).

Active aeolian systems

These are landforms that are almost in their entirety free from vegetation and represent a rejuvenation of the old aeolian field, where the dominant process seems to have been the development of numerous blowouts (Súnico 1996). Their morphology is complex, with a parabolic shape with maximum dimensions of 5 km diameter by 2 km advance front, and it encompasses smaller landforms such as parabolic and linear sand dunes and barchanoid ridges.

There is another area covered in aeolian sediments, in the northern sector of the peninsula, located to the east of the Gran Salitral, stratum-like and fixed by vegetation.

Coastal area. Geomorphological unit Ca

Erosion forms

The predominant process along the perimeter of the peninsula is erosion, represented by pediment surfaces, active cliffs, and wave erosion platforms. They develop on sedimentary rocks corresponding to the Tertiary and only pediment surfaces can be mapped at the scale of this work (Fig. 6).

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Accumulation forms

Caleta Valdés is the most conspicuous accumulation form in the Atlantic coastal area of Península Valdés. It runs from Punta Norte to Punta Cantor and its length is 48 km. According to Rovereto (1921), this cove is located in a depressed area that was caused by a semicircular north–south fault. This basin is almost entirely covered by coastal ridges of gravel, sand, and shells from the Pleistocene, the Holocene, and the Present. Other accumulation forms are the coastal sand dunes and coastal ridges that are discontinuously scattered along the coasts of both gulfs. They are not mappable at the scale of this work.

Hydrogeology

Based on the stratigraphic sequence shown in Fig. 4, the local hydrogeological system is formed by an unsaturated zone corresponding to the Quaternary deposits (mainly sand, gravel, and silt) and partly to the Tertiary sediments, depending on their topographic position. Then there is a phreatic aquifer that is contained, depending on its spatial position, within these same deposits or in the sands of the Puerto Madryn Formation, and which is exploited mainly in the region. Below it there are one or more semi-confined or confined aquifers, limited by clayey or silty-clay strata in the same Puerto Madryn Formation or in the underlying Gaiman Formation. The information available on these deeper aquifers is scarce because they are of no qualitative interest for exploitation. In Fig. 7 a schematic column of the hydrogeological profile can be observed. It is worth mentioning that aquifers are unconsolidated and porous.

The recharge of the system as a whole is originated exclusively by in situ precipitation, since the configuration of the peninsula prevents underground inflow. This happens due to the high soil moisture deficit already mentioned, caused by a combination of special mechanisms in arid regions as described by Hernández et al. (2002) and Hernández (2005).

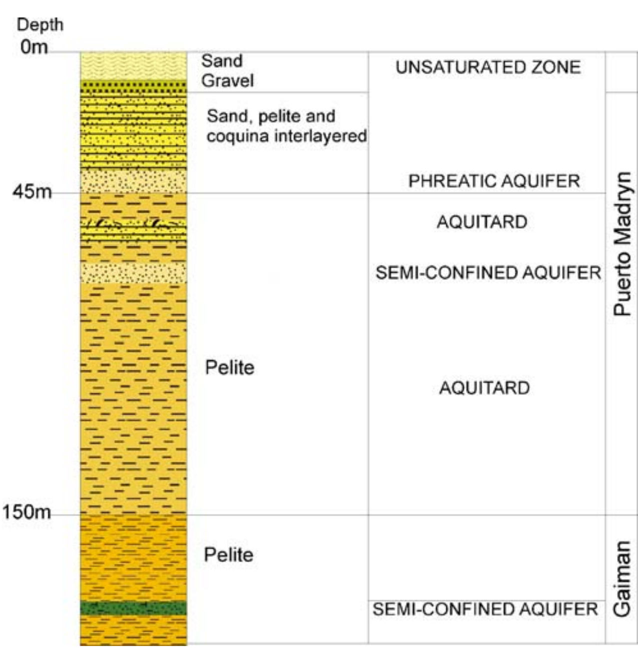

Fig. 7 Hydrogeological sequence

In the case of the phreatic aquifer, the recharge is direct and produced mainly in the sand dune area (SdSl unit), where the combination of a highly permeable soil with sectors practically devoid of vegetation makes the vertical infiltration and percolation of rainwater through the unsaturated zone possible. As regards the deeper underlying aquifers, the recharge is indirect as it is produced by vertical percolation through the aquitard(s), and which is made easier by the presence of joints in the Puerto Madryn and Gaiman Formations. In turn, the coastal accumulation forms (Ca unit) hold lower salinity lenses in a regional context of brackish water, which are the consequence of a recharge favored by the same conditions existing in the main sand dune area. The regional discharge runs towards the Golfo San José and Golfo Nuevo, and the Atlantic Ocean, with significant local components such as the internal drainage system of endorheic basins, including springs (Alvarez et al. 2006), such as the one originally used to supply Puerto Pirámides. The equipotential line that encloses both salt pans is very noticeable on the map, and its central sector reaches −40 m a.s.l. (Fig. 8).

For the phreatic aquifer that is the object of this study, the groundwater flow is represented on the equipotential map. A radial phreatic morphology can be observed, with a tendency towards a convergent cylindrical design around saline bodies and a cylindrical divergent design in the sand dune systems of the southern sector (SdSl). The average hydraulic gradient (i) is 3×10^{-3}, with a maximum value of around 1.6×10^{-2} in the south of Salina Grande and a minimum value of 2×10^{-4} in the southern sector of the peninsula.

By means of the hydraulic conductivity coefficient (K) and the storage coefficient (S), the latter equal to the effective porosity (Φ) in phreatic aquifers, the effective flow rate can be calculated based on Darcy's expression:

$$Ve = K \cdot i/\Phi \tag{1}$$

where, Ve = effective velocity [m/d], K = hydraulic conductivity coefficient [m/d], i = hydraulic gradient [-], Φ = effective porosity [-].

Calculation parameters were obtained by means of constant flow pumping tests in large diameter wells (more than 1 m), which are the most common in the region (Fig. 8), using the Papadopoulos-Cooper method (Kruseman and De Ridder 1975) with values between 25 and 65 m/d for K, 50 to 80 m^2/d for transmissivity (T), and 10^{-3} for Φ. It should be noted that the results yielded by tests carried out in large diameter wells are less reliable than those obtained with conventional diameter drillings, as they depart from the Theisian condition of infinitely small diameter.

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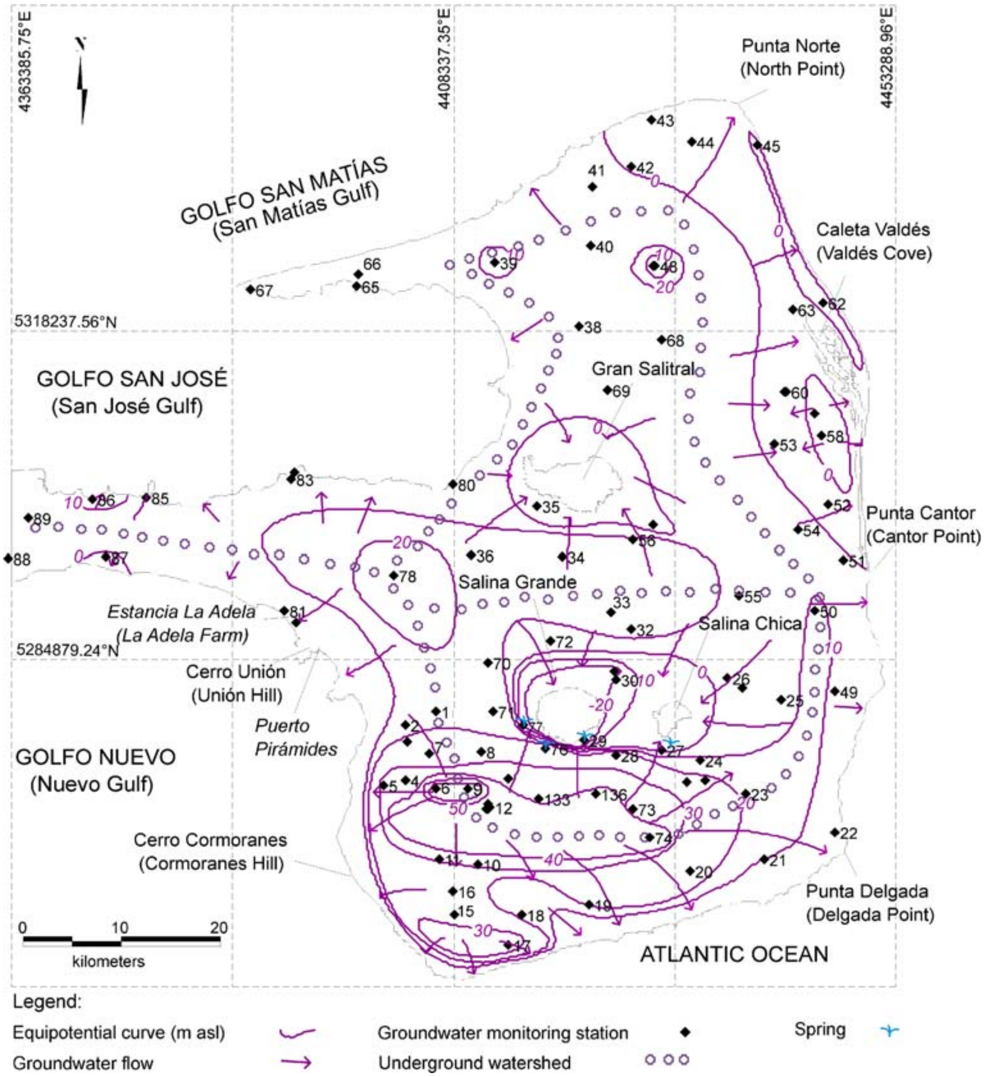

Fig. 8 Equipotential map

The effective velocity for the mean values weighed based on these results would be around 135 m/d, with extreme values of 720 m/d and 10.8 m/d. These results are important as they indicate the anisotropy and heterogeneity of the aquifer.

As regards the semi-confined aquifer, which was observed by means of a set of conventional vertical wells that were close to each other, cased and isolated from the phreatic aquifer, it was not possible to determine its hydrodynamics due to the proximity of these wells and the lack of others to define its groundwater flow. These wells (which are represented as 'well 12' owing to the map scale, Fig. 8) were tested by means of the Hantush-Jacob non-equilibrium constant flow method (Kruseman and De Ridder 1975) with vertical leakage. The results were $T=1.15\times10^{1}\,\mathrm{m^2/d}$, $K=5.79\times10^{0}\,\mathrm{m/d}$, $S=1.64\times10^{-4}$.

It should be stated once again that the limited amount of hydraulic tests, caused by the lack of suitable wells for such a purpose, creates a certain degree of uncertainty in the definition of the hydraulic properties.

As regards the hydrochemical characteristics, Fig. 9 shows a map with the electrical conductivity ranges (μS/cm), which is directly related to salt contents. It reveals the increase that occurs towards discharge areas: near Caleta Valdés the values are above 16,000 μS/cm; the Golfo Nuevo and Golfo San José, as well as the Gran Salitral, Salina Grande and Salina Chica salt pans with values between 8,000 and 16,000 μS/cm; and specific inner areas where similar values are reached. The lowest values correspond to the main recharge areas, located in the SdSl (<4,000 μS/cm) and Tp Terrace level I (4,000 to 8,000 μS/cm) units. Surface and subsurface waters in salt pans have values above 30,000 μS/cm.

In order to improve the hydrochemical description, it would be important to expand the analysis and interpretation of the ionic composition, which is contemplated in future stages of this research project.

Regarding the ionic composition of the water, the major families present are those corresponding to the

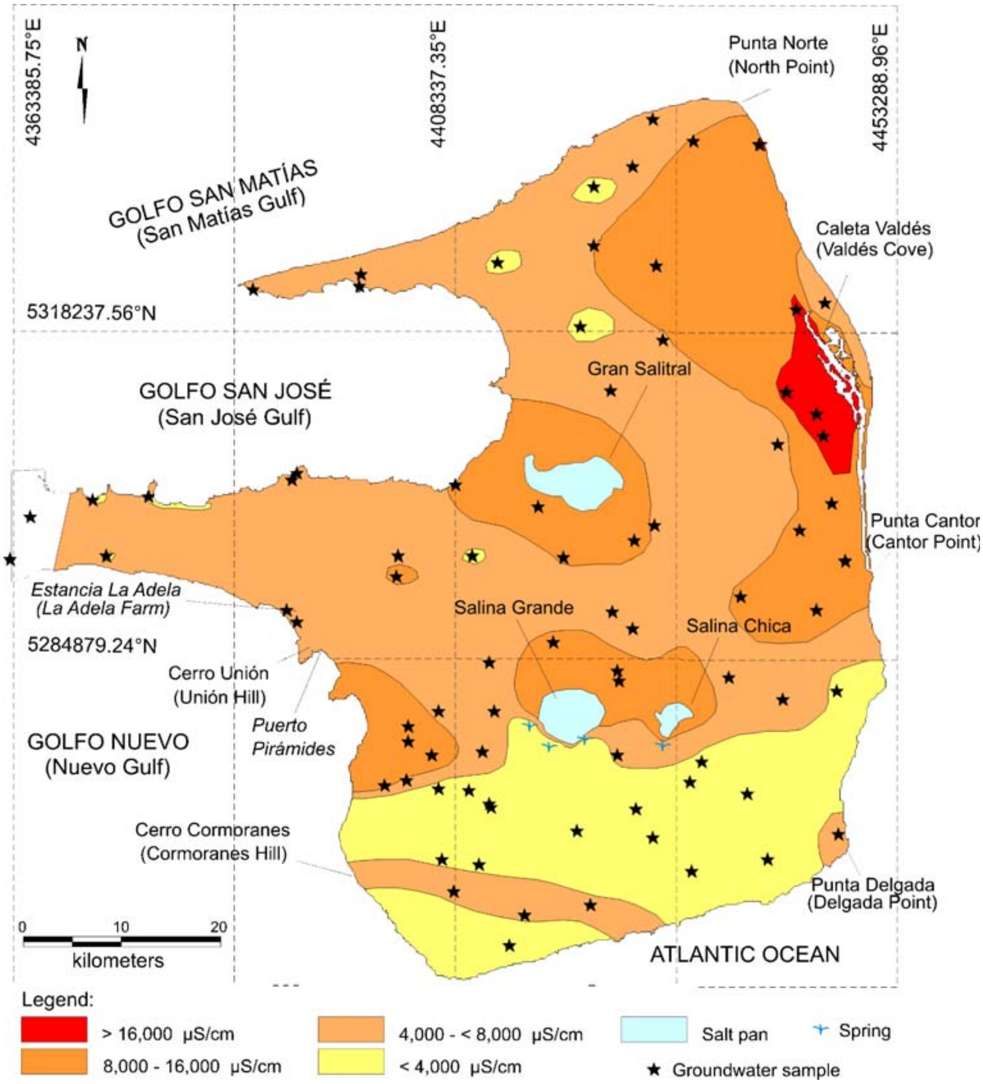

Fig. 9 Electrical conductivity ranges

geomorphological units Ed, SdSl, Tp, and Ca; ions coming from springs have been included as well.

In the case of the endorheic depressions, the groundwater chemistry is mainly a sodium chloride water type, with localized occurrences of sodium chloride-sulfate water type (Fig. 10). The prevalence of chlorides marks the evolution of water and corroborates the discharge properties of the unit.

The SdSl unit presents sodium chloride-bicarbonate and sodium bicarbonate-chloride water types (Fig. 10), with only one sample showing the presence of the calcium/sodium chloride-bicarbonate type. These waters belong to a recent recharge process, as it is evident by the relative abundance of the bicarbonate ion when compared to the other units.

The behavior of the Tp unit does not seem to correspond to the circulation phenomenon essentially, which is suggested by the level of sulfates (Fig. 10), since in this case they are of sodium chloride-sulfate water type and are quite similar to those of the Ed unit. This is possibly due to the fact that there are smaller basins within

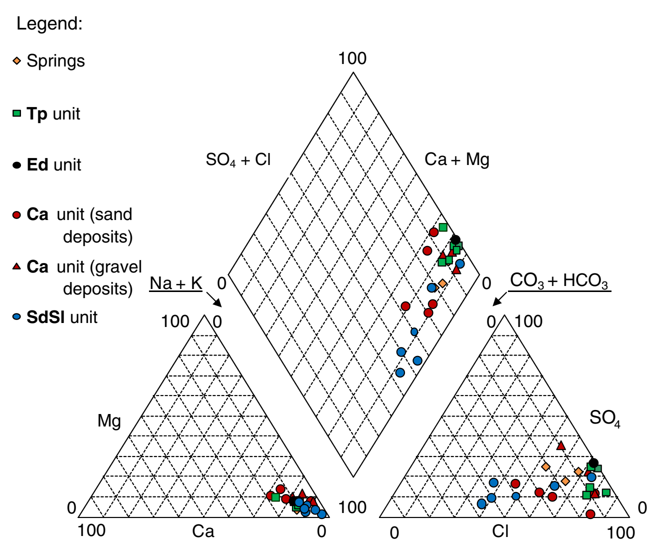

Fig. 10 Piper diagram for major ion composition of spring and groundwater samples from the hydrogeomorphological units of Península Valdés

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the plain, as well as the low flow velocity of the groundwater.

Coastal accumulation forms composed of sandy material present water ranging from sodium chloride-bicarbonate to sodium chloride-sulfate at greater depths. Shapes constituted by gravel material are the same water type, mainly sodium chloride-sulfate (Fig. 10).

Despite the fact that morphologically the spring samples (Fig. 9) belong to the Ed unit, they were graphed separately in Fig. 10, where it can be observed that they are classified as sodium chloride-sulfate water type, with a larger proportion of bicarbonate and a smaller proportion of total salts than the water from the unit containing them.

A better assessment of the chemical evolution in relation to groundwater flow may be carried out by comparing the hydrodynamic map and the one showing the electrical conductivity of the water.

Hydrogeomorphology

As mentioned when describing the methodology used, an analysis was carried out to establish a correspondence between geomorphological units and the hydrogeological phenomenon by considering the hydrolithological, hydrometric, hydrodynamic, and hydrochemical aspects so that units could be described as hydrogeomorphological units (Table 1).

The SdSl unit corresponds to major recharge areas (highly permeable aeolian sands), where the phreatic surface has a radial morphology with a tendency towards a divergent cylindrical one, with a mean gradient of 0.85%. These are low salinity waters (600–2,000 µS/cm), and their water types are sodium chloride-bicarbonate and sodium bicarbonate.

The Tp unit has the most extensive groundwater circulation areas, including local recharge-discharge areas, with the lowest hydraulic gradients in the region (<0.1%) and in general a radial morphology. Its waters are mainly salty with local freshwater sites (1,200–9,500 µS/cm) and mainly a sodium chloride-sulfate water type.

The Ed unit presents the most relevant inland discharge areas (Salina Grande, Salina Chica, and Gran Salitral salt pans) showing a typical radial phreatic morphology with a tendency towards a convergent cylindrical pattern and high hydraulic gradients (the highest in the region) of the order of 3%. Discharge also occurs through stratigraphic and talweg springs as groundwater runs towards salt bodies (Alvarez et al. 2006). Waters are extremely evolved, with electrical conductivity values between 8,000 and 17,000 µS/cm, and are classified as brackish to saline.

The springs that emerge on the southern margin of the endorheic depressions (Salina Grande and Salina Chica salt pans) behave differently. They are less evolved and their conductivities are of the order of 3,000 to 4,000 µS, due to their proximity to the main recharge area located in the sand dune area.

The Ca unit is a local recharge area whose morphology is that of a divergent radial flow field and it is independent from the regional hydrogeomorphological behavior. Its waters are chloride-bicarbonate to chloride types, and they are found in sand dunes whose salinity is lower than that of the coastal ridges.

Conclusions

The research undertaken has shown the usefulness of geomorphologically surveying and interpreting arid regions, where there is a greater correspondence between hydrogeological units and the landforms containing them, which can be easily identified by interpretation of satellite images due to the lack of vegetation cover and the great contrast between materials.

In an arid climate with rainfall of 232 mm/year and a soil moisture deficit of 472 mm/year, the hydrogeological system of Península Valdés is formed by a phreatic aquifer and one or more semi-confined/confined aquifers. Once the main hydrodynamic characteristics had been identified and the hydraulic parameters for these aquifers had been determined (as well as their hydrochemical behavior), it was observed that the dynamics of the phreatic aquifer and its hydrochemical characteristics are closely related to the different geomorphological units, which enabled the delimitation of hydromorphological units that bear a

Table 1 Summary of characteristics of hydromorphological units in Península Valdés

Geomorphic unit	Phreatic level (m a.s.l.)	Hydrodynamics	Electrical conductivity (µS/cm)	Hydrochemistry
Sand dunes and sandy layers (SdSl)	Between 70 and 20	Main recharge areas, radial divergent cylindrical morphology	600–2,000	Sodium chloride-bicarbonate and sodium bicarbonate-chloride
Terrace-like plains (Tp)	Between 0 and 20	Main circulation areas, local recharge and discharge areas	1,200–9,500	Sodium chloride-sulfate
Endorheic depressions (Ed)	Between 0 and −40	Local discharge areas, radial convergent cylindrical morphology	8,000–17,000	Sodium chloride with localized occurrences of sodium chloride-sulfate
Coastal area (Ca - accumulation forms)	Between 45 and −3	Local recharge areas	1,100–7,500	Chloride-bicarbonate to chloride

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significant relationship with recharge, circulation, and discharge areas.

Therefore, hydromorphological interpretation may be extremely useful as a tool for the hydrogeological analysis of arid and semi-arid regions with scarce information, as is the case of the Argentinean extra-Andean Patagonia.

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References

Alvarez MP, Weiler NE, Hernández MA (2006) Geohidrología de humedales cercanos a la costa con cota bajo nivel del mar, Península Valdés, Argentina [Geohydrology of below sea level nearshore wetlands, Península Valdés, Argentina] In: Rev Latinoam Hidrogeologia [in Spanish] 6(1):35–42

Ameghino F (1906) Les formations sédimentaires du Crétacé supérieur et du Tertiaire de Patagonie [The Upper Cretaceous and Tertiary sedimentary formations of Patagonia] Records of the Museo Nacional de Buenos Aires [in French] (8) Buenos Aires, Argentina

American Public Health Association (1998) Standard methods for the examination of water and wastewater, 20th edn. American Public Health Association, Washington, USA

ASTM D 4448-85a (2001) Standard Guide For Sampling Groundwater Monitoring Wells, ASTM International West Conshohocken, PA, USA

Barros V, Rodríguez Seró JA (1981) Measurement strategies: use of short observation records for estimating the annual wind variations. Proceedings of the International Colloquium on Wind Energy and BHRA Fluids Engineering, Brighton, UK, pp 3–28

Beltramone CA (1983) Rasgos fisiográficos de Península Valdés (Chubut, Argentina) [Physiographic features of Península Valdés (Chubut, Argentina)] Terra Aridae [in Spanish] 2 (1):168–188

Brodtkorb A (1999) Salinas Grande y Chica de la Península de Valdés, Chubut. [Salina Grande and Salina Chica salt pans of Península Valdés, Chubut] In: Zappettini EO (ed) Recursos Minerales de la República Argentina (SEGEMAR) [in Spanish]

Codignotto JO (1983) Depósitos elevados y/o de acreción Pleistoceno-Holoceno en la costa fueguino-patagónica. [Pleistocene-Holocene elevated and/or accretion deposits on the coast of Tierra del Fuego and Patagonia] Proceedings of the Simposio Oscilaciones del Nivel del Mar durante el último Hemiciclo Demiglacial en la Argentina (CIC), Mar del Plata, Argentina, pp 12–26 [in Spanish]

Fasano JL, Isla F, Schnack E (1984) Significado paleoambiental de los depósitos del Pleistoceno Tardío de Camet Norte (Partido de Mar Chiquita, Provincia de Buenos Aires) [Paleoenvironmental meaning of the Late Pleistocene deposits in North Camet (County of Mar Chiquita, Province of Buenos Aires] Rev Asoc Geol Argent [in Spanish] XXXIX(3–4):244–250

Feruglio E (1949–1950) Descripción geológica de la Patagonia [Geological description of Patagonia] In: Dirección General Yacimientos Petrolíferos Fiscales, (1–3) Buenos Aires, Argentina [in Spanish]

Fidalgo F, Riggi JC (1970) Consideraciones geomórficas y sedimentológicas sobre los Rodados Patagónicos [Geomorphological and sedimentological considerations about the Rodados Patagónicos] Rev Asoc Geol Argent [in Spanish] XXV(4):430–443

Haller MJ (1979) Estratigrafia de la región al poniente de Puerto Madryn [Stratigraphy of the region to the west of Puerto Madryn] Proceedings of the 7°Congreso Geológico Argentino, Neuquén, Argentina [in Spanish] (1):285–297

Haller MJ (1981) Estructura y mineralización en la Cordillera Patagónica [Structure and mineralization in the Patagonian mountain range] PhD Thesis, Universidad de Buenos Aires, Argentina [in Spanish] p 125

Haller M, Monti A, Meister C (2001) Hoja Geológica 4363-I, Península Valdés [Geological Sheet 4363-I, Península Valdés] SEGEMAR Buenos Aires, Argentina [in Spanish]

Hernández MA (2005) Mecanismos de recarga de acuíferos en regiones áridas (síntesis) [Aquifer recharge mechanism in arid regions (abstract)] Proceedings of the II Seminario Hispano Latinoamericano sobre Temas Actuales de la Hidrología Subterránea. Río Cuarto, Córdoba, Argentina [in Spanish] pp 249–254

Hernández MA, González N, Sánchez R (2002) Mecanismos de recarga de acuíferos en regiones áridas. Cuenca del Río Seco, Provincia de Santa Cruz, Argentina [Aquifer recharge mechanism in arid regions. Río Seco basin, Province of Santa Cruz, Argentina] Proceedings of the XXXII IAH Congress and VI Congreso ALHSUD, CD-ROM. Mar del Plata, Buenos Aires, Argentina [in Spanish]

Kostadinoff J (1993) Estudio geofísico de la Península de Valdés y los golfos norpatagónicos [Geophysical study in Península Valdés and the North Patagonian gulfs] Rev Asoc Geol Argent [in Spanish] 47(2):229–236

Kruseman GP, De Ridder NA (1975) Análisis y Evaluación de los Datos de Ensayos por Bombeo [Analysis and Evaluation of Pumping Test Data] Published by the Intl Inst for Land Reclamation and Improvement Wageningen, The Netherlands

Labraga JC, Davies EC (2008) Datos de la estación meteorológica del Centro Nacional Patagónico - CONICET [Data from the meteorological station of the National Patagonian Center - CONICET] http://www.cenpat.edu.ar/. Cited 20 January 2008 [in Spanish]

Monteith JL (1965) Evaporation and the environment. In: The state and movement of water in living organisms. Proceedings of the 19th Symposium, Society of Experimental Biology, Cambridge Univesity Press, London, UK

Rostagno CM (1981) Reconocimiento de suelos de Península Valdés [Reconnaissance of soils in Península Valdés] Contribución N° 44, Centro Nacional Patagónico [in Spanish] pp 1–24

Rovereto G (1921) Studi di geomorfologia argentina. V: La Penisola Valdés [Research on Argentinian geomorphology. V: Valdés Península] Boll Soc Geol Ital, Rome, Italy [in Italian] 30:1–47

Scasso RA, del Río C (1988) Ambientes de sedimentación, estratigrafía y proveniencia de la secuencia marina del Terciario superior de la región de Península Valdés, Chubut [Sedimentation environments, stratigraphy and origin of the upper Tertiary marine sequence of Península Valdés] Rev Asoc Geol Argent [in Spanish] XLII(3–4):291–321

Súnico A (1996) Geología del Cuaternario y ciencia del suelo: relaciones geomórficas-estratigráficas con suelos y paleosuelos [Quaternary geology and soil science: geomorphic/stratigraphic relationships with soils and paleosoils] PhD Thesis, Universidad Nacional de Buenos Aires, Argentina [in Spanish]

Thornthwaite CW, Mather JR (1957) Instructions and tables for computing potential evapotranspiration and water balance. Drexel Institute of Technology, Laboratory of Climatology. Publ Climatol 3(10):183–311

Vàzquez Suñé E (2002) Easy_Quim 6.0. Departamento de Ingeniería del Terreno de la Universidad Politécnica de Cataluña, Barcelona, Spain [in Spanish]

Weiler NE (2000) Holocene sea levels and volcanic ash to the southwest of Golfo San José, Península Valdés, Argentina. In: Coastal Interactions during Sea-Level Highstands Proyecto

IGCP N° 437 (UNESCO-IUGS): Comisión de Líneas de Costa - Unión Internacional para el Cuaternario (INQUA) Comisión de Sistemas Costeros - Unión Geográfica Internacional (IGU). Patagonia 2000 International Conference (Puerto Madryn, Chubut), 29 October to 3 November 2000, (abstracts):83–86

Windhausen A (1921) Informe sobre un viaje de reconocimiento geológico en la parte noreste del Territorio de Chubut, con referencia especial a la provisión de agua de Puerto Madryn. Con un estudio petrográfico de algunas rocas por R. Beder [Report on a geological reconnoissance expedition to the northeast of the Chubut territory, with a special reference to the water supply of Puerto Madryn. With petrographic research on some rocks by R Beder] Bulletin 24B. Dirección General de Minas, Buenos Aires, Argentina [in Spanish]

 DOI 10.1007/s10040-009-0528-x