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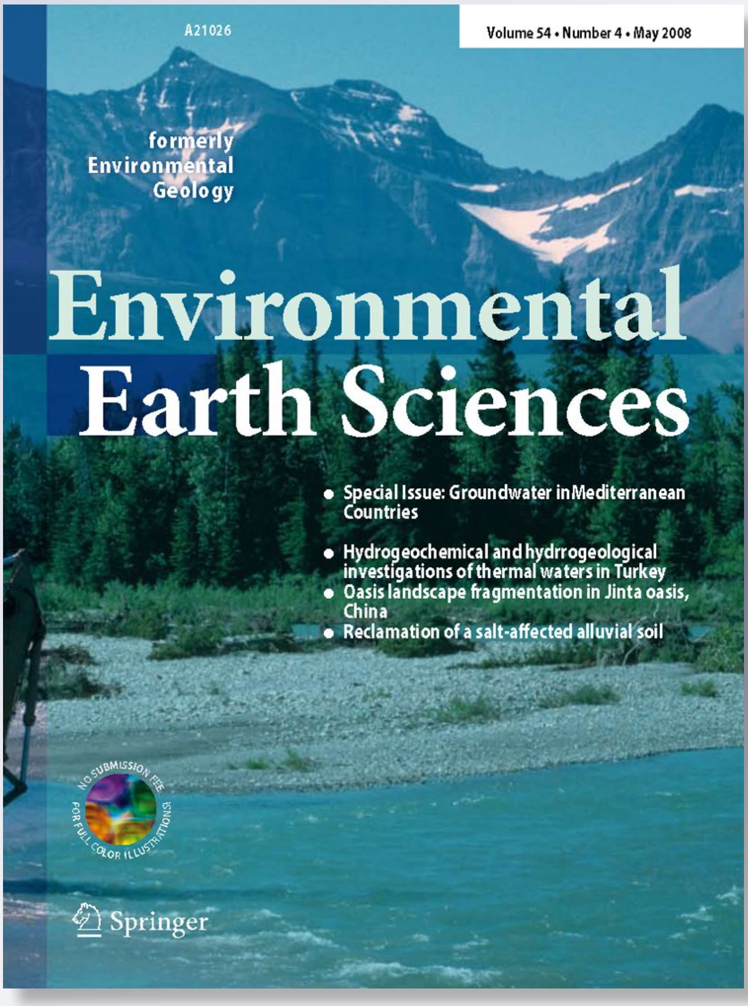

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ORIGINAL ARTICLE

Groundwater flow model, recharge estimation and sustainability in an arid region of Patagonia, Argentina

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Abstract The Península Valdés, in northeastern Patagonia, Argentina, is characterised by its arid climate and the lack of perennial watercourses; thus, all economic activities depend on the groundwater resources. Water demand is mainly associated with tourism, which is centralised in Puerto Pirámides and supplied by a water desalination plant, and to sheep farming, supplied by the local aquifer. Due to the exponential growth of tourism, the government is planning to exploit groundwater and convey it by aqueduct to the abovementioned locality. The objectives of this study were to corroborate the conceptual geohydrological model, to develop a mathematical model to simulate the response of the aquifer to different scenarios, and to assess the incidence of water input into the system as a variable—a function that poses difficulties in the models for arid regions. The Visual Modflow 4.1 code was used, calibrating it in trial-and-error mode, changing the recharge and hydraulic conductivity parameters with different variants in the recharge zone and in the inclusion or exclusion of the evapotranspiration module. Results indicate the importance of the recharge analysis by treating rainfall at daily time steps. The adjusted model was exposed to four scenarios with variations in water input and in output by pumping. It can be concluded that under different input conditions, but with a controlled extraction, the system responds in a sustainable manner.

Keywords Groundwater model · Recharge · Arid region · Patagonia · Argentina

Introduction

One of the main natural limitations to the social and economic development of arid and semi-arid regions is their limited water availability. This is the reason why research into groundwater resources is especially relevant.

In this regard, there are many contributions worldwide dealing with the subject from a regional or thematic viewpoint (Schoeller 1959; UNESCO 1979; Stephens and Knowlton 1986; Edmunds et al. 1988; Sharma 1989; Lerner et al. 1990; Cook et al. 1994; Flint et al. 2004; Scanlon et al. 2002, 2006; among many others), but only few focus on the arid and semi-arid southern area of Argentina, the Extra-Andean Patagonia (Stampone and Cambra 1983; Auge et al. 2006; Hernández et al. 2008, 2010; Trovatto et al. 2007; Alvarez et al. 2008a, 2010a). A common denominator of all prior contributions at a local level is the absence of numerical, analytical and forecasting models as aids in the management of sustainable use, despite the critical situation of the available water supply. In the aquifer systems of arid and semi-arid regions, the most important variable, and yet the most difficult one to quantify in modelling—once the mechanisms involved have been identified conceptually—is the recharge. It is exactly this aspect that to a large extent this contribution aims at addressing.

In the Extra-Andean Patagonia, which is the site chosen for this study, the lack of permanent watercourses—except for snow-fed exotic streams—has caused groundwater resources to become the basis of all economic activities. Within this region, the study area is located in the northern sector, to the south of the Península Valdés, between latitudes 42°32′ and

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42°53′S and longitudes 63°34′ and 64°22′W, covering an area of 1,700 km^2. The northern limit is constituted by a coinciding surface and groundwater divide; to the west the limit is the Golfo Nuevo; and to the south and east, the Atlantic Ocean (Fig. 1). In this area the water demand was historically associated to the extensive sheep farming practised all throughout the peninsula, and eventually to tourism, which is centralised in Puerto Pirámides (with 500 permanent inhabitants and over 300,000 tourists a year). The sheep farming industry is supplied by the local Tertiary aquifer, and tourism by a seawater desalination plant located on the coast of the Golfo Nuevo. As a result of the exponential growth in tourism in the last few decades, the current government is planning to exploit groundwater and convey it by aqueduct to Puerto Pirámides. All prior hydrogeological studies carried out to evaluate the aquifer resources have consisted in regional surveys, which focused on locating springs for local supply (Stampone and Cambra 1983) and in conceptual syntheses as the ones mentioned above, which created the need to develop contributions that are more detailed.

The aim of this work is to validate the conceptual model for the geohydrological system (Alvarez 2010) and to develop a mathematical model to simulate the response of the aquifer to different scenarios, both climatic and anthropic. It is also an objective to assess the incidence of water input into the system as a variable in the modelling, as it is a function that usually creates difficulties in the mathematical models of arid regions.

General characteristics

Climate

The climate is described on the basis of monthly rainfall records from the Estancia La Adela, a local farm, and daily rainfall, temperature and wind records from the weather station of the Centro Nacional Patagónico (CENPAT), in Puerto Madryn.

The mean annual rainfall is 234 mm according to the records of the Estancia La Adela (1912–2006) and 223 mm according to the records of the CENPAT (1979–2008). Even if the spatial variability is not significant, the range of the annual records should be highlighted, as they fluctuate between 50 and 500 mm/year (Fig. 2). This is a typical characteristic of arid and semi-arid climates, in which a storm may alter substantially the annual mean, which becomes relevant when analysing the recharge phenomenon. Regarding its intra-annual distribution, an autumn–winter seasonality can be observed, with a rainy period in the May–July quarter and a drier quarter in November–January.

The mean annual temperature is 13.4°C, varying between extremes of 6.4°C (July) and 20.4°C (January). Concerning the wind, its annual mean velocity is 16.6 km/h with a maximum of 19.4 km/h in December and a minimum of 14.8 km/h in May (Labraga and Davies 2008), the dominant directions being southwest and west throughout the year.

The minimum wind velocities occur in winter, which is of particular hydrological importance since winter is the season in which maximum precipitations, minimum temperatures and potential evapotranspiration, and maximum relative humidity occur, generating increased recharge possibilities.

According to the Köppen–Geiger–Pohl classification (Geiger and Pohl 1954), the study area can be classified as a BWk climate (arid with less than 400 mm precipitation, with a water deficit and a mean annual temperature below 18°C).

Geology and geomorphology

According to Haller et al. (2001), the surface geology shows a predominance of Plio-Pleistocene deposits in the

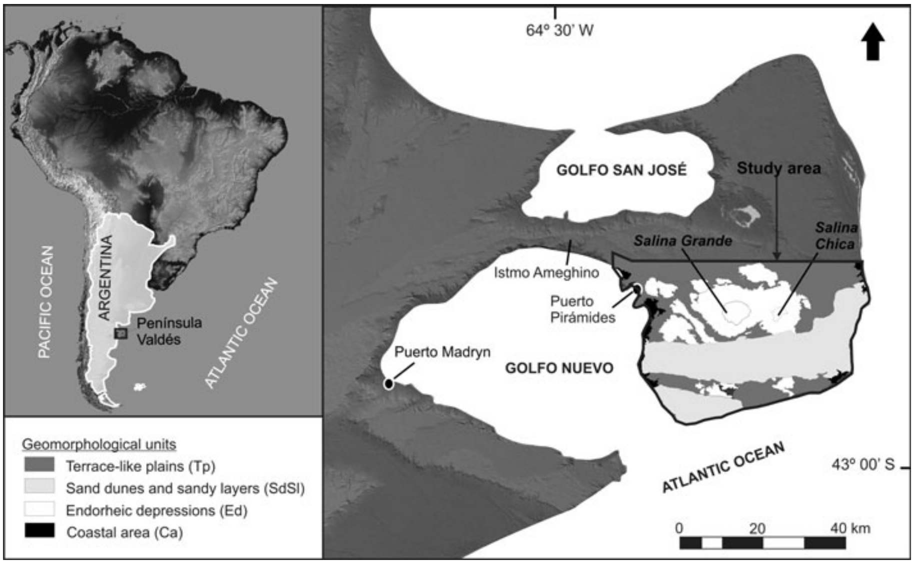


Fig. 1 Location and geomorphological map of the study area in Península Valdés, Chubut, Argentina

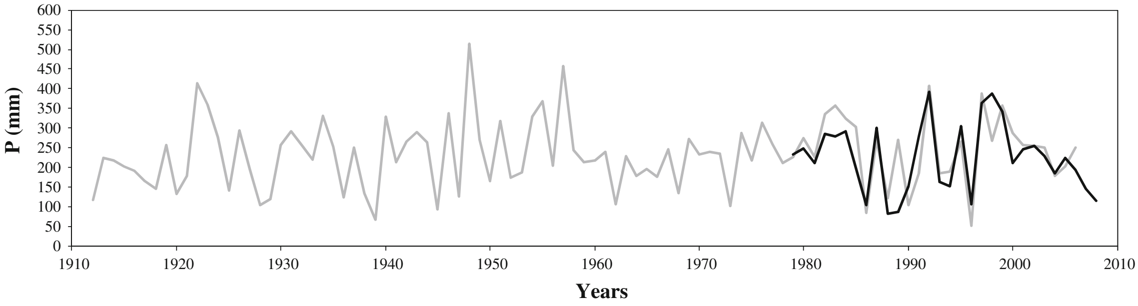


Fig. 2 Annual precipitation recorded at the Estancia La Adela (*grey line*) and CENPAT stations (*black line*)

northern section of the study area, composed of partially cemented lithic gravels supported by a silty/clayish matrix (i.e., the Rodados Patagónicos, or Patagonian Shingle Formation); to the south, eolian Quaternary deposits (i.e., sand and silt) predominate, which occurs as well to the south of the topographic depressions in the centre of the study area, where these deposits overlie colluvial and alluvial sediments. The Tertiary outcrops of the Puerto Madryn Formation (i.e., interbedded silt, clay, sand, tuff and coquina) are limited to the southern boundary of the depression containing the Salina Grande salt pan and to the coastal cliffs that predominate along the coastal area.

In the subsurface, below a thin Quaternary cover, the sequence is characterised by the presence of the Puerto Madryn Formation, with a thickness of up to 150 m, overlying the Gaiman Formation, with an estimated thickness of 280 m and composed of ashy mudstones.

According to its topographic and geomorphological characteristics (Fig. 1), the landscape is represented by four main units: a system of Terrace-like Plains (Tp), with a plane-concave relief, carved on Tertiary sediments and covered almost completely by the Rodados Patagónicos; Endorheic Depressions (Ed), small depressions of eolian origin and large ones of mixed origin, easily distinguished by the ephemeral salt water bodies they contain (the Salina Grande and Salina Chica salt pans) and which may reach topographic heights below sea level; two strips of Sand Dunes and Sandy Layers (SdSl), in an east–west direction, which develop over the southern sector, covering both the Terrace-like Plains and the Endorheic Depressions; and a Coastal Area (Ca), reflecting the predominance of erosive processes over accumulation processes, which can be observed mainly in the occurrence of active cliffs and pediment surfaces.

Soils are coherent with the large-scale landforms, the parental materials and the climate. The only soil orders that occur are Aridisols and Entisols, supporting a typically xerophytic vegetation with a high degree of specialisation in water economy.

Hydrogeology

The hydrolithological profile (Alvarez et al. 2010b) begins with an unsaturated zone of variable thickness (between 0 and 70 m, depending on the topographic position). Then there is a phreatic aquifer occurring in Quaternary and/or Tertiary sediments, followed by an aquitard of irregular geometry, which separates a semi-confined aquifer that may be overlying the Puerto Madryn Formation or the Gaiman Formation, depending on its relative depth. Even though the hydrolithological characteristics of the underlying formation are not well known, the analysis of previously-drilled wells (Alvarez et al. 2010b) would suggest the existence of other aquifer levels, possibly confined by aquiclude strata.

Hydrodynamics

The description of the hydrodynamic cycle begins with the characterisation of the recharge phenomenon, and then it focuses on the circulation, ending with the discharge.

Despite the fact that recharge is the most important process in the cycle, it is the input function of the system that causes most difficulties when trying to quantify it, especially in arid regions where the necessary data to assess it is usually insufficient.

The characteristics of the limits of the study area rule out the possibility of infiltration from streams and/or outside recharge for the main aquifer studied and, having discarded the possibility of imported water, the only alternative to explain the presence of groundwater in the study area is water of meteoric origin.

On the basis of climatological data and piezometric measurements, the recharge was quantified by the soil water balance method and piezometric fluctuation analysis.

The monthly or annual soil water balance is the most widely disseminated method used to calculate recharge (Carrica 2009), except in arid regions where it becomes inadequate, as well as any other empirical or semi-empirical modular method to assess real evapotranspiration, since it would yield a water deficit, thus numerically ruling out the possibility of recharge (Hernández 2005). A daily time-step soil water balance, which is recommended for arid regions (Simmers 1997), was used in the SdSl and Tp units, as their soils represent two different types. The Balshort software was used (Carrica 1993), which yielded for the 1979–2008 period a mean value of 50 mm/year in the SdSl unit and 21 mm/year in the Tp unit, representing 22 and 9% of the total rainfall (223 mm) respectively. The results for the simulation period (2005–2008) are presented below, when the calibration of the mathematical model is discussed.

In order to contrast such a value, an assessment of the recharge was undertaken on the basis of a water level fluctuation analysis in three wells located in the SdSl unit, where the maximum water level fluctuations recorded in different years within the simulation period (380, 280 and 610 mm) could be attributed to natural fluctuations. Considering the mean value (423 mm) multiplied by the estimated effective porosity (0.12), the increase of the water table was calculated at 51 mm, which would represent approximately 23% of the mean annual precipitation.

On the other hand, contributions focusing on similar areas of the Extra-Andean Patagonia have indicated recharge values on the order of 0.34 with respect to precipitation (Hernández et al. 2002).

In comparing the estimates obtained on the basis of the daily time-step water balance surplus (50 mm), of the water table fluctuation method (51 mm), and of the estimate which would have been obtained by applying the 0.34 recharge factor (76 mm), an acceptable correspondence can be observed between the different methods, which makes all of them potentially applicable. The daily time-step water balance value was chosen for the simulation, as it was the most conservative, and because this method allows for the discretisation of time.

Effective recharge is favoured by mechanisms such as the real reduction of consumptive water loss, fast infiltration, fast concentration, delayed recharge, supply by stream loss and concurrent mechanisms (Hernández et al. 2010). The identification of the different mechanisms makes it possible to zone the area by considering the possible input into the system, once the real reduction of consumptive water loss and the fast infiltration processes, as well as the concurrent mechanisms, have been determined.

The reduction of consumptive water loss occurs due to the type of vegetation (xerophytes), which exhibits several adaptive features to withstand the lack of water (Rolando et al. 1998), and the low vegetation cover, which rarely reaches 80%, generally reaching 60%, and in the sand dunes almost 0%.

Fast infiltration occurs when the surface geological material is highly permeable, such as in the case of eolian sands, glacial-fluvial gravels, and alluvial and colluvial deposits.

The SdSl unit (Fig. 1)—a landform with a high primary permeability, constituted by ancient (vegetated) and active (non-vegetated and without edaphic development) eolian deposits—overlies the Rodados Patagónicos and/or the Puerto Madryn Formation. This vertical arrangement of the hydrogeological cross-section allows the precipitation to infiltrate rapidly and to reach the Tertiary formation, thus recharging the aquifer. This mechanism is also aided by the low retention capacity of the soils (Aridisols or Entisols), whose low field capacity values foster relatively high infiltration rates.

Finally, the convergence of the reduction of consumptive loss and fast infiltration mechanisms in the SdSl area could be confirmed. In this unit, the presence of loose sand, very poorly developed or absent soils, and sparse xerophytic vegetation represents the optimal recharge conditions.

The regional hydrodynamic characterisation was defined by Alvarez et al. (2010a) on the basis of the survey of 89 wells in the Península Valdés, where two main groundwater divides could be observed. One of them runs parallel to the coast of the peninsula and separates the regional discharge into the sea (i.e., towards the Atlantic Ocean, and the Golfo Nuevo, Golfo San José and Golfo San Matías gulfs) from the local discharge towards the centripetal depressions (i.e., the Gran Salitral, Salina Grande and Salina Chica salt pans). The other divides the area into a northern and a southern sector, at the latitude of the isthmus (Fig. 3); the latter being the study area.

In the surveying and groundwater level monitoring field trips (2006, 2007 and 2008), 79 monitoring points were selected in the study area, as well as other peripheral wells in the region. On the basis of the information obtained, an equipotential map for each of the 3 years was constructed and, given the similarities in the morphology of the water table, the data corresponding to 2008 was chosen for the conceptual interpretation and description. Figure 3 shows a predominantly radial divergent morphology in the central–southern sector, coinciding with the groundwater divide, which indicates this is the preferential recharge area. This morphology corresponds to the SdSl geomorphological unit, which had already been identified as a recharge area in the recharge analysis of the system. Water flows from this sector towards the Golfo Nuevo and the Atlantic Ocean, and towards the Ed unit (Salina Grande and Salina Chica).

The main circulation areas are located between the SdSl and Ed units, and between the SdSl and Ca units, whereas the Tp unit is the landform that better represents circulation in the hydrodynamic cycle.

Local discharge can be observed on the southern slopes of the Ed unit (between topographic heights 0 and −40 m asl) as springs or wet spots (Alvarez et al. 2008b).

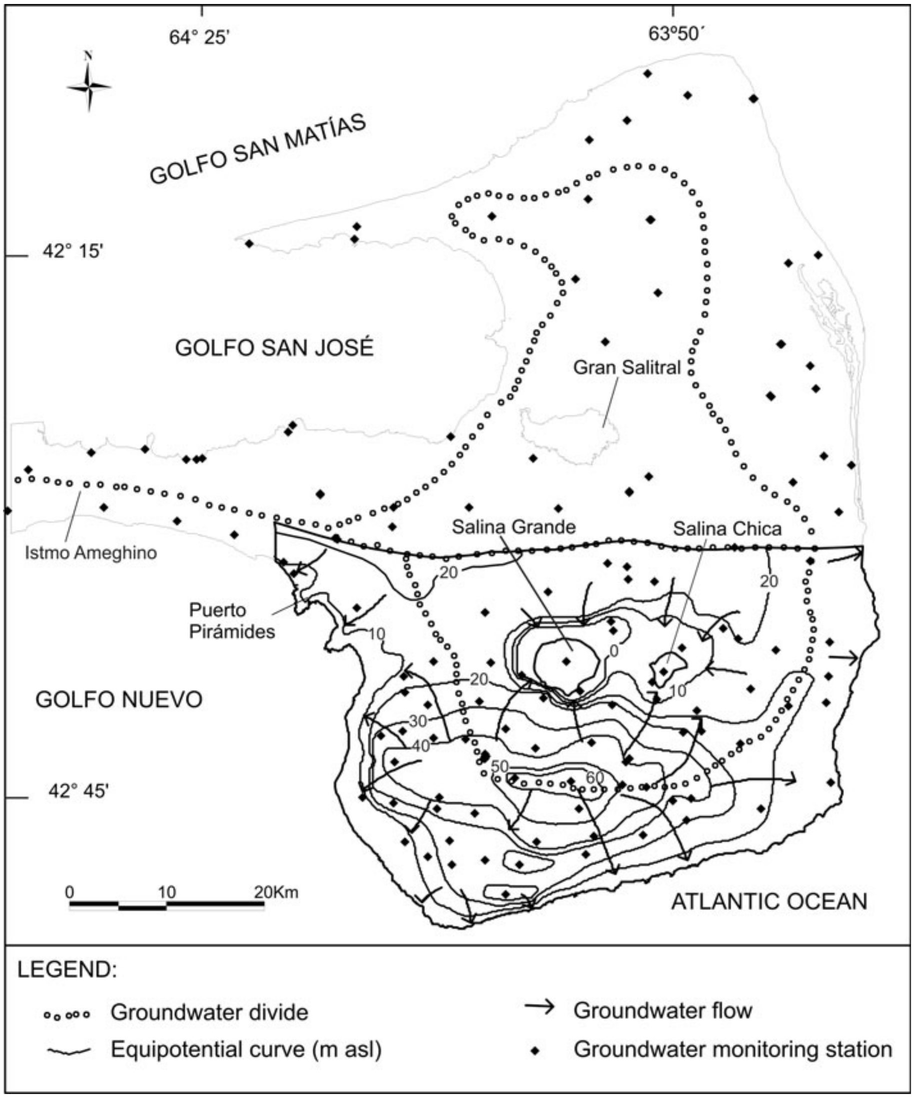


Fig. 3 Equipotential map of the southern sector of the Península Valdés

Once discharge has occurred in the depressions, water leaves the system as evaporation in the salt pans. Regional discharge, which occurs in a southwesterly direction towards the Golfo Nuevo, and in a southerly and southeasterly direction towards the Atlantic Ocean, becomes evident on the coastal cliffs as 'chorrillos', consisting in wet spots and changes in vegetation, which are easily identifiable from the beach. The consumptive loss that might occur regionally is insignificant due to the physiological adaptations of the xerophytic vegetation and the fast infiltration mechanism.

Hydrochemistry

Two clearly identifiable zones can be observed: a freshwater zone and another one with brackish to saline characteristics. The low salinity zone, with TDS values between 300 and 1,500 mg/l, develops in the southern sector, coinciding with the SdSl unit and the radial divergent morphology of the water table, defined as the main recharge area. The high salinity zone, with TDS values above 3,000 mg/l, occurs in the northern and western sectors, coinciding with the circulation and discharge areas (Alvarez et al. 2008c).

The predominant major-ion water type is sodium chloride, with sodium-bicarbonate type water occurring only in the low salinity zone (Alvarez et al. 2010a).

Conceptual model

Due to the topographic and geological characteristics of the study area and the hydrodynamic behaviour observed in the equipotential map dated November 2005 (Fig. 3), the limits of the geohydrological system are defined as follows:

- lateral limits to the east, south and west: defined by the coastline and their negative permeability; northern

limit: coinciding with an impermeable groundwater divide, in an east–west direction,
- the upper limit: coinciding with the topographic surface, with positive permeability and variations depending on the outcropping material and,
- the lower limit: arbitrarily presumed to be impermeable, represented by the aquiclude layers of the Tertiary formations.

On the basis of the characteristics assigned to the physical component of the system, the input variables were analysed.

As groundwater inflow is eliminated as a variable, and given the lack of natural and anthropic surface inflow, input is reduced to water of meteoric origin, mainly rainfall, supported by the surplus of the daily time-step water balance. Assuming precipitations are the only source of input, recharge is direct over the whole area, and it is maximised in the SdSl unit by the real reduction of consumptive loss and fast infiltration mechanisms.

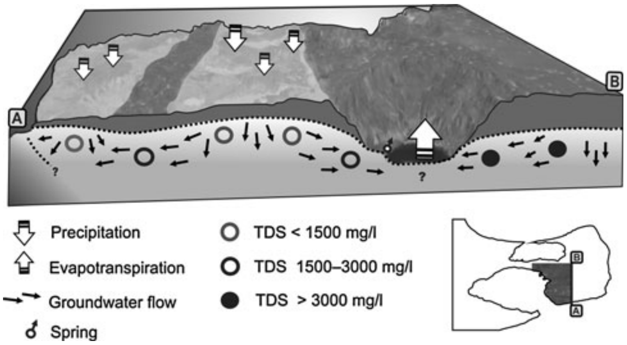


Fig. 4 Conceptual model of hydrological behaviour of the study area, showing groundwater flow and salinity distribution

Circulation follows a general radial pattern, with a tendency towards convergence and divergence. Regional discharge is localised along the coast of the peninsula towards the Golfo Nuevo and the Atlantic Ocean, whereas local discharge mainly occurs in a convergent radial water table pattern surrounding the depressions of the Salina Grande and Salina Chica.

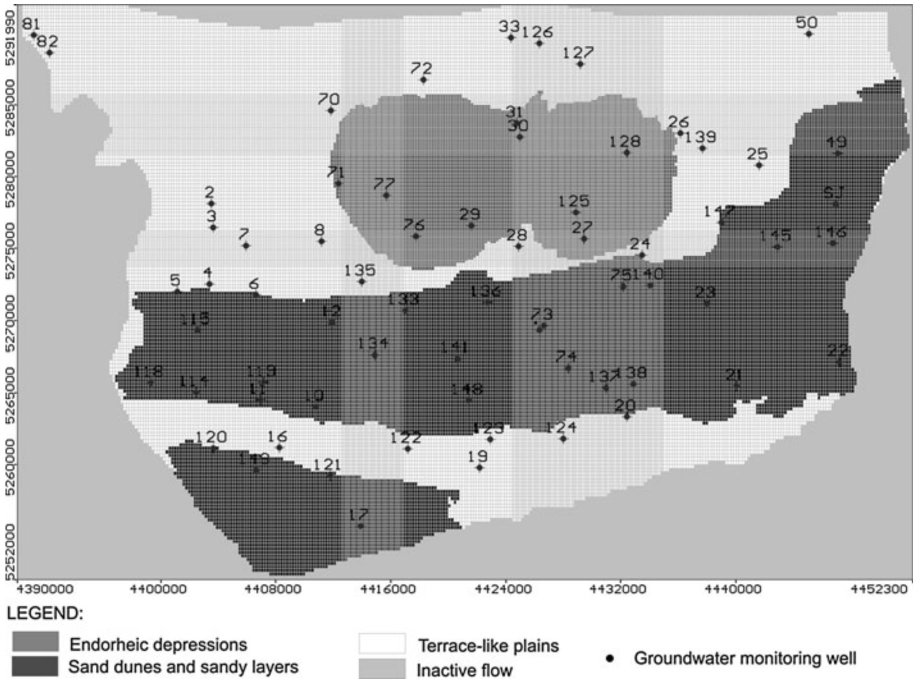
The hydrodynamic conceptual model is supported by the hydrochemical evidence, with two clearly differentiated behaviours: one characterised by low salinity water localised in the recharge area, the other one by brackish to almost saline water mainly occurring in the circulation and discharge areas.

To summarise, in Fig. 4 the system limits and its input and output variables are shown, and in a south–north cross-section (A-B) the groundwater dynamics and hydrochemistry (TDS) are represented.

Mathematical model

The conceptual model of groundwater flow has been represented in a mathematical model by using the Visual Modflow 4.1 simulation code (Waterloo Hydrogeologic Inc. 2005) with the block-centred finite difference method, with the constant density flow and properties within each

Fig. 5 Grid geometry, location of groundwater monitoring wells and distribution of recharge areas



cell treated as homogeneous. The 'Recharge', 'Evapotranspiration', 'Pump Wells' and 'Observation Wells' modules were used, and the WHS Solver option set as default to solve differential equations.

The three-dimensional geometry was defined on the basis of the spatial discretisation of a 1,700 km^2 area, setting up a grid with 187 rows, 396 columns and 4 layers, adding up to a total of 74,054 cells. At the beginning, the area of each particular cell was 1,000 m × 1,000 m, and subsequently a gradation was determined in those areas with a variable topographic slope, dividing them into 50 × 50 m^2 cells, so as to ensure flow continuity. The maximum densification of the grid was reached around the salt pan depressions.

Out of the four layers that constitute the model (differentiated according to their hydraulic properties), the upper layer (i.e., the topographic surface) was derived from an SRTM DEM with a ground resolution of 90 m, and the lower layer was defined horizontally at −45 m asl, taking into consideration the height of the Salina Grande (−42 m asl). The middle layers were determined, respecting the sub-horizontality of the geological strata, with an approximation to thickness based on the information derived from certain wells.

According to the limits described in the conceptual model, from a hydraulic point of view the following boundary conditions were defined: No Flow (watershed) for the northern boundary and Constant Head (CH, regional groundwater discharge or effluence of the aquifer) for the coastal boundary, with a head value of 0, as it represents the sea level.

The input required includes the location and pumping well rates, observation well head value, hydraulic conductivity of the system, and recharge and evapotranspiration rates.

The field trips carried out in November 2005, October 2006, June 2007 and March 2008 focus on 67 observation wells, 57 of which are pumping wells, with an average rate of 24 m^3/day per well.

Hydraulic conductivity (K) was determined on the basis of four pumping tests (Kruseman and de Ridder 1975). In one case the Papadopulos–Cooper method was applied in a large diameter well located in eolian deposits, the result being $K = 25$ m/day. In two other cases, in which the diameter was conventional, the Tertiary aquifer was tested using the Theis recovery method, which yielded a value of $K = 0.5$ m/day. Finally, by using Jacob's approximation, and the Theis recovery method, a deeper level within the Tertiary sediments was tested, which resulted in K values between 2.7 and 11.8 m/day and a storage coefficient of 2.3×10^{-4}–1.6×10^{-4}.

Recharge and evapotranspiration rates were incorporated into the model by means of zoning on the basis of the incidence of the different landforms and associated materials, depending on the possibility of rainfall infiltration. As shown in Fig. 5, three zones with distinct recharge rates can be observed, one of them coinciding with the SdSl unit,

Table 1 Simulation after an 875-day period (November 2005–March 2008) divided into 40 stress periods depending on the recharge records of the daily time-step water balance

Stress period	Start time (day)	Stop time (day)	Recharge (m/day) SdSl unit	Recharge (m/day) Tp unit
1	0	30	0	0
2	30	46	0	0
3	46	47	0.0364	0
4	47	59	0	0
5	59	60	0.0009	0
6	60	61	0	0
7	61	92	0	0
8	92	120	0	0
9	120	151	0	0
10	151	181	0	0
11	181	212	0	0
12	212	242	0	0
13	242	267	0	0
14	267	268	0.0212	0.0201
15	268	269	0.0357	0
16	269	273	0	0
17	273	286	0	0
18	286	287	0.02	0.0013
19	287	304	0	0
20	304	334	0	0
21	334	365	0	0
22	365	395	0	0
23	395	426	0	0
24	426	457	0	0
25	457	485	0	0
26	485	516	0	0
27	516	546	0	0
28	546	577	0	0
29	577	607	0	0
30	607	638	0	0
31	638	669	0	0
32	669	699	0	0
33	699	729	0	0
34	729	739	0	0
35	739	740	0.019	0
36	740	759	0	0
37	759	790	0	0
38	790	821	0	0
39	821	849	0	0
40	849	875	0	0

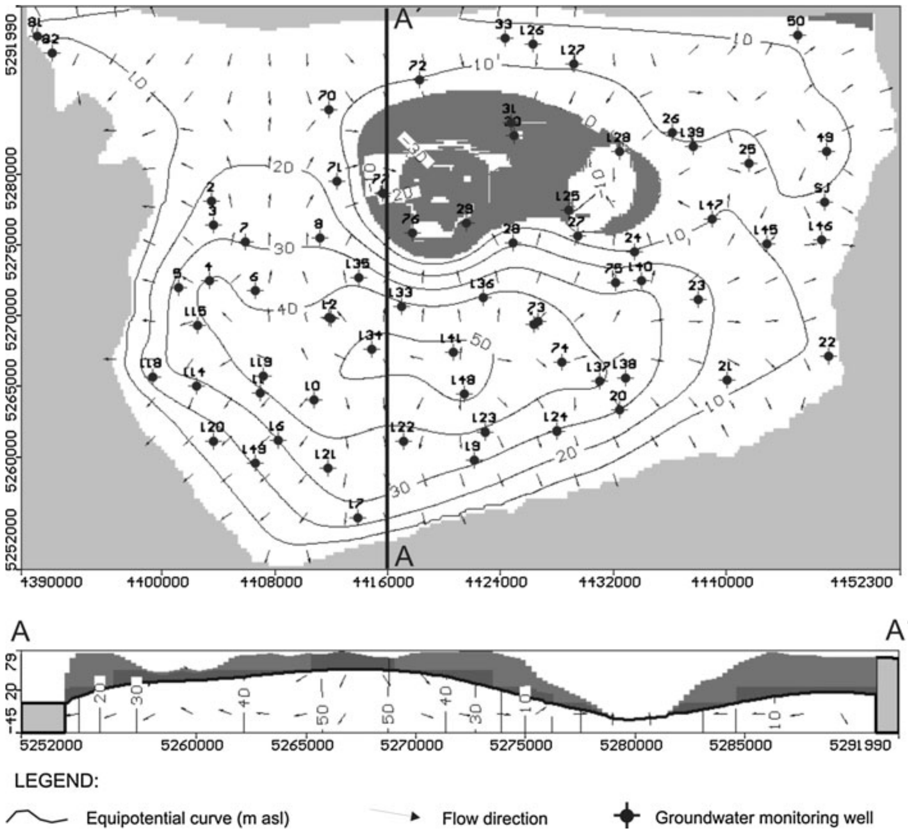


Fig. 6 Calculated equipotential map and A–A′ cross-section showing groundwater flow vectors

another one with the Ed unit, and the third one with the Tp unit. The rate assigned to each of them is the net infiltration (i.e., precipitation minus actual evapotranspiration), and the value entered corresponds to the surplus of each balance; in the case of the Ed unit, a zero value was assigned as it is a discharge area. In this zone, the evapotranspiration module was applied by assigning monthly potential evapotranspiration values obtained by the Penman–Monteith method, using the CROPWAT 8.0 model (Swennenhuis 2006).

Calibration

At first the model was tested by running it in permanent regime (Trovatto et al. 2007), which was the basis to improve the grid design, the boundary conditions and to adjust the hydraulic conductivity values, subsequently running it in transient regime. In both cases, the calibration was carried out in trial-and-error mode, changing the input parameters of recharge and hydraulic conductivity with different variants in the recharge zoning and in the inclusion or exclusion of the evapotranspiration module, using for contrast the positions measured in the field.

In the transient regime, the simulation time of 875 days (November 2005–March 2008) was divided into shorter stress periods depending on the surplus records of the daily time-step water balance, thus it was discretised into 40 smaller intervals (Table 1).

In the process, the recharge was dealt with in the first place, considering the surplus of the daily balances carried out with the Balshort software (Carrica 1993), both in the SdSl unit and the Tp unit. The potential evapotranspiration and precipitation (2005–2008) input parameters were common to both units, with the field capacity (Fc) of the soil remaining as the adjustment variable. In order to calculate it, a previous soil analysis was used (Rostagno 1981) as well as reference table values (Thornthwaite and Mather 1957; Waterloo Hydrogeologic Inc. 2005), using in the trial-and-error calibration procedure Fc values of 25, 50 and 75 mm in the case of the SdSl unit (sand) and 50, 75 and 125 mm in the Tp unit (silt). Finally, the combination of 25 mm in the first case and 75 mm in the second was chosen, as it was the best adjusted option when assessing the qualitative and quantitative calibration, and the system input volumes. The daily surplus for each stress period is shown in Table 1.

The following variable was the hydraulic conductivity, which—on the basis of the values provided by the pumping tests and by means of the trial-and-error procedure—was defined for the X and Y coordinates as: Layer 1, $K = 10$ m/day (SdSl unit) and $K = 5$ m/day (Tp unit); Layer 2, $K = 0.5$ m/day; Layer 3, $K = 2.75$ m/day; and Layer 4, $K = 0.005$ m/day. Finally, the vertical hydraulic conductivity values were defined as being one order of magnitude less.

Table 2 Quantitative calibration after a 365-day, 605-day and 875-day period

Quantitative calibration	365 days	605 days	875 days
Number of calibration points	50	50	56
Maximum residual (m)	−7.486	−9.6	−9.101
Minimum residual (m)	0.026	0.006	0.013
Residual mean (m)	−0.815	−1.852	−1.311
Absolute residual mean (m)	2.295	3.066	3.011
Standard error of the estimate (m)	0.396	0.51	0.488
Root mean squared (m)	2.9	4.023	3.85
Normalised RMS (%)	3.971	6.5	6.152
Correlation coefficient	0.964	0.969	0.972

Both the qualitative and quantitative results of the calibration showed a good correspondence with the levels measured in the period mentioned above. The correspondence of the qualitative results becomes evident in comparing the equipotential map calculated (Fig. 6) with the equipotential map generated with the 2008 measurements (Fig. 3), and also in observing that the water table contours are similar in both cases. The same situation is repeated for October 2006 and June 2007, but the results for 2008 were chosen as they were the most recent. This can also be observed in a cross-section for the same year (Fig. 6), where the flow vectors reproduce approximately those represented in the cross-section, which summarises the conceptual model of hydrogeological behaviour of the system (Fig. 4). In the quantitative results, the contrast between the value observed and the one calculated by the software is expressed by means of residual correlation (average, absolute average, root mean square, normalised average and standard deviation). The results for 365, 605 and 875 days are shown in Table 2 and can be observed in the dispersion graphs in Fig. 7, where an acceptable adjustment can be seen, with normalised RMS values of <10%.

Transient scenarios

Once the simulation for the measured conditions was carried out, and on the basis of the adjustment applied, the model was exposed to different forecast conditions taking into consideration the current socio-economic situation, an exploitation of 500 m^3/day with a water pump station located in the SdSl unit, and certain future variations in the exploitation rate and recharge conditions.

The period for which the predictions were made extended for 1,750 days, twice as many as the period used for simulation and calibration (875 days), as suggested by Faust et al. (1981), and Anderson and Woessner (1992).

As Puerto Pirámides is in the regional discharge area, all of the water pumped to supply it was regarded in the

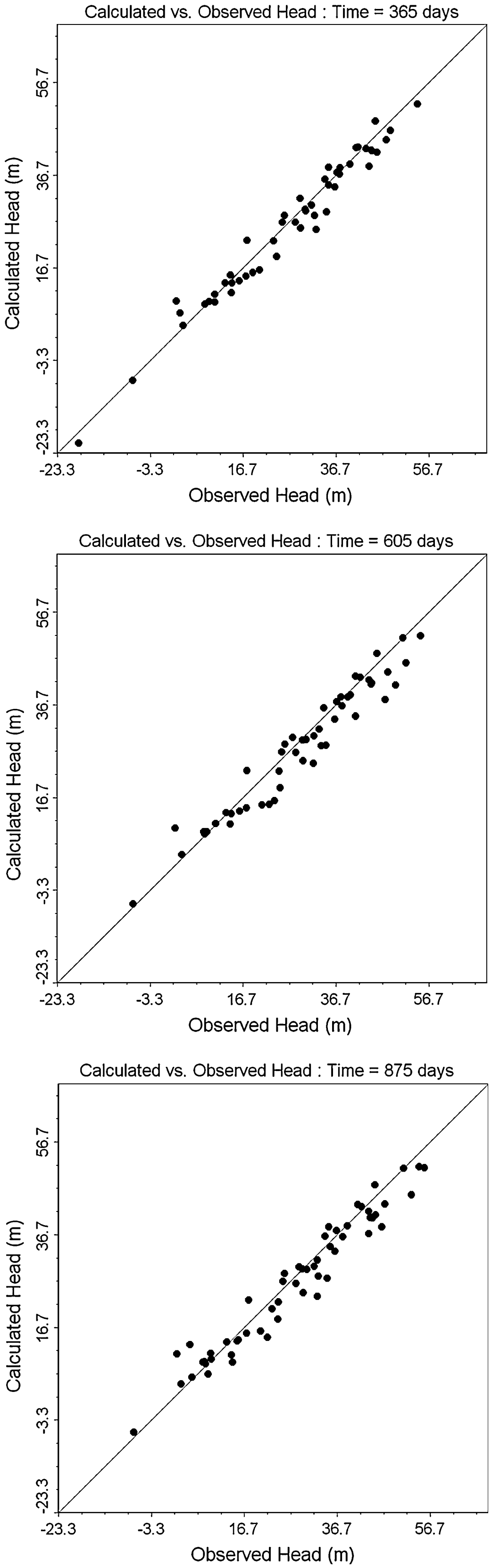


Fig. 7 Calibration graphs of the simulation after a 365-day, 605-day and 875-day period

simulation as system output. Concerning the discharge rate, it was maintained at a steady rate of 24 m^3/day per well in every well except the one representing the future water pump station, which varied as from the 876th day depending on the exploitation rate projected for each scenario.

It should be clarified that the system input was entered with a daily time-step, maintaining until the 875th day the values used in the simulation and calibration, from then on reproducing the same modules in scenarios 1 and 2, and considering non-recharge in the other two.

Scenario 1

The combination of exploitation and recharge used is the most similar to the one projected, that is, a pumping rate of 500 m^3/day and a recharge equivalent to the one employed in the simulated November 2005–March 2008 period.

In Fig. 8a the response of the aquifer may be observed, with a slight decrease in the level as the pumping was increased on the 876th day, followed by a recovery associated to the recharge events, reaching towards the end of the 1,750-day period a similar level to the initial one.

Scenario 2

With the intention of predicting the aquifer response to a future demand, a simulation was conducted for the same well with an exploitation of 2,500 m^3/day, maintaining the system input used in scenario 1. It can be observed that as from the 876th day, even if there are slight recoveries in the level owing to recharge events, there is a general decreasing tendency that at no point reaches the initial heads (Fig. 8b).

Scenario 3

The exploitation situation in scenario 1 is reproduced, but considering a drought period in which as from the 876th day there would be no recharge. It can be observed that in the predicted period, even if there is a decrease in level at the onset of pumping, subsequently it reaches a position that remains constant until the end (Fig. 8c).

Scenario 4

The discharge situation is similar to scenario 2, except for the absence of recharge as from the 876th day. The decrease in level is constant, with no recorded recovery in the level (Fig. 8d).

Conclusions

The original geohydrological model has been corroborated, as the main aquifer in the area has been identified in the Tertiary sediments of the Puerto Madryn Formation, with direct recharge mainly occurring in the SdSl unit and local discharge in the Salina Grande and Salina Chica, where it evaporates and flows out into the Atlantic coast.

In order to reproduce the groundwater dynamics by means of a mathematical model, relationships between calculated heads versus observed heads with an acceptable adjustment level were obtained.

A variable of great importance in the model was the analysis of recharge, where the estimation of net infiltration was obtained by means of the treatment of rainfall with a daily time-step. In the adjustment and calibration stages

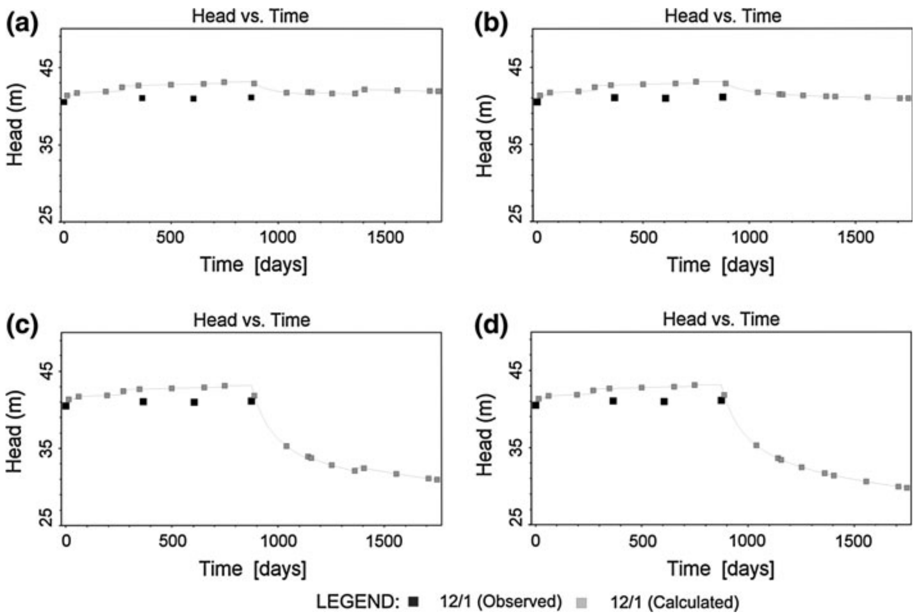


Fig. 8 Transient scenarios: **a** Scenario 1 (pumping 500 m^3/day, with recharge); **b** Scenario 2 (pumping 2,500 m^3/day, with recharge); **c** Scenario 3 (pumping 500 m^3/day, without recharge); **d** Scenario 4 (pumping 2,500 m^3/day, without recharge)

prior to obtaining the results, the modelling was sensitive to changes in the recharge and distribution values, as well as in the hydraulic conductivity.

The adjusted model was exposed to four future scenarios with variations in the water input and in the output by pumping from the planned location of exploitation to supply Puerto Pirámides. It can be interpreted from the results that in different recharge conditions, but with an exploitation of 500 m^3/day, the system responds in a sustainable manner. Even if the simulated recharge is maintained, when attempting to pump 2,500 m^3/day the levels decrease constantly; and this decrease is more significant when it is made to coincide with a drought period.

In the face of the good adjustment with the measured positions, the model can be considered appropriate to predict future situations and to help in making decisions related to the sustainable use of the resource, taking into consideration that the predicted period should not exceed twice the length of the simulated period.

Even if the model was calibrated for 68 pumping wells and three perforations drilled ad hoc, it is necessary to perform more pumping tests to better adjust the values of hydraulic conductivity and its spatial variability. The performance of new measurements that would help optimise the calibration is regarded as necessary as well, as it would consequently extend the predicted period.

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References

Alvarez MP (2010) Investigación geohidrológica en un sector de Península Valdés, provincia de Chubut. PhD Thesis. Universidad Nacional de La Plata

Alvarez MP, Hernández L, Hernández MA, González N (2008a) Relación aguas subterráneas - aguas superficiales en Patagonia extrandina. República Argentina. Revista Latino-Americana de Hidrogeología 6:43–48

Alvarez MP, Weiler NE, Hernández MA (2008b) Geohidrología de humedales próximos a la costa con cota bajo el nivel del mar. Península Valdés. Argentina. Rev Latinoam Hidrogeologia 6:35–42

Alvarez MP, Hernández MA, Gómez JC (2008c) Relación Hidroquímica-Hidrodinámica en un sector semiárido de Patagonia Extrandina, República Argentina. IX Congreso Latinoamericano de Hidrología Subterránea. ALSHUD, Edición CD-ROM. Quito, Ecuador

Alvarez MP, Weiler NE, Hernández MA (2010a) Linking geomorphology and hydrodynamics: a case study from Península Valdés, Patagonia, Argentina. Hydrogeol J 18:473–486. doi: 10.1007/s10040-009-0528-x

Alvarez MP, Bilmes A, Hernandez MA (2010b) Hidrogeología del Sur de Península Valdés, Chubut, Argentina. Rev. Latinoam. Hidrogeología 8 (in press)

Anderson MP, Woessner WW (1992) Applied groundwater modeling: simulation of flow and advective transport. Academic Press, San Diego

Auge M, Wetten C, Baudino G, Bonorino G, Gianni R, González N, Grizinik M, Hernández M, Rodríguez J, Sisul A, Tineo A, Torres C (2006) Hidrogeología de Argentina. Boletín Geológico y Minero 117(1):7–23

Carrica JC (1993) Balshort: Un programa de balance hidrológico diario del suelo aplicado a la región sudoccidental pampeana. XII Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos 4:243–248 (Mendoza)

Carrica JC (2009) Cálculo de la recarga en zonas áridas y semiáridas. In: Carrica J, Hernández M, Mariño E (eds) Recarga de acuíferos. Aspectos generales y particularidades en regiones áridas, Amerindia, pp 71–80

Cook PG, Jolly ID, Leaney FW, Walker GR (1994) Unsaturated zone tritium and chlorine 36 profiles from southern Australia: their use as tracers of soil water movement. Water Resour Res 30:1709–1719

Edmunds WM, Darling WG, Kinniburgh DG (1988) Solute profile techniques for recharge estimation in semi-arid and arid terrain. In: Simmers I (ed) Estimation of Natural Groundwater Recharge. Reidel Publishing Co, Higham, pp 139–157

Faust CR, Silka LR, Mercer JW (1981) Computer modeling and groundwater protection. Ground Water 19(4):365–632

Flint AL, Flint LE, Hevesi JA, Blainey JB (2004) Fundamental concepts of recharge in the Desert Southwest: a regional modeling perspective. In: Hogan JF, Phillips FM, Scanlon BR (eds) Groundwater recharge in a desert environment: the Southwestern United States, water science and applications series, vol 9. American Geophysical Union, Washington, DC, pp 159–184

Geiger R, Pohl W (1954) Revision of the Köppen–Geiger Klimakarte der Erde. Erdkunde 8:58–61

Haller M, Monti A, Meinster C (2001) Hoja Geológica 4366-1 Península Valdés. Boletín Nro. 266. Buenos Aires: Servicio Geológico Minero Argentino

Hernández MA (2005) An overview vision on groundwater resources in Latin America. In: Bocanegra E, Hernández MA, Usunoff E (eds) Grounwater and human development. Leiden, The Netherlands, pp 9–14

Hernández MA, González N, Sánchez RA (2002) Mecanismos de recarga de acuíferos en regiones áridas. Cuenca del Río Seco, Provincia de Santa Cruz. Argentina. XXXII IAH Congress—VI Congreso ALHSUD. Mar del Plata, Ed. CD Rom y Libro de Resúmenes

Hernández MA, González N, Hernández L (2008) Late cenozoic geohydrology of extra-Andean Patagonia, Argentina. In: Rabassa J (ed) The Late Cenozoic of Patagonia and Tierra del Fuego, vol 24. Elsevier, Amsterdam, pp 497–509

Hernández MA, González N, Hernández L (2010) Procesos de recarga de acuíferos en regiones áridas de Argentina. Rev. Latinoam Hidrogeología 7:71–78

Kruseman GP, de Ridder NA (1975) Análisis y evaluación de los datos de ensayos por bombeo. Int. Institute for Land Reclamation Wageningen, Holanda

Labraga JC, Davies EC (2008) CENPAT-Unidad de Investigación de Oceanografía y Meteorología. http://www.cenpat.edu.ar/. Accessed 11 August 2008

Lerner DN, Issar AS, Simmers I (1990) Groundwater recharge. IAH vol 8. Heise Ed. Hannover

Rolando LJ, Bran D, Collantes M, Paruelo JM, Soriano A (1998) Grandes unidades de vegetación de la Patagonia extra andina. Ecol Austral 8:125–144

Rostagno CM (1981) Reconocimiento de Suelos de Península Valdés. Contribución N° 44, Centro Nacional Patagónico, pp 1–24

Scanlon BR, Healy RW, Cook PG (2002) Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol J 10:18–39

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmubds WM, Simmers I (2006) Global synthesis of groundwater recharge in semiarid and arid regions. Hidrol Process 20:3335–3370. doi: 10.1002/hyp.6335

Schoeller H (1959) Arid zone hydrology. Recent developments in Arid Zone Research, XII,1. UNESCO. Paris

Sharma ML (ed) (1989) Groundwater recharge. A.A. Balkema, Rotterdam

Simmers I (1997) Groundwater recharge principles, problems and developments. In: Recharge of phreatic aquifers in (Semi-) arid areas. IAH, A.A. Balkema, Rotterdam, Brookfield, vol 19, pp 1–18

Stampone J, Cambra H (1983) Estudio hidrogeológico del área Sur de Península Valdés. XI Congreso Nacional del agua, pp 139–171 (Córdoba)

Stephens DB, Knowlton RJ (1986) Soil water movement and recharge through sand at a semiarid site in New Mexico. Water Resour Res 22:881–889

Swennenhuis J (2006) CROPWAT Version 8.0. Water Resources Development and Management Service, FAO, Rome

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

Trovatto MM, Álvarez MP, Hernández MA, González N (2007) Modelo matemático preliminar del sector Sur de la Península Valdés, Región Patagónica, Argentina. Actas del V Congreso Argentino de Hidrogeología. Paraná, Entre Ríos, pp 392–399

UNESCO (1979) Map of the world distribution of arid regions. Man and Biosphere Tech Notes, no. 7, UNESCO: Paris

Waterloo Hydrogeologic Inc. (2005) Visual Modflow v.4.1. Waterloo Hydrogeologic Inc. A. Schlumberger Company. Ontario, Canada