Local and Regional Water Flow Quantification in Groundwater-dependent Wetlands

E. Carol · E. Kruse · M. Mancuso · M. Melo

Abstract Runoff, groundwater recharge and discharge, and surface water–groundwater interaction are the main driving forces of wetlands. The quantification of such flows is crucial information in the restoration and management of groundwater-dependent wetlands. The objective of this work is to quantify groundwater inflow at the level of the hydrogeological basin, which discharges into the wetland in the coastal plain of the Río de la Plata (Argentina). It also aims at evaluating whether such inflow is affected by groundwater exploitation in the high plain adjacent to the wetland. On the basis of water level data, a model of hydrological behaviour was developed and then a numerical simulation to quantify groundwater inflow was carried out. The evolution of groundwater levels was analyzed considering three situations: one of them in natural conditions and two others under different groundwater exploitation conditions. In the first case, the inflow originates in the recharge from precipitation, in the local groundwater discharge from the adjacent high plain and in the regional one from the semi-confined aquifer. The exploitation of the semi-confined aquifer in the high plain causes the formation of a cone of depression which modifies the hydrodynamics of the wetland in the area adjacent to the extraction wells. The quantification of flows shows that groundwater exploitation in areas of the basin located out of the wetland may cause the volume of water flowing into the wetland through groundwater discharge to decrease by approximately 25 %. The importance of considering discharge wetlands as part of regional hydrogeological systems should be highlighted, mainly as regards the management of natural resources.

Keywords   ·   ·   ·   ·
Hydrogeological system

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1 Introduction

The importance of wetlands lies in the wide variety of goods and services that they provide to the ecosystems and to society, among them water storage and treatment, carbon fixation in vegetation and the soil, opportunities for hunting and fishing, natural forage for livestock farming and flood mitigation. Many wetlands have been destroyed worldwide or are being degraded by anthropogenic activities. This is due to the fact that in the past wetlands were regarded as unsanitary land, associated with malaria and other water-borne diseases. For this reason, a large part of them have been destroyed by being filled or drained, and such activities were frequently promoted by means of government incentives or laws. Such a situation led to many countries losing a large percentage of wetlands, which were used for crop and livestock farming (Custodio 2010).

The main driving force of a wetland is its hydrological component, that is to say, runoff, groundwater recharge and discharge, surface water–groundwater interaction, or a combination of these (Krause et al. 2007; Roets et al. 2008). A large part of wetlands depend totally or partially on groundwater discharge. In a regional system, these discharge areas may be related to local, intermediate and/or regional flow systems (Tóth 1995), and the wetlands occurring in them represent—at a hydrological basin level—only a small portion of the extension of the aquifer.

The quantification of water flow is crucial information in the restoration and management of groundwater-dependent wetlands. Groundwater inflow estimation in this type of wetland has usually been carried out on the basis of local measurements of the hydrodynamic or chemical characteristics of the wetland itself (Hunt et al. 1996; Logan and Rudolph 1997; Boswell and Olyphant 2007; Cook et al. 2008; Roets et al. 2008; Wang et al. 2010) and not on the basis of the regional hydrogeological conditions.

The coastal plain of the Río de la Plata (Argentina) constitutes a vast wetland located in the discharge area of a regional hydrogeological basin which has its source in the high plain adjacent to the wetland. Within this basin, the groundwater resources are only intensively exploited in the high plain to supply the population residing in it. The objectives of this work are to analyze water flow in the wetland at the level of the hydrogeological basin in order to quantify the groundwater inflow from local and regional flow systems discharging into the wetland and, in turn, to assess if it is affected by groundwater exploitation in the high plain.

The hydrological conservation of wetlands is an issue of growing interest worldwide, which is why the methodology proposed in this work may constitute a useful tool to generate guidelines for the sustainable management of the water resources in this type of environment.

2 Study Area

The study area 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).

The coastal plain of the Río de la Plata (Fig. 1) is a low-lying wetland (heights below 5 m asl) whose topographic slope is below 10^{-4}. It extends between the Río de la Plata to the northeast and the high plain—which reaches a height of 30 m asl—to the southwest.

A number of streams which have their sources in the high plain and flow towards the river go through the wetland. These surface drainage basins coincide at a regional level with the
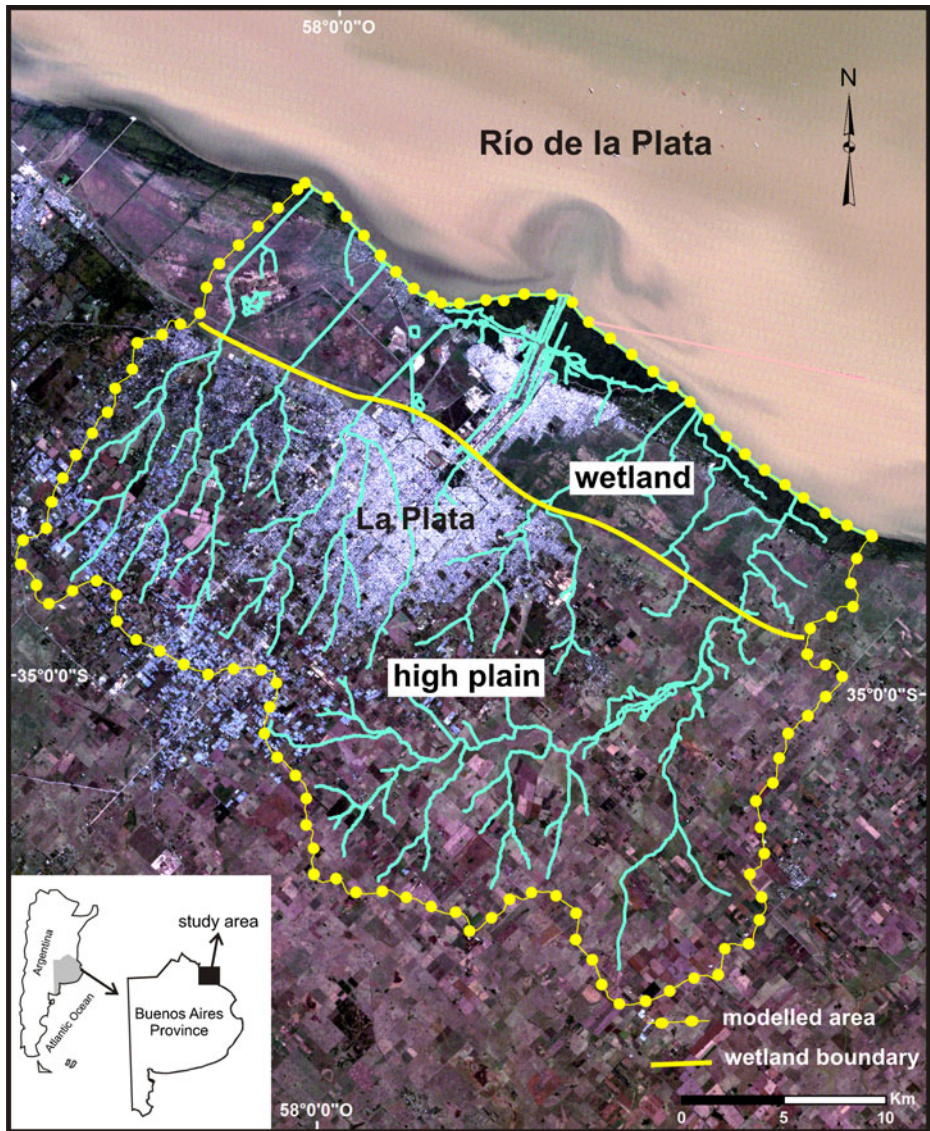
Fig. 1 Location of the study area. Black line indicates boundary between the wetland and the high plain

hydrogeological basins regulating the dynamics of groundwater flow. The wetland constitutes a discharge area of groundwater originating from a hydrogeological section which comprises an unconfined and a semi-confined aquifer.

The watershed divide in the high plain constitutes an area in which groundwater recharge from precipitation predominates. Recharge is in situ and direct to the water table and indirect by downward vertical percolation to the semi-confined aquifer (Kruse et al. 2004). In the upper section of the sedimentary sequence, the fine- to medium-grained quartz sands of fluvial origin composing the semi-confined aquifer (Arenas Puelches) overlie green clays (Paraná Formation). The sands are overlain by silt with carbonate intercalations (Sedimentos Pampeanos), in which the

water table occurs. The semi-confined aquifer is separated from the water table by a more clayey layer, which acts as an aquitard.

In the wetland there is no groundwater exploitation as the water is saline, mainly due to the processes of salt dissolution of the sediment of marine origin (Logan et al. 1999). Even though the wetland is located on the coast of the Río de la Plata estuary, there is no intrusion of seawater as in the area the river has an average salinity of 1 g/L (Acha et al. 2008). In the high plain, on the other hand, the semi-confined aquifer is intensively exploited in order to supply drinking water to the city of La Plata.

3 Methodology

The evolution of groundwater levels was analyzed at a regional scale in the whole of the hydrogeological basin considering three situations: one of them under natural conditions and two others under different exploitation conditions of the semi-confined aquifer in the high plain (1940 and 2008). The groundwater flow map for natural conditions was drawn on the basis of primitive data on groundwater levels, whereas the map for 1940 was made with historical data (Artaza 1943). The 2008 map was compiled from level measurements obtained from both public drinking water supply wells and private wells pumping from the unconfined and the semi-confined aquifer. All of this data was processed in a geographic information system (ArcGIS).

A numerical simulation was carried out and the groundwater inflow towards the wetland was calculated for the three situations. 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. MODFLOW was applied for steady state (natural conditions) and transient state simulations.

The regional model was developed for a 915 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-layered system with a thickness ranging from 22 m to 45 m in Layer 1 (unconfined aquifer), 5 m in Layer 2 (aquitard) and 25 m in Layer 3 (semi-confined aquifer) was defined.

For boundary conditions, a specified-head boundary of 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 (watershed divide).

The hydraulic parameters used in each of the modelled layers are based on the values estimated in the field tests (Kruse et al. 2004). In the unconfined aquifer, the hydraulic conductivities vary between 3 and 10 m/d, with the average transmissivity being 200 m^2/d and the effective porosity, 0.08. This layer was divided into two zones: one coinciding with the high plain area, and the other with the wetland. At the aquitard level, the hydraulic conductivities are low, between 10^{-3} and 10^{-4} m/d, and the vertical transmissivity is 5 10^{-4} m/d. In the semi-confined aquifer, the hydraulic conductivity is 20 m/d, the effective porosity is 0.30, and the transmissivity is 500 m^2/d. An underlying impermeable layer of clay was considered for modelling purposes.

Recharge from precipitation and the drainage system were indicated on the first layer (unconfined aquifer), and the pumping wells were located on the third layer (semi-confined aquifer). As in the periods analyzed there are no significant variations in time in the water balance (Kruse et al. 2004), the recharge value used was 6.16 10^{-4} m/d for all simulations; such a value represents the rainwater infiltration entering the unconfined aquifer throughout the modelled area.

The model was calibrated under natural steady state flow conditions and in transient state simulating the groundwater exploitation for 1940. According to such a calibration (transient state, hydraulic parameters and piezometry for 1940), the situation of exploitation for 2008 was simulated. In all cases, actual well distribution, depth of extraction (−45 m asl) and exploitation rate were used. For 1940, 45 wells were considered with an exploitation rate of 2,018 m^3/d per well; and for 2008, 154 wells were considered with a rate of 1,440 m^3/d per well. Simulations were carried out using 10-year periods as the model reaches an equilibrium after such a period.

The hydraulic parameters of the aquifer are the variables exerting the highest impact on the approach to the model and the simulation results; therefore, a sensitivity analysis of such parameters was done to quantify the uncertainties in the calibrated transient model. It was carried out by systematically changing the value of one of the hydraulic conductivity or storage coefficient parameters within plausible intervals and focusing on the relative changes in the response of the model. The horizontal hydraulic conductivity of the semi-confined aquifer was found to be the most sensitive of all the tested parameters. Nevertheless, the grain-size of the sand in the semi-confined aquifer and the existing pumping tests show that horizontal hydraulic conductivity values of about 20 m/d are relatively constant in the study area, as well as in this aquifer at a regional level. The assumed value is not likely to change significantly.

The variations in precipitation may directly modify the groundwater flow entering the wetland, as they recharge the unconfined and semi-confined aquifers discharging into the wetland. However, the periods analyzed in the models have similar precipitation and temperature values (1,024 mm/year and 15.9 °C for the decade that includes 1940, and 1,069 mm/year and 16.0 °C for the one including 2008), which is why there are no significant variations in the components of the water balance.

4 Results

4.1 Groundwater Flow

In natural conditions, the water tables in the wetland crop out or remain near the surface and the groundwater flow discharges locally into the streams and regionally towards the Río de la Plata. The analysis of the groundwater levels shows that the wetland is a discharge area for the local flows from the unconfined aquifer occurring in the high plain and regional flows from the semi-confined aquifer (Fig. 2).

The exploitation of the semi-confined aquifer in the high plain causes the formation of a cone of depression which modifies the hydrodynamics of the wetland in the area adjacent to the exploitation wells. In turn, the remote areas exhibit a hydrodynamic behaviour which is similar to the one described for natural conditions (Fig. 2).

In 1940, the volume of groundwater exploited was 33 hm^3/year and the cone of depression resulting from this exploitation had a surface of approximately 20 km^2, with the apex at −15 m asl (Fig. 2). The northeastern limit of the cone (water table contour line of 0 m asl) affects the adjoining wetland area, causing a deepening of the water tables. As a result, there is a local inversion of the groundwater flow, and an inflow from the wetland towards the high plain occurs, with the consequent decrease in water accumulated on the surface.

In 2008, the increase in population required more extraction wells (154), from which 80 hm^3/year were pumped. This caused an increase in the area of influence of the cone of depression, which
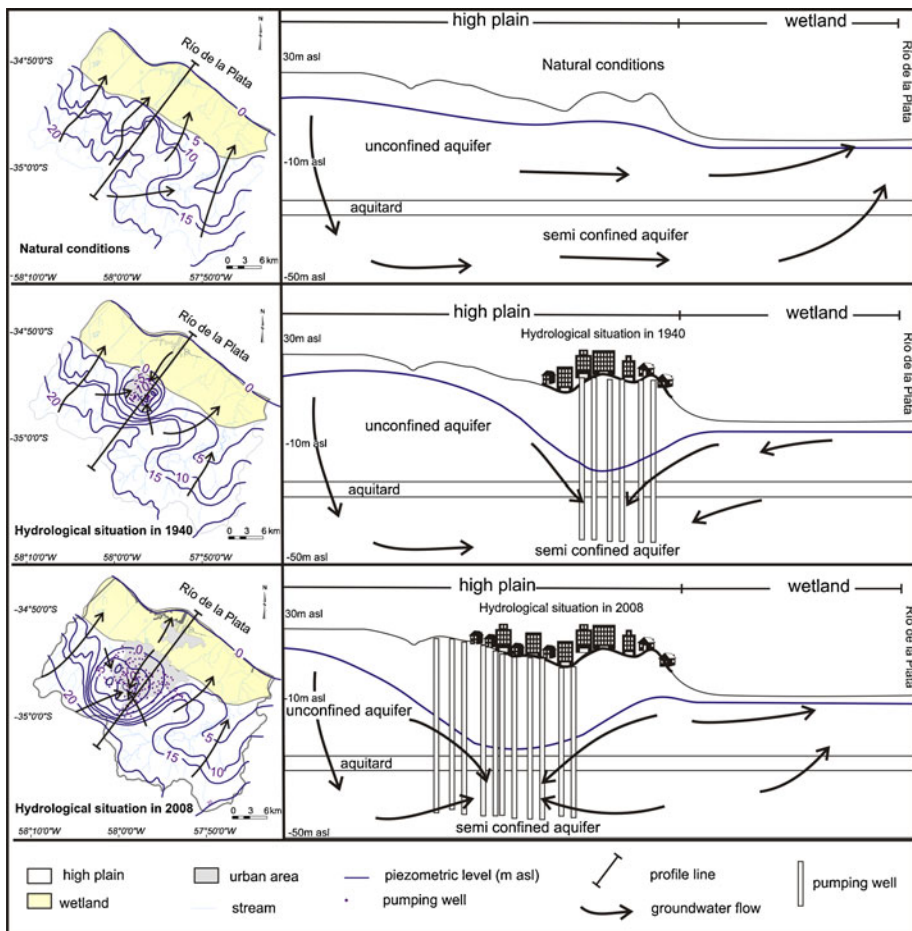
Fig. 2 Evolution of groundwater flow at a regional scale (left) and hydrogeological cross-section of the exploitation area (right)

continued to affect locally the groundwater flow of the wetland (Fig. 2). The decrease in water tables also causes the alteration in the surface water–groundwater relationship in the areas affected by the cone of depression, where the streams change from effluent to influent.

4.2 Quantification of Water Flows

The analytical models developed for natural conditions and for those with groundwater exploitation (1940 and 2008) make it possible to quantify the variation in groundwater inflow discharging into the wetland. The water volume recharging the hydrogeological basin, circulating between the aquifers, and discharging into the streams and the wetland in each modelled situation is shown in Figs. 3, 4 and 5.

For natural conditions, the model reproduces the level data recorded with a percentage discrepancy in the water balance of −0.0003. In the model (Fig. 3) it can be observed that the volume of groundwater entering the wetland originates in the recharge from precipitation and in the discharge from the unconfined aquifer occurring in the high plain and the semi-
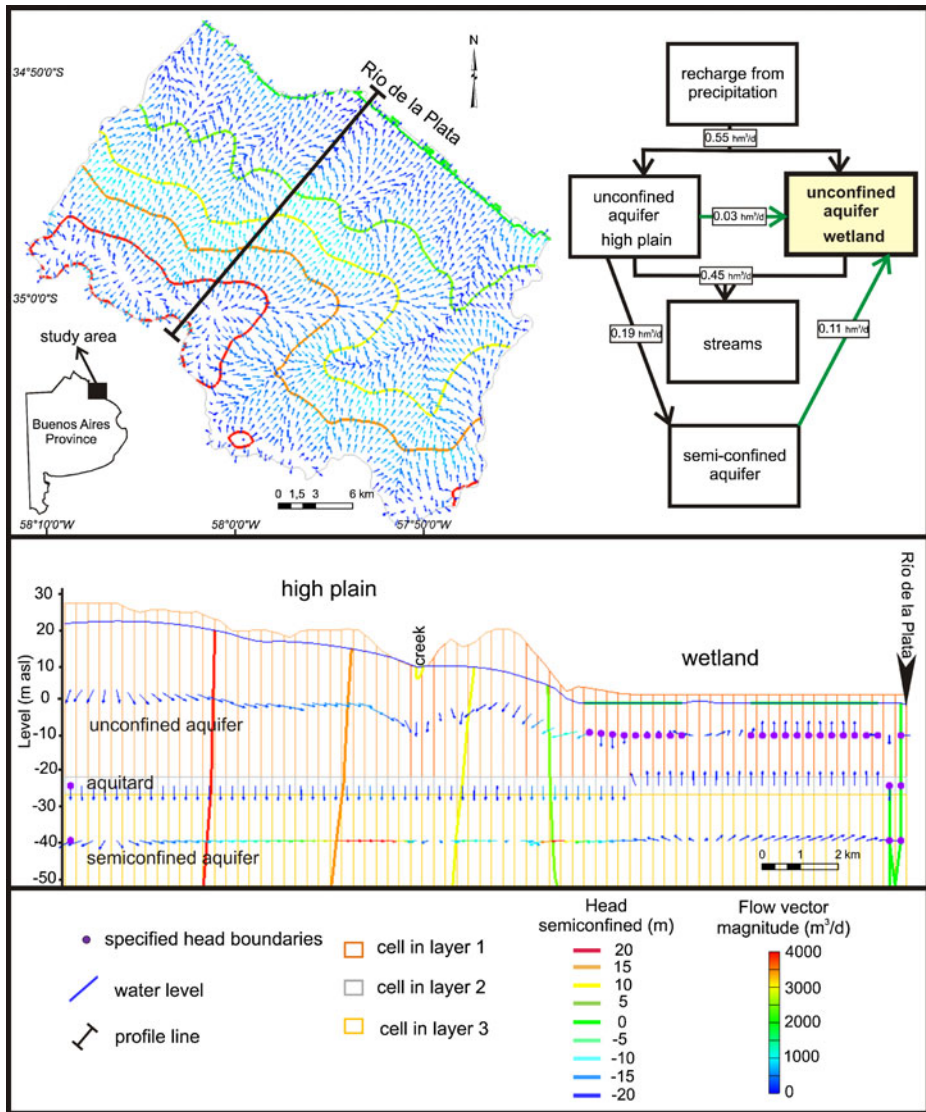
Fig. 3 Flow map and profiles resulting from the mathematical modelling for natural conditions. Cross-section of the hydrogeological basin located in the exploitation area. In the upper right-hand corner the water volume and flow transfer diagram of the hydrogeological basin are shown. Groundwater inflow towards the wetland is highlighted in green

confined aquifer. Out of the total volume of water from groundwater discharge, 0.03 hm³/d originate in the unconfined aquifer occurring in the high plain and 0.11 hm³/d in the semi-confined aquifer. Surface water originates in the discharge from both the unconfined aquifer in the high plain and in the wetland. Out of the total volume of water drained by the streams (0.45 hm³/d), 0.33 hm³/d originate in the wetland area. In natural conditions, the recharge of the semi-confined aquifer only comes from the water table in the high plain, and it is 0.19 hm³/d.
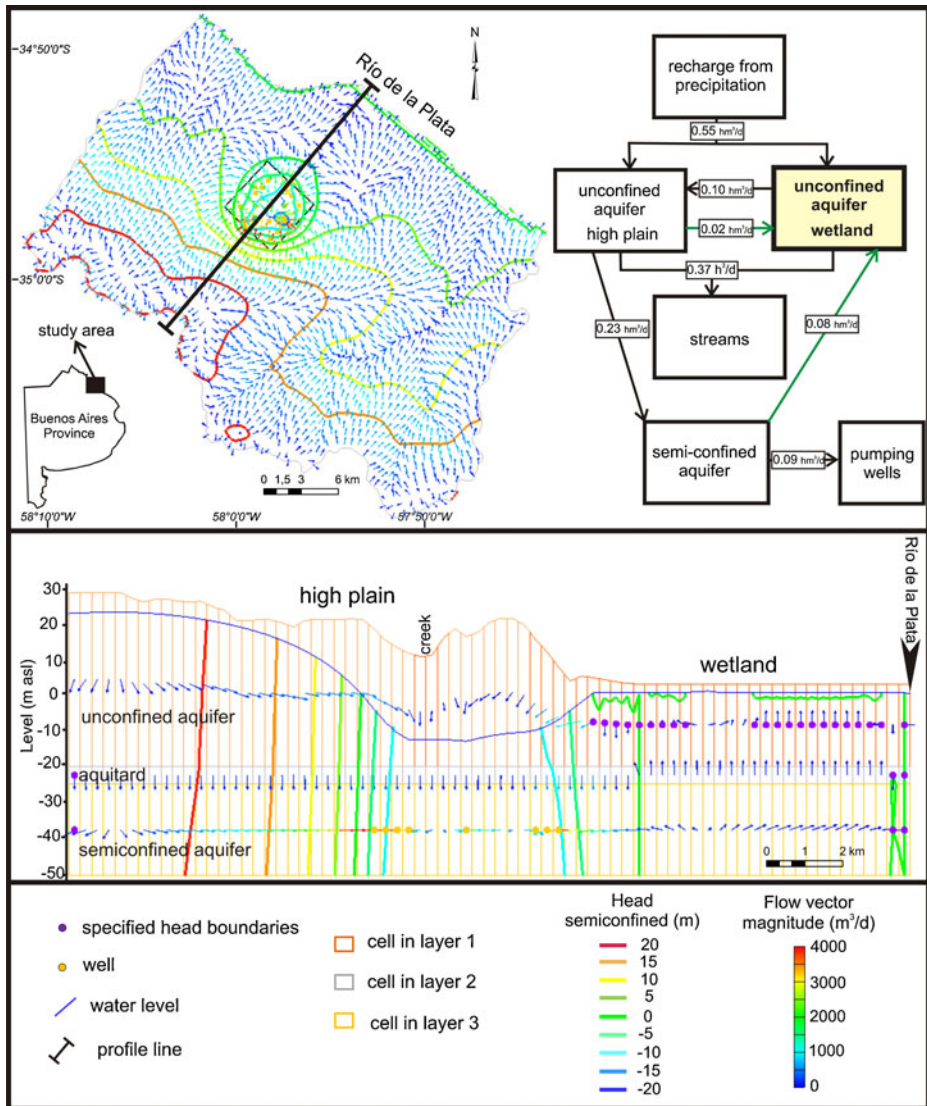
Fig. 4 Flow map and profiles resulting from the mathematical modelling for conditions of exploitation of the semi-confined aquifer in 1940. Cross-section of the hydrogeological basin located in the exploitation area. In the upper right-hand corner the water volume and flow transfer diagram of the hydrogeological basin are shown. Groundwater inflow towards the wetland is highlighted in green

The simulation for 1940 (transient state) reproduces the level data recorded for such a period with a percentage discrepancy in the water balance of −0.0005. As in the conceptual model, the analytical model (Fig. 4) shows that the hydrodynamics of the wetland is only affected in the section adjacent to the groundwater exploitation area in the high plain, with no alterations recorded in the remote areas. The hydrogeological profile in the exploitation area shows the formation of a cone of depression in the high plain, which causes the local inversion of the groundwater flow in the wetland. In such conditions, the unconfined aquifer of the wetland contributes water to the cone of depression. A similar alteration can be
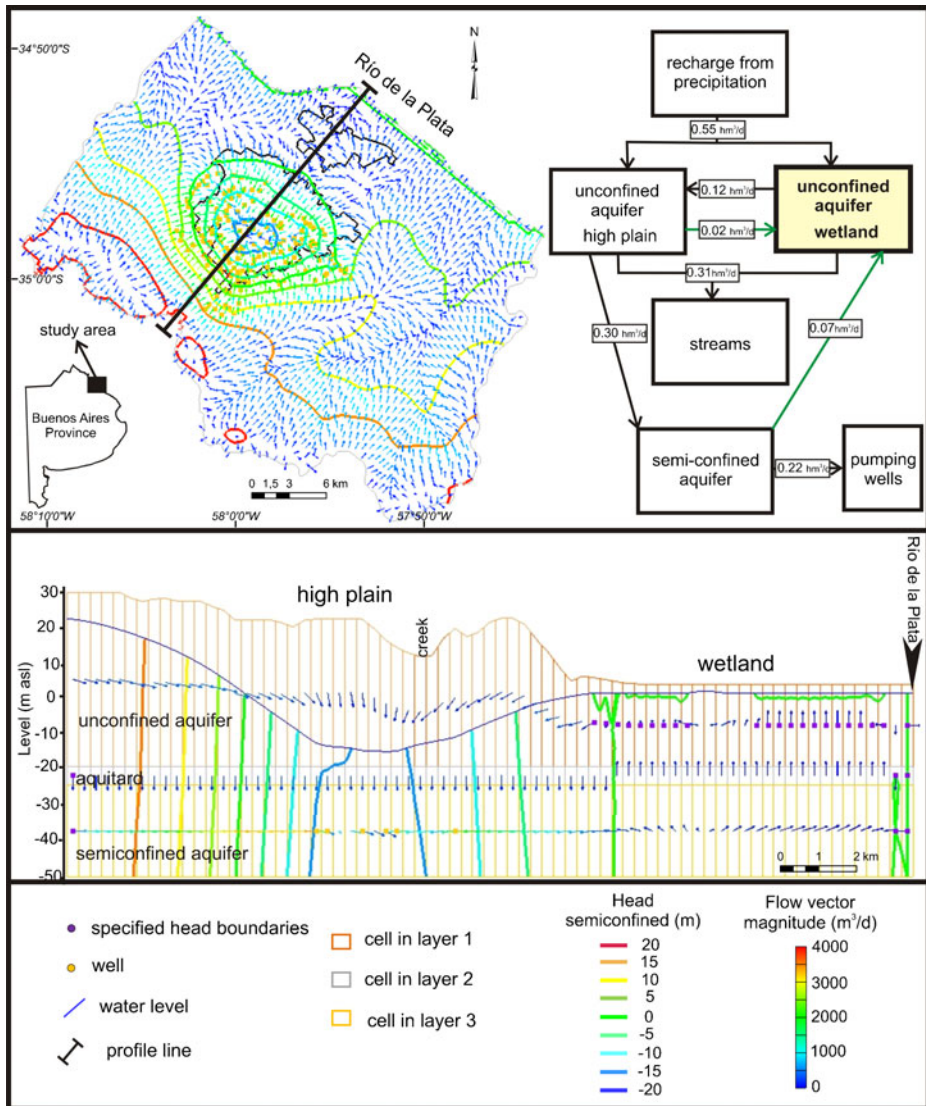
Fig. 5 Flow map and profiles resulting from the mathematical modelling for conditions of exploitation of the semi-confined aquifer in 2008. Cross-section of the hydrogeological basin located in the exploitation area. In the upper right-hand corner the water volume and flow transfer diagram of the hydrogeological basin are shown. Groundwater inflow towards the wetland is highlighted in green

observed in the unconfined aquifer occurring in the high plain, which contributes water to the exploitation wells instead of discharging into the wetland. This causes a decrease in water inflow towards the wetland which only affects the area adjacent to those exploitation wells. The quantification of water flows at the level of the hydrogeological basin—the model covers 915 km^2, including both the groundwater exploitation area and the unexploited areas —shows that the formation of the cone of depression causes an increase in the volume of water recharging into the semi-confined aquifer (0.23 hm^3/d). Part of this volume originates

in the unconfined aquifer of the wetland as a consequence of the inversion of the groundwater flow caused by the formation of the cone of depression. Likewise, the pumping of water affects the groundwater flow that naturally discharges into the wetland, decreasing groundwater discharge. On the basis of the model, it can be estimated that a volume of water of 0.10 hm^3/d leaves the wetland towards the high plain and that there is a decrease in the discharge towards the wetland of 0.01 hm^3/d from the unconfined aquifer and of 0.03 hm^3/d from the semi-confined aquifer (Fig. 4).

The simulation for 2008 (Fig. 5) shows a more significant alteration of the hydrodynamics of the wetland as a result of the increase in the number of wells and in the exploitation rate, (0.22 hm^3/d) and the consequent expansion in the cone of depression in the high plain. In turn, the areas of the wetland which are far from the groundwater exploitation area display a behaviour similar to the one observed in natural conditions.

In the hydrogeological profile the enlargement of the cone of depression can be observed in the high plain. As observed in the simulation for 1940, this causes the unconfined aquifer in the wetland to contribute water to the cone of depression, and part of the water discharging from the unconfined aquifer in the high plain to the wetland to be diverted to the exploitation wells.

The quantification of water flow shows that in such conditions there is an increase in recharge from the unconfined aquifer towards the semi-confined aquifer (0.30 hm^3/d) to the detriment of the water flow discharging into the wetland. This causes an increase in the volume of water flowing from the wetland to the high plain (0.12 hm^3/d), and a decrease in discharge to the wetland from the unconfined aquifer in the high plain (0.02 hm^3/d) and from the semi-confined aquifer (0.07 hm^3/d) (Fig. 5).

5 Conclusions

A mathematical model at the level of the hydrogeological basin made it possible to quantify the water inflow in the wetland, and its decrease as a result of groundwater exploitation in the adjacent areas. In the case studied, it can be observed how groundwater exploitation in areas of the basin located out of the wetland may cause a decrease of approximately 25 % in the water volume flowing into the wetland. The results obtained show that water inflow towards the wetland is strongly dependent on the hydrological alterations and processes occurring at the level of the hydrogeological basin, which is why its quantification could not have been carried out with local studies undertaken within the wetland area. This highlights the importance of regarding discharge wetlands as part of regional hydrogeological systems, mainly concerning issues related to their administration and management. The conservation of wetlands may be seriously affected by the hydrological alterations undergone in the recharge and groundwater flow areas in the basin.

The methodology proposed in this work provides a tool for the hydrological study of wetlands which can be applied in other regions worldwide. Due to the increasing water demand, there will be an increase in groundwater exploitation, which may jeopardize the integrity of the wetlands that depend on groundwater.

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