Recharge assessment in an urban area: a case study of La Plata, Argentina

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Abstract Leakage from water mains, storm drainage and sewer systems in urban areas constitutes a source of recharge that is difficult to identify and quantify at a regional scale. The objective of this work is to apply a methodology that would make it possible to evaluate urban recharge at a regional scale, taking as a case study the city of La Plata (Argentina). In the study area, population growth and an increase in water demand has caused the intensive exploitation of groundwater with resulting alteration in groundwater flow. The methodology used was developed on the basis of a water balance and the simulation of the temporal evolution of the cones of depression and the volumes of water extracted from the aquifer. The method consists of adjusting the piezometry resulting from the numerical modelling to the measured piezometry, by means of the variation of the recharge parameter in the urban area. The results obtained make it possible to identify and quantify urban recharge, which in this case represents a volume of water similar to the recharge from precipitation.

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Introduction

Groundwater recharge is one of the most highly modified components of the hydrological cycle in urban areas (Hibbs and Sharp 2012). At present, the general belief that the land-surface impermeabilization derived from urbanization generates a decrease in recharge with respect to recharge in natural conditions is rejected. Urban recharge derives from leakage from water mains, storm drainage and sewer systems and may cause a greater increase in water infiltration into the aquifers than the decrease in natural recharge due to impermeabilization (Lerner 2002). Several studies have shown that this situation takes place particularly when the drinking-water supply includes import water from outside of the local groundwater system (Healy 2010; Yang et al. 1999). In the areas lacking a sewerage system, it is estimated that over 90 % of the domestic water supply is eliminated by means of pit toilets, cesspits or septic tanks, which is an important source of poor quality water recharge, limiting the use of shallow wells (Mather et al. 1996).

The identification and quantification of urban recharge is difficult (Tellam et al. 2006). Local-scale methods—e.g., localized or linear leakage detection tests in pipe networks, infiltration through cracks in paved areas, etc.—are based on continuous record and/or detailed piezometric studies carried out in the vicinity (Lerner 1986; Wiles and Sharp 2008), tracer analysis or chemical balances (Barrett et al. 1999; Yang et al. 1999; Kumar et al. 2011), and water balances (Lerner et al. 1993). When studying urban recharge at a regional scale, the interest no longer lies in the identification of individual points of recharge, but in demonstrating that a large number of individual sources have an impact on recharge. In such cases, the use of chemical tracers and water balances are the most widely preferred methods (Lerner 2002).

La Plata, Argentina, is a city located approximately 10 km from the coast of the Río de la Plata (an estuary at the confluence of the Uruguay River and Paraná River; Fig. 1). The population growth and the increase in water demand have caused an intensive exploitation of groundwater, which has led to a hydrodynamic disturbance due

to the ensuing cone of depression, and a chemical disturbance due to the migration of pollutants from the surface (Sala et al. 1982; Auge 2005). Such problems are exacerbated by the limited, irregular and sometimes confusing hydrogeological knowledge available, as is the case in many developing countries, where there has never been any planned management or groundwater control, or they have been rudimentary (Llamas and Custodio 1999). In these cases, the increase in exploitation is frequently based on water demand instead of on the knowledge of the hydrogeological behaviour and the groundwater reserves.

Urban recharge estimation at a regional scale provides government authorities and managers with useful data as a basis to assess the location of new wells and to set guidelines for the sustainable management of groundwater. The objective of this work is to evaluate urban recharge at a regional scale on the basis of the temporal evolution of the hydrodynamic conditions, taking as a case study the city of La Plata, Argentina. In the methodological development, the limited data from previous studies were adapted and current surveys on groundwater level were specially carried out for this evaluation. The shortage of data on groundwater monitoring makes it impossible to identify the local influence of the sources of urban recharge on the basis of more precise methodologies such as the ones implemented in other cities in industrialized countries, for example Austin, Texas (Wiles and Sharp 2008), Barcelona (Vázquez-Suñé et al. 2010) and Hong Kong in China (Lerner 1986). In this case, a regional estimation of urban recharge is sought, in order to handle the management and preservation of groundwater resources instead of the detailed evaluation required to define specific pumping rates or to repair sewer pipes and water mains.

Study area

The study area is a flat area with a gentle regional slope towards the NE (0.1 %), traversed by a number of creeks draining into the Río de la Plata. It is characterized by a humid temperate climate; the mean annual temperature is 16 °C and the mean annual precipitation is above 1,000 mm. According to the water balance, the mean precipitation is 1,061 mm/year, actual evapotranspiration is 783 mm/year, infiltration is 225 mm/year and runoff is 53 mm/year (Kruse et al. 2004).

Two geomorphological units can be identified: a high plain, where La Plata is located, and a coastal plain (Fig. 1). The high plain—between 5 and 30 m above sea level (asl)—includes the upper and middle basins of the drainage network. The coastal plain, which runs parallel to the shoreline of the Río de la Plata, has a variable width between 5 and 8 km (Fig. 1). It is a depressed area (less than 5 m asl) with badly drained soils. It includes the lower basin of the creeks, most of which are channelized and/or straightened to enable their flow into the Río de la Plata.

La Plata was founded in 1882, and since 1885 there has been a public water-supply network fed by groundwater resources. It was the first city in Argentina where the potable water demand was supplied exclusively with groundwater. Even though at the time the possibility of supplying it with surface water was considered, that source was initially rejected due to the cost of building an aqueduct from the Río de la Plata to the city. The possible rates of extraction and the water quality of the semi-confined aquifer, located at a depth between 40 and 60 m, made groundwater exploitation more advantageous.

The population of La Plata has grown progressively, registering 222,695 inhabitants in 1940, 521,936 inhabitants in 1991 and 694,613 inhabitants in 2010 (INDEC 2010). This urban expansion took place from the inner city area towards the periphery, especially towards the south. By 1940, the surface of the developed area was approximately 26 km^2, whereas at present it is about 98 km^2.

Potable water supply to the urban area is the most important use of the groundwater resources. In the rural area, most of the surface is devoted to extensive agriculture and grazing, which due to the climate do not require irrigation, with cattle being the greatest consumer of groundwater. In a more restricted sector, far from the urban area, there is an intensive horticultural development in small pieces of land with an important produce where supplementary flood irrigation was introduced in the 1980s and drip irrigation in the 1990s. Groundwater withdrawal for irrigation represents an almost insignificant volume at basin level.

At present, the water supply represents an approximate volume of 200 hm^3/year, including the combined use of groundwater and surface water from the Río de la Plata. Until 1955, the network was fed exclusively by groundwater, when the service was reinforced with surface water. The first supply wells were located in the inner city area. The need to expand the potable water-supply service led to the drilling of more wells, and the new ones were built in the peri-urban area located towards the southwest. Nowadays, exploitation takes place mainly in peri-urban and rural areas to the south of the city, and the groundwater which feeds the water-supply network reaches a volume of over 80 hm^3/year.

Methodology

The methodology included the development of the conceptual hydrogeological model and, subsequently, of the numerical model, in order to simulate the temporal variations which occurred between 1940 and 2008.

Conceptual model

To develop the conceptual model of the system, two aspects have been analyzed: the characterization of the physical medium—i.e., hydrostratigraphic units, system boundaries, water balance, aquifer parameters and
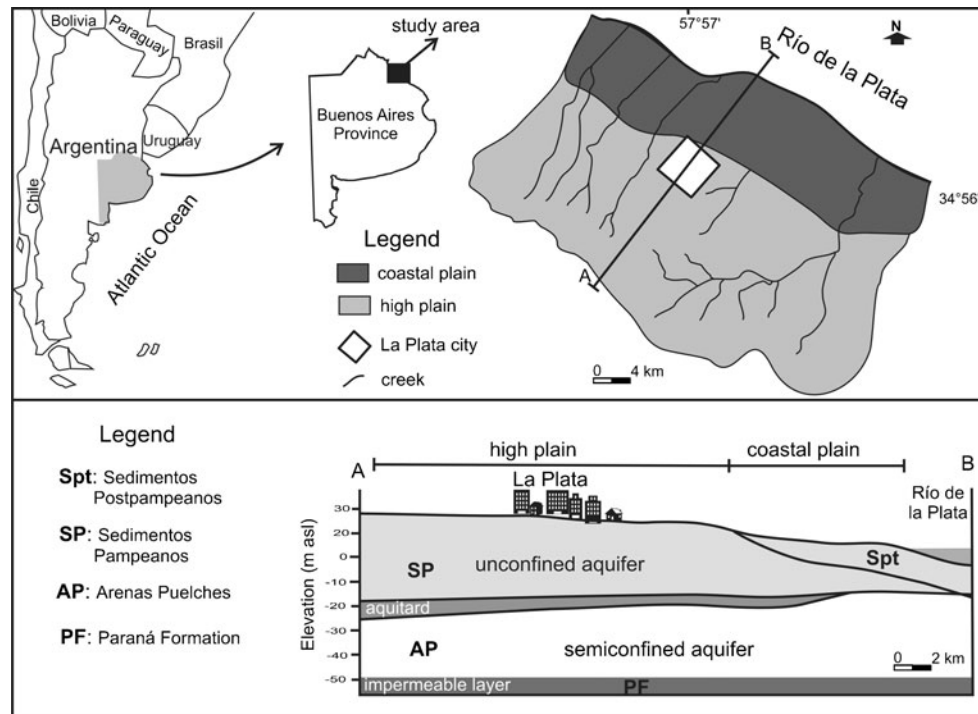
Fig. 1 Location of the study area and hydrogeological cross-section

hydrologic stresses—and the historical evolution of groundwater levels in the area of exploitation. All of this information was entered into the geographic information system (ArcGIS).

The hydrogeological characterization focused on identifying aquifer thickness variation, for the top and bottom aquifers, as well as on selecting hydrological parameters. Stratigraphic data from wells and the available bibliographic records were analyzed (Artaza 1943; EASNE 1972; M. Auge, Convenio IDRC-UBA, unpublished report, 1995). A groundwater flow map of the natural conditions was made according to the limited data obtained from primitive wells in the region and to the configuration of groundwater flow maps of neighbouring basins unaltered by exploitation. As there is no systematic record of groundwater level variations, the different aspects of the hydrodynamic evolution have been analyzed on the basis of those situations on which there are historical well records. In this way, groundwater flow maps were made for the aquifers for the years 1940, 1988 (partial) and 2008.

Together with groundwater exploitation, the growth of the urban area and the temporal and spatial evolution of the impervious areas were considered. This information was determined on the basis of the interpretation and analysis of cadastral maps of 1940 (1:10,000), aerial photographs of 1988 (1:20,000) and 15-m resolution SPOT satellite images of 2008.

Numerical simulation

A numerical model was used to analyze the hydrological behaviour of the aquifers, to reproduce the historical evolution of the groundwater levels influenced by exploitation, and to assess the recharge in an urban area. Based on the hydrogeological conceptual model, a three-layer porous media system was adopted for the mathematical model, in order to simulate the unconfined aquifer, the aquitard level and the semi-confined aquifer. An underlying impermeable layer of clay (Paraná Formation) was considered for modelling purposes. The numerical model was applied to support the hydrogeological characterization and to study the dynamics of the system under stress. For simulation purposes, a 3D finite-difference code, MODFLOW (Harbaugh et al. 2000), was employed to simulate variably saturated flow in porous media.

The regional model was developed for a 914 km^2 basin, drained by five creeks. This modelled area was discretized into 440 m×315 m cells in x and y directions. In the z direction, a three-layer system with a thickness ranging from 22 to 45 m in the first layer (unconfined aquifer), 5 m in the second layer (aquitard) and 25 m in the third layer (semi-confined aquifer) was defined.

For boundary conditions, a specific head boundary with 0 m asl was considered at the northeastern limit of the basin, where the Río de la Plata is, which is a natural discharge boundary. The basin limits were considered as no flow at the northwest, southwest and southeast boundaries. Recharge from precipitation and the drainage system were indicated on the first layer (unconfined aquifer), and pumping wells were located on the third layer (semi-confined aquifer).

MODFLOW was applied for steady state (natural conditions) and transient state simulations (a 10-year simulation before 1940, 1988 and 2008). The simulations were carried out for 10-year periods as the model reaches

an equilibrium after such an amount of years. The numerical model was calibrated under steady state for the natural flow conditions, in order to simulate the situation before urbanization.

Results

Description of the conceptual model
In the study area, the groundwater feeding the water-supply network proceeds essentially from the exploitation of a semi-confined aquifer located in the upper section of the sedimentary sequence. This aquifer is composed of fine-to-medium-grained quartz sand of fluvial origin (Arenas Puelches), which are deposited over green clays (Paraná Formation). Overlying the sand, there is silt with carbonate intercalations (Sedimentos Pampeanos), containing the water table. A more clayey layer separates the semi-confined aquifer from the water table, and it acts as an aquitard (Fig. 1).

Groundwater recharge occurs due to the infiltration of rainfall excess. If the 10-year moving average values for the rainfall records (1909–2011) are considered, it can be observed that in the years analyzed in this work, the mean precipitation values are relatively similar (1,024 mm/year in 1940, 1,020 mm/year in 1988 and 1,069 mm/year in 2008). Besides, the variations in the mean annual temperatures are slight, with values of 16.1 °C for the decade that includes 1940, 15.9 °C for the one including 1988 and 16.0 °C for the one including 2008. With such values, there are no significant changes in evapotranspiration at a regional scale (Table 1).

The water table occurs in silt and clay sediments whose base lies at −20 m asl and which have a variable thickness ranging from 45 m in the upper sections of the basin and 20 m in the coastal area. Hydraulic conductivity values vary between 3 and 10 m/d, the average transmissivity is 200 m²/d and the effective porosity is 0.08. The clayey aquitard has an average thickness of 5 m (−20 and −25 m asl), with low hydraulic conductivities between 10^{-3} and 10^{-4} m/d, and a vertical transmissivity of 5×10^{-4} 1/d. The semi-confined aquifer occurring in sandy sediments has an average thickness of 25 m (between −25 and −50 m asl), a hydraulic conductivity of 20 m/d and a transmissivity of 500 m²/d.

In natural conditions (prior to exploitation), regional groundwater flows towards the NE to the Río de la Plata. Groundwater recharge is of meteoric origin, and it can be characterized as local and direct into the water table, and indirect by means of downward vertical infiltration into the semi-confined aquifer. Local groundwater discharge flows into the creeks, and the regional discharge into the Río de la Plata (Fig. 2).

In 1940, the volume exploited was 33 hm³/year and the cone of depression of the semi-confined aquifer was located in the inner city area. The estimated surface of the cone was approximately 20 km², with an apex that met the water table at −15 m asl (Fig. 2). In 1988, an exploitation of 44 hm³/year, associated to an increase in the number of wells with respect to 1940, caused the cone of depression to expand towards the S and NW sectors of the city (Fig. 2). In this period the data regarding the levels do not extend to all of the exploitation wells, which is why the estimated depth of the apex (−20 m asl) and the surface (26 km²) of the cone represent an approximation to the water situation.

In 2008, as a result of an extraction of 80 hm³/year and a further increase in the number of wells towards the SW, the cone of depression of the aquifer migrated towards the area with new wells. Under these exploitation conditions, the estimated surface of the cone of depression was approximately 34 km² and the apex had a depth of −15 m asl (Fig. 2). The expansion of the cone of depression caused the inversion of the natural hydraulic gradients of the water tables. As a consequence, the natural relationship between surface water and groundwater changed. The pumping of groundwater from the semi-confined aquifer caused the formation of a cone of depression both in this aquifer and in the water table, whose apex has changed in geographical location along time from the SW of the inner city area towards the periurban areas.

Mathematical modelling

Parameter definition
Based on the model under steady-state conditions, the calibration was performed in transient state to simulate the situation of water exploitation in 1940. According to such a calibration (transient state, hydraulic parameters and piezometry in 1940), the situation of water exploitation in 2008 was simulated, taking as an intermediate control point the situation of exploitation in 1988. In order to analyze the effects of the exploitation of the aquifer, the pumping wells were located according to the real distribution and depth of extraction for the years 1940, 1988 and 2008. For 1940, 45 wells with an exploitation volume of 2,018 m³/d per well were considered, whereas for 1988 the battery of wells was increased to 80 with an exploitation volume of 1,500 m³/d per well, and for 2008 to 154 wells with an exploitation volume of 1,440 m³/d per well.

A constant recharge of 6.1 10^{-4} m/d given by the rainfall infiltration from the surface (first layer) was considered for the whole area, except for the urban area. The infiltration rate was set as constant because the years considered for the simulation (1940, 1988 and 2008) show similar hydrological situations regarding the average conditions of the water balance (Table 1). In the urban area, the analysis of the cadastral map for 1940 shows that 40 % of the inner city area (4 km²) is covered by roofed areas and the rest are urban open spaces and cobbled streets. Therefore, a recharge of 0 m/d was considered for the roofed areas and 6.1 10^{-4} m/d in the urban open spaces and cobbled streets. For 2008, at first the model was run considering a hypothetical recharge of 0 m/d and then it was increased until the modelled piezometry matched the actual piezometry, thus obtaining the value of urban

Table 1 Data used in the models and precipitation, evapotranspiration and infiltration values corresponding to water balances for the decade prior to the running of the model

Year	Definition of urban area	Urban area (km²)	Number of pumping wells	Pumping rate (m³/d)	Period (water balances)	Precipitation (mm/year)	Mean annual temperature (°C)	Actual evapotranspiration (mm/year)	Infiltration (mm/year)	Infiltration (m/d)
1940	Cadastral maps (1:10,000)	26	45	2,018	1931–1940	1,024	16.1	756	217	0.00059
1988	Aerial photographs (1:20,000)	78	80	1,500	1979–1988	1,020	15.9	753	216	0.00059
2008	SPOT satellite images	98	154	1,440	1999–2008	1,069	16.0	788	226	0.00061

recharge. Such a value represents the water entering the groundwater system due to leakage from water mains, storm drainage and sewer systems, primary or secondary permeability of road surfaces, urban open spaces, etc. The data used to define the area covered by urban development, the number of wells and the extraction rates used in the models are shown in Table 1.

Sensitivity analysis

The hydraulic parameters resulting from the calibration of the numerical model for natural flow condition are shown in Table 2. In order to quantify the uncertainties in the transient model calibrated for 1940, a sensitivity analysis of the hydraulic parameters of the aquifer was carried out, as they represent the variables with the greatest impact on
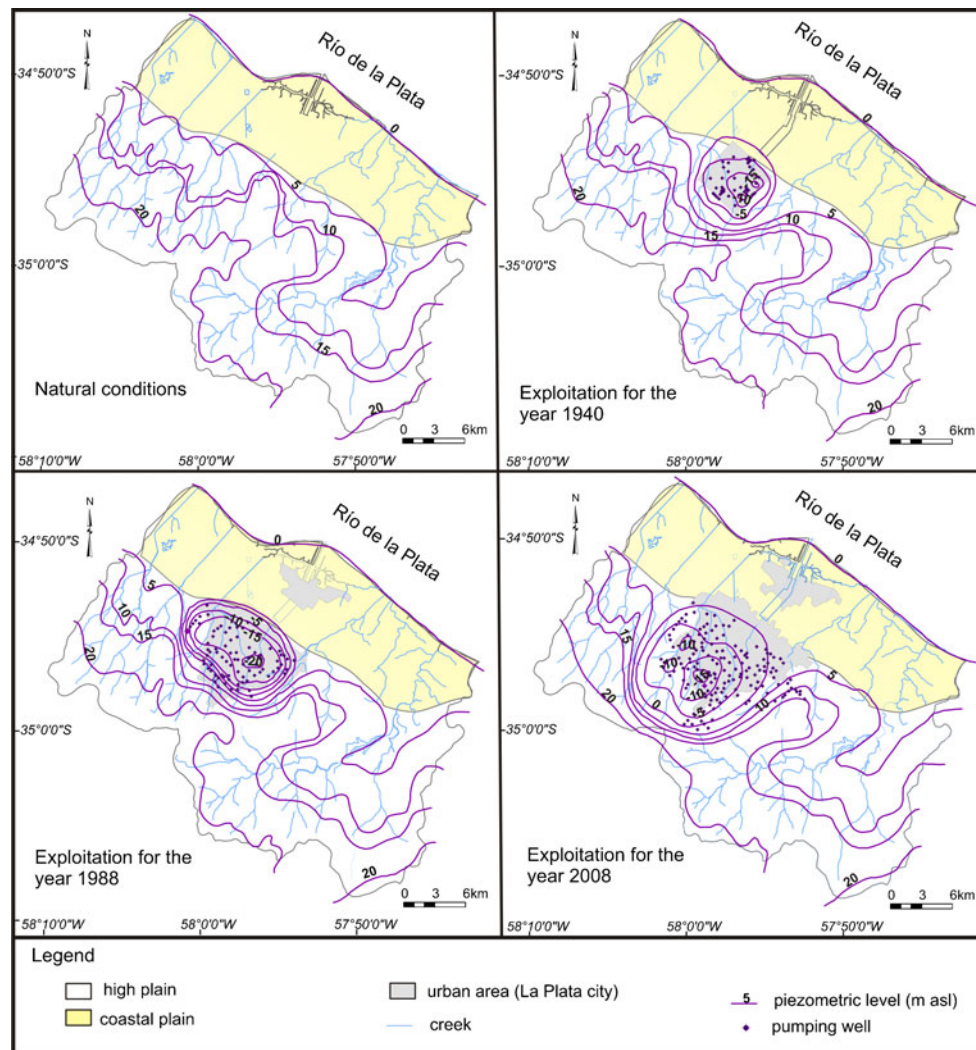

Fig. 2 Evolution of the piezometric levels of the semi-confined aquifer

Table 2 Hydraulic parameters resulting from the calibration of the model

System aquifer	K_h (m/d)	K_v (m/d)	Storage coefficient	Effective porosity
Unconfined	5	1.0	0.08	0.08
Aquitard	0.04	0.004	0.005	0.05
Semi-confined	20.0	2.0	0.005	0.3

K_h horizontal hydraulic conductivity; K_v vertical hydraulic conductivity

the model results. The sensitivity analysis was carried out by systematically varying within a plausible interval the value of one of the hydraulic conductivity or storage coefficient parameters, observing the relative changes in the response of the model.

As regards horizontal hydraulic conductivity, the most significant changes in the unconfined aquifer result in $a - 50$ % variation and cause a mean change in the groundwater level of -1.5 m; whereas in the semi-confined aquifer, $a + 50$ % variation represents a change of 4.1 m (Table 3).

A sensitivity test for storage coefficient in the unconfined aquifer showed a mean head change of 1 m as a result of a ±50 % variation. Similar differences were obtained by changing the specific storage in ±50 % in the semi-confined aquifer (1–1.3 m; Table 3).

By assessing the effect on the spatial head distribution during the sensitivity analysis, it can be observed that the

Table 3 Results of the sensitivity analysis

Hydraulic parameter varied	Value of the hydraulic parameter simulated	Percent of change[a]	Resulting changes Average difference[b] (m)		
			Mean	Absolute mean	Root mean square
Unconfined aquifer					
K_h (m/d)	1.5–5.0	−50	−1.51	1.51	1.54
	2.25–7.5	−25	−0.73	0.73	0.74
	3.75–12.5	+25	0.67	0.67	0.69
	4.5–15.0	+50	1.29	1.29	1.32
K_v (m/d)	0.5–0.05	−50	0.02	0.02	0.02
	1.5–0.15	+50	−0.01	0.01	0.01
S	0.040	−50	−1.08	1.08	1.12
	0.120	+50	0.99	0.99	1.03
Aquitard					
K_v (m/d)	0.002	−50	0.00	0.00	0.00
	0.003	−25	0.00	0.00	0.00
	0.005	+25	0.00	0.00	0.00
	0.006	+50	0.00	0.00	0.00
Semi-confined aquifer					
K_h (m/d)	18	−10	−0.45	0.45	0.55
	25	+25	2.36	2.36	2.50
	30	+50	4.09	4.09	4.31
K_v (m/d)	1.0	−50	0.00	0.00	0.00
	3.0	+50	0.00	0.00	0.00
S	0.003	−50	−1.29	1.29	1.34
	0.008	+50	−1.00	1.00	1.06

[a] Percent changes of the hydraulic parameter values

[b] Average difference between simulated hydraulic heads for test and for calibrated transient model

K_h horizontal hydraulic conductivity; K_v vertical hydraulic conductivity

urban area, which is highly stressed by pumping wells, is the main area affected by parameter changes. Among the tested parameters, the most sensitive one was the horizontal hydraulic conductivity of the semi-confined aquifer, for a 10-year transient-state simulation. However, according to the existing pumping tests and the grain-size characteristics of the sand in the semi-confined aquifer, values of about 20 m/d for horizontal hydraulic conductivity are relatively constant not only in the study area, but also for this aquifer at a regional level. It is unlikely that changes of such significance (50 %) may occur in the value assumed.

Recharge quantification

The results obtained for the natural flow condition (steady-state model) show that the values of the water-table contour lines decrease from 20 m asl in the upper sections of the basin to 0 m asl in the coastal area (Figs. 3a and 4). The resulting flow system indicates that the water table discharges locally into the creeks, whereas regionally the groundwater discharges into the Río de la Plata. The semi-confined aquifer shows, at basin level, a recharge area in the upper sections and a discharge area towards the lower basin of the creeks and into the Río de la Plata. In natural conditions, the semi-confined aquifer is mainly recharged by vertical local infiltration from the unconfined aquifer and through the clay layer, with an estimated recharge volume for this aquifer of 0.19 hm³/d from the unconfined aquifer.

The water balance resulting from the calibrated model indicated a recharge by precipitation of 0.55 hm³/d for the unconfined aquifer, and discharges of 0.45 hm³/d for the creek system. The percent discrepancy in the water balance was −0.0005.

The exploitation of the semi-confined aquifer modified the natural hydrodynamic behaviour of the groundwater. The simulation run for the year 1940 (transient state) shows the formation of a cone of depression occupying the inner city area, whose shape and apex depth, up to −18.7 m asl, are similar to the ones measured for the same period (Figs. 3b, 4 and 5). The water table accompanies the cone of depression of the semi-confined aquifer. The hydraulic connection between the unconfined and the semi-confined aquifers, and the difference in hydraulic head generated by the formation of the cone of depression cause the occurrence of recharge in the intermediate basin area. This leads to an increase of 0.04 hm³/d in the volume of water recharging the semi-confined aquifer, estimated at 0.23 hm³/d. This volume mainly derives from the water naturally stored in the unconfined aquifer, and which enters the semi-confined aquifer as a result of the inversion in hydraulic head difference.

The water balance resulting from the model for the year 1940 indicated a recharge by precipitation of 0.54 hm³/d for the unconfined aquifer, and discharges of 0.38 hm³/d for the creek system. The exploitation of the semi-confined aquifer represents a water output of 0.09 hm³/d, out of which 0.02 hm³/d come from the storage coefficient of the system. The percent discrepancy in the water balance of the numerical model was 0.0003.
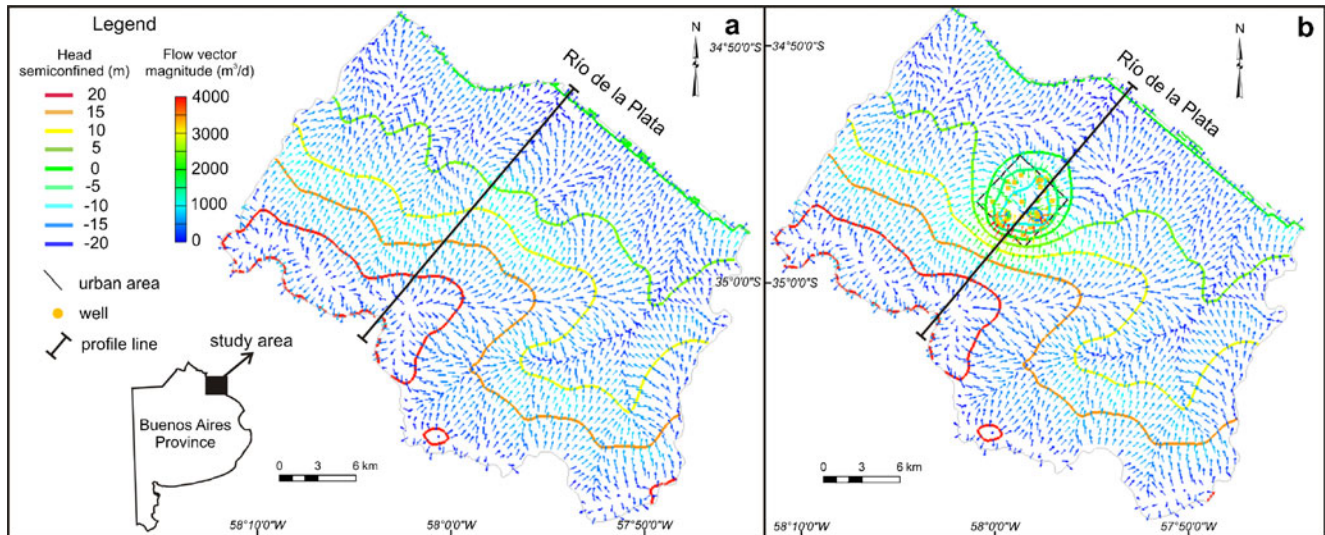
Fig. 3 Piezometric levels modelled for the calibration in **a** natural flow; **b** situation of groundwater exploitation for the year 1940

It can be observed that in the case study the occurrence of an urban area causes the recharge from precipitation into the unconfined aquifer to decrease 0.01 hm³/d. The limited expanse of the urban area (26 km²) with respect to the area modelled (914 km²) determines that the decrease in recharge due to impermeabilization is very small.

The evolution of the piezometric levels simulated until 2008 was carried out on the basis of the model calibrated for 1940, considering the variation in location, in the quantity and pumping volume of the wells, and the increase in urbanized surface, taking the data recorded for 1988 as an intermediate control point. The simulation obtained shows that the piezometric levels modelled for 2008 do not match those observed (Fig. 5) when a hypothetical recharge of 0 m/d is considered in the urban area. In that case, the cone of depression simulated has a larger surface than the one measured, causing the levels to deepen to the point that dry cells can be found in the water table throughout the area of the cone of depression. Under these conditions, the unconfined aquifer has no saturated zone in the urban area, whereas the semi-confined aquifer locally becomes an unconfined aquifer.

In order to simulate the situation observed—that is, to reduce the area and deepen the cone of depression—it is necessary for recharge within the urban area to occur, deriving from pipe and storm drainage-system leakage, infiltration into small urban open spaces or paved areas with original permeability or caused by cracks, etc. The adjustments in the measured piezometry with the piezometry resulting from the numerical model was carried out on the basis of the variation of the recharge parameter in the urban area, which represents urban recharge in the system (Figs. 6 and 7). Based on this methodology, the results obtained determined that the increase in recharge in the urban area which is necessary to adjust the piezometry of the simulation to the one observed is 0.06 hm³/d, which, if weighted per the area involved, represents a similar value to the natural recharge by rainfall infiltration (Fig. 5).

In turn, the increase in the number of exploitation wells leads to a larger difference in hydraulic head between the water table and the semi-confined aquifer. This characteristic generates an increase of 0.12 hm³/d in recharge from the unconfined aquifer to the semi-confined aquifer with respect to the natural situation of the system. It is
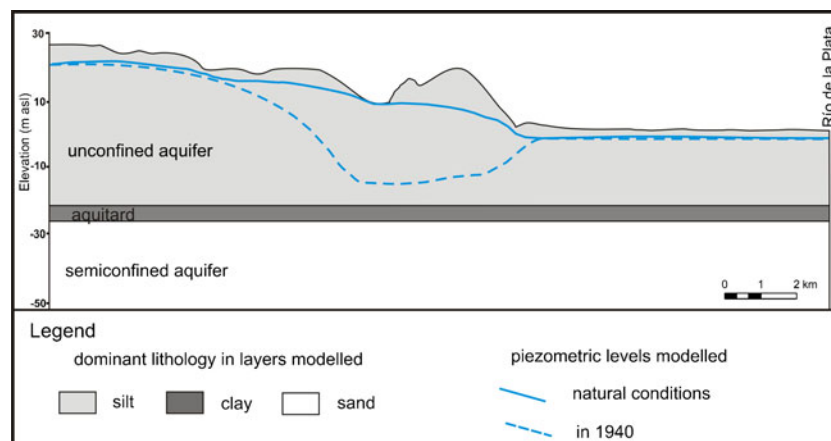

Fig. 4 Cross-section showing piezometric levels modelled in the natural condition and in the situation of groundwater exploitation for the year 1940
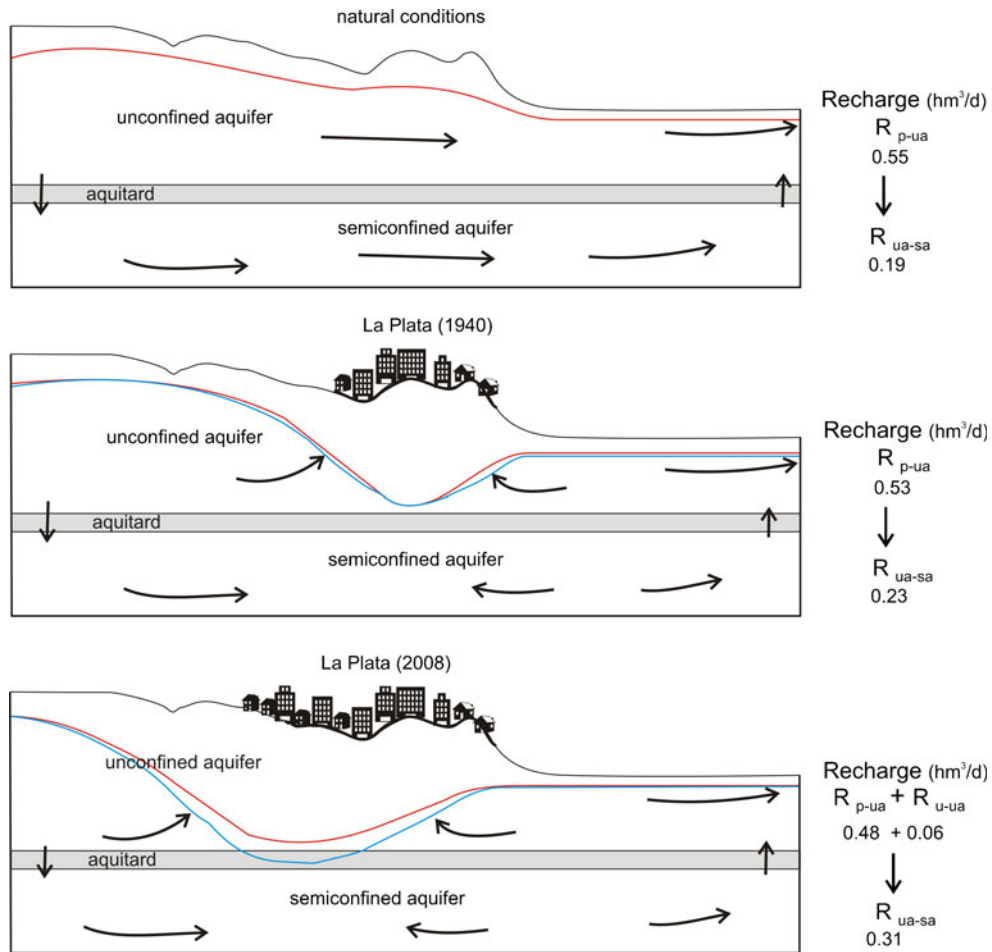
Fig. 5 Groundwater flow diagram (*red line*: piezometric level observed; *blue line*: estimated piezometric level) and recharge values estimated on the basis of the mathematical model (R_{p-ua} recharge from precipitation to the unconfined aquifer; R_{ua-sa} recharge from the unconfined aquifer to the semiconfined aquifer; R_{u-ua} urban recharge to the unconfined aquifer)

estimated that the contribution of the unconfined aquifer to the semi-confined aquifer is 0.31 hm^3/d (Fig. 5), whereas 0.037 hm^3/d is the contribution originating from system storage. Another consequence of the exploitation is the decrease in the discharge of semi-confined aquifer water in the lower portions of the unconfined aquifer, near
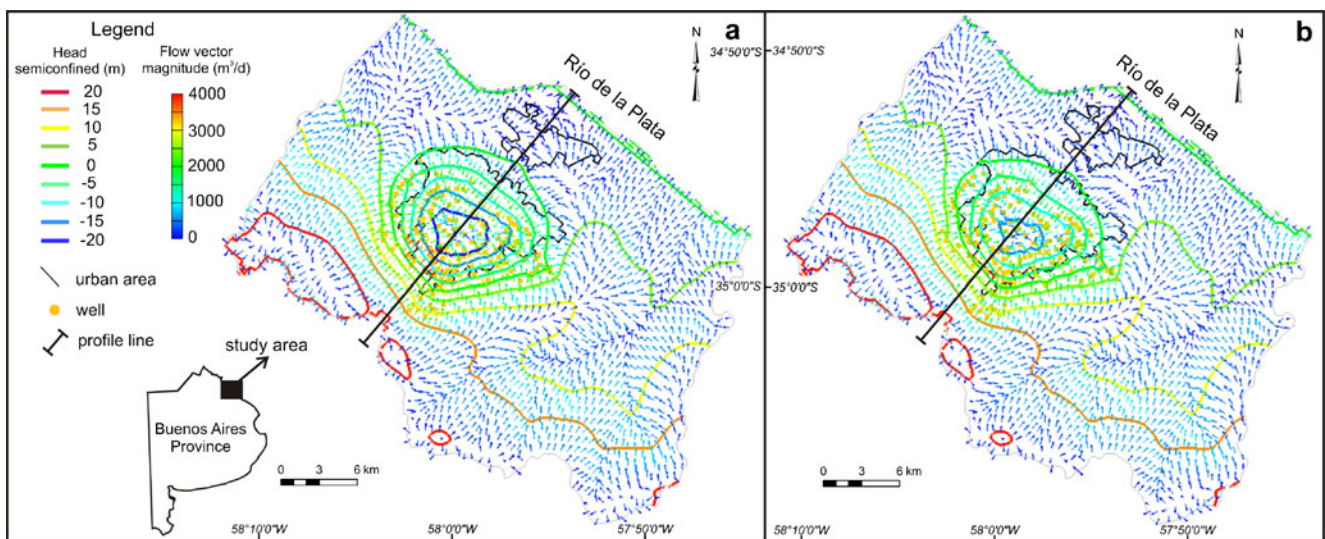

Fig. 6 Piezometric levels modelled for **a** situation of exploitation for the year 2008 without urban recharge; **b** situation of exploitation for the year 2008 with urban recharge
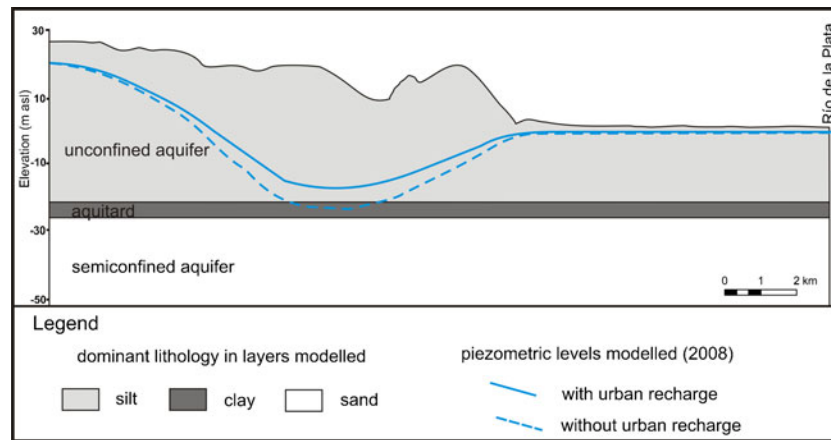
Fig. 7 Cross-section showing piezometric levels modelled for the situation of exploitation for the year 2008 without and with urban recharge

the Río de la Plata, and the decrease in deep discharge, with a value of 0.066 hm³/d.

The exploitation of the semi-confined aquifer also reduces the discharge from the unconfined aquifer into the creeks. When the water balance resulting from the simulation of the natural conditions of the system is compared to the one for the year 2008, a decrease of 0.13 hm³/d can be observed in such volumes of flow. Today, there is an increase in dry creeks in the study area.

Discussion

There is a large quantity and variety of publications on different methodologies to calculate the groundwater balance in urban areas; however, accurate recharge estimation in time and space remains a challenge (Schirmer et al. 2012). The relationship between recharge rates in urban and natural areas shows major variations; there are studies in which urbanization causes recharge to increase, decrease or does not cause significant changes. For instance, Lerner (2002) indicates that in certain areas urban recharge increases and in others it decreases with respect to non-urban recharge. García-Fresca and Sharp (2005), in a compilation on 21 cities worldwide, state that in most of the cases shown, urban recharge increases. For the city of Perth, Australia, Appleyard (1995) estimates that non-urban recharge is 15–25 % of the annual precipitation, whereas urban recharge is 37 %. Lerner (2002) mentions that in Wolverhampton, UK, the total recharge reported (220–300 mm/year) is higher than the estimated pre-urban recharge (120–250 mm/year). On the other hand, Jeppesen et al. (2011) in Copenhagen, Denmark, show that an increase in recharge caused by an increase in precipitation is balanced by the effects of urbanization.

In the case analyzed in this work, the urban recharge values obtained (21 % of the annual precipitation) on the basis of the modelling at a regional level are of a similar order of magnitude as recharge in the non-urban area. This value is relatively similar to the one obtained for the inner city area of La Plata by Auge (2005) on the basis of a

local water balance in the exploitation area. In that work, the author estimates that recharge in the urban area is 19 % of the precipitations, which he calculates on the basis of the difference between the volume of groundwater extraction and the volume of groundwater flow entering the cone of depression along the equipotential curve for 0 m asl.

The examples quoted and the case study show the variability in the estimation of urban recharge, which is influenced by different factors such as climatic conditions, water balance, exploitation and water uses. Another significant factor to be considered is the influence of water deriving from leakages in the city's water supply network and sewerage, which are part of the imported water in the urban area (Schirmer et al. 2012), depending on the state of preservation of the networks and the consequent possibility of recharge.

Conclusions

A methodology was developed in order to estimate regional urban recharge on the basis of a water balance and the simulation of the temporal evolution of the cones of depression and the volumes of water extracted from the aquifer. The method consists of adjusting the piezometry resulting from the numerical modelling to the measured piezometry, by means of the variation of the recharge parameter in the urban area. In order to do so, it is necessary to calibrate the model to reproduce a water situation in a steady state and another in a transient state with groundwater exploitation and no urban recharge.

According to the simulation, if a hypothetical recharge of 0 m/d is considered for the urban area, the cone of depression simulated would have a surface area 1.2 times larger than the cone of depression measured. For the adjustment to the measurements of the actual situation, it is necessary to have urban recharge, derived from pipe and storm drainage system leakage, which represents a relatively similar value to natural recharge due to rainfall excess.

The use of the numerical modelling makes it possible to verify the existence of urban recharge, and by means of the water balance it is possible to quantify it, identifying the

origin of the water extracted from the system in its new hydraulic condition. On the basis of this model, it is feasible to quantify the increase in recharge to the semi-confined aquifer being exploited as a result of the increase in hydraulic head difference with respect to the unconfined aquifer. The water recharging this aquifer in the zone of the cone of depression also derives from the urban recharge of the system.

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