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ORIGINAL ARTICLE

# Eco-hydrological role of deep aquifers in the Salado sedimentary basin in the Province of Buenos Aires, Argentina

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**Abstract** Although not well known, the eco-hydrological functions of deep aquifers (those having no contact with surface hydrological events) play an important role in the hydrological regime because they can affect the type of habitats, the availability of water and nutrients and the salinity of the medium, among other environmental features. This work aims at characterizing the deep Tertiary hydrogeological units of the Salado sedimentary basin in the Province of Buenos Aires, Argentina, at a regional scale, and to determine their environmental importance in the hydrological cycle. The geological characterization of the study area is based on the drilling profiles from oil exploration wells bored by different oil companies between 1948 and 1994, and also from the existing literature. The conclusion is that water exchange between quaternary surface aquifers in contact with atmospheric events and deep tertiary aquifers is one of the main processes that keep the hydrologic balance of the region. Not only is this crucial for the conservation of the numerous and well-developed ecosystems in the basin wetlands, but also significant for the agricultural and cattle-raising activities of the region.

**Keywords** Deep aquifers · Hydrological cycle · Groundwater flow · Argentina

## Introduction

In a large sedimentary basin, it is possible to distinguish local, intermediate and regional groundwater flows (Tóth 1963). According to the hydraulic continuity concept (Tóth 1995), the basic distribution of flow systems exhibits three distinctly different groundwater flow regimes, such as the recharge, midline and discharge regions. These regions are characterized by descending, lateral and ascending flows, respectively.

Regional groundwater flux in sedimentary basins is associated with deep aquifers, which have been defined as those having no contact with the hydrological events occurring at the surface and in the soil moisture zone (infiltration, evaporation and transpiration) (Kovács and Associates 1981). Therefore, charging and discharging processes in this type of aquifers take place only through water exchange between neighboring aquifers. The eco-hydrological functions of deep aquifers are ordinarily not well known. However, they play an important role in the hydrological regime because they can affect the type of habitats, the availability of water and nutrients, and the salinity of the medium, among other environmental features (Zalewski et al. 1997; Rodríguez-Iturbe 2000). Deep aquifers exhibit very low hydraulic gradients, long travel times and high temperatures, very few fluctuations in the average flux, and a relatively constant volume and chemical composition (Stuyfzand 1999). Groundwater flux and their associated hydrochemical processes depend on the geological features (lithology, mineralogy and structure) of the rocks in which groundwater is contained. Interaction

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between groundwater and environment may be chemical (associated with dilution, hydration and hydrolysis processes), physical (related to lubrication and pore-pressure modification processes) and kinetic (connected with water, aqueous and non-aqueous matter and heat transport processes) (Tóth 1999). Chemical interactions within deep aquifers are favored by the relatively slow flux, long residence time and high thermal energy. Because of this, water in these aquifers is normally saline with salinities that sometimes exceed the average salinity of the world ocean (about 35 g/L). Despite the low average flux, transport processes at a regional scale involve the move of huge quantities of water that can modify the environmental features. For example, the chemical balance of low salinity or freshwater shallow aquifers can be changed by the discharge of deep groundwater flow into them. Upward fluxes can affect the ecology and produce changes in the environmental characteristics of discharge zones (Klijn and Witte 1999).

The objective of this work is to characterize the deep hydrogeological units of the Salado sedimentary basin in the Province of Buenos Aires, Argentina, at a regional scale, and to determine their environmental importance in the hydrological cycle.

## Study area

The Salado sedimentary basin is located in the center-east sector of the Province of Buenos Aires, Argentina, between the Precambrian—Paleozoic Uruguayan and Tandilia structural highs, and extends along a northwest-southeast direction towards the continental shelf (Fig. 1). It has an area of about 70,000 km$^2$, of which 44,000 km$^2$ are inland and 26,000 km$^2$ in the continental shelf (Criado Roque et al. 1959; Zambrano 1974). The whole basin is very flat with topographic gradients that decrease from 0.05% in the northwestern sector to 0.02% in the southeastern sector. Slopes in the continental shelf are similar to those of the southeastern sector. The continental portion of the Salado sedimentary basin, called the Salado Depressed Zone, is a significant productive region with a humid temperate climate. Human activities are largely devoted to agriculture in the northwest and cattle raising in the southeast; both are strongly influenced by dry and humid cycles that produce short- or long-range changes in water availability. Many wetlands of great ecological importance develop along the coastal zone. One of them, the coastal fringe of the Samborombon Bay, was selected as a Ramsar site in 1997. Changes in the hydrological processes are therefore critical in any analysis and prediction of the behavior of this productive and ecological environment.

## Geology

The Salado sedimentary basin is one of the many extensional Mesozoic basins along the east coast of South America and the west coast of Africa produced by the continental rifting that accompanied the breaking of the Gondwana super continent. The structural tectonic evolution of the Salado sedimentary basin is mainly extensional

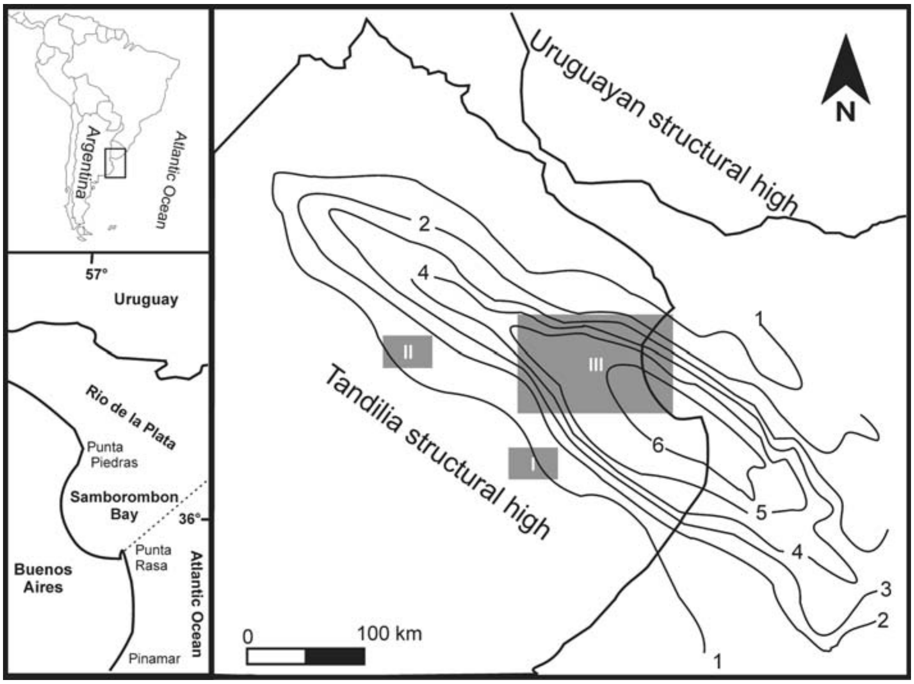


**Fig. 1** Location map and isopachs (km) of the Salado sedimentary basin. The *rectangles* in *gray* show (I) the Arroyo Azul subwatershed; (II) the Arroyo Grande subwatershed; and (III) the region covered by the severe floods occurred in 1980 (see text and Fig. 6)

and began during the upper Jurassic and lower Cretaceous (Ponte et al. 1978; Bracaccini 1980; Nullo 1991). Four stages can be identified in the tectonic evolution, namely pre-rift, rift, sag and passive margin (Tavella and Wright 1996; Yrigoyen 1999; Tavella 2005). The northern, southern and eastern boundaries of the Salado sedimentary basin are formed by direct faults that reach several kilometers of throw. This faulting has produced positive areas composed of blocks of igneous metamorphic basement covered by a few tens or hundreds of meters of sediments (Yrigoyen 1975).

The geological characterization of the study area is based on the drilling profiles from oil exploration wells bored by oil companies (YPF, Yacimientos Petroliferos Fiscales, Kerr McGee, SIGNAL, UNION, SUN, Chevron and Amoco) between 1948 and 1994 (Fig. 2). As detected seismically at its deepest part, the Salado sedimentary basin is filled up with about 6,000 m of Mesozoic–Cenozoic consolidated sedimentary rocks (Fig. 1). Inside the basin, these sedimentary rocks lie on two basement units. One of these units consists of metamorphic rocks of Precambrian age intruded by granitic rocks of the same age; the other unit is a metasedimentary basement of the Proterozoic to Eopaleozoic ages.

The basement was always found at the boundaries of the basin or outside it; towards the axis of the basin the geologic profile becomes abruptly deeper (Bracaccini 1972). A sequence of consolidated sedimentary rocks of decreasing grain size lies over the basement. This sequence, termed the Rio Salado (River Salado) formation, is composed of conglomerates, sandstones and reddish-brown mudstones interbedded by effusive and volcanic rocks. It has a maximum thickness of 3,500 m (Zambrano and Urien 1970) (Fig. 3).

Immediately upwards, there is a subsidence stage with consolidated sedimentary rocks of the *red beds* type belonging to the General Belgrano formation, and deposited in angular unconformity, with maximum thicknesses of 886 m (Zambrano and Urien 1970). These rocks correspond to facies developed in a proto-oceanic environment.

The stratigraphic sequence continues with the deposition of deltaic and transitional sediments composed of siltstones with small quantities of lime and sandstones. These sediments belong to the upper Cretaceous and have a maximum thickness of 1,190 m. They represent the first apparent marine ingression throughout the basin, and are termed the Las Chilcas formation (Zambrano 1971).

Between the Eocene and lower Miocene, and over the marine units, transitional tertiary sediments are deposited followed by continental red layers of regressive character that belong to the Los Cardos and Olivos formations. Eastwards, these formations pass into deltaic and marine deposits that become dominant before reaching the continental slope. The whole sequence has a maximum thickness of about 800 m.

Another large sea-level rise, represented by the deposits of the Paraná formation, took place during the lower to middle Miocene. This formation is composed of a series of clay, clayey sands and green sands with calcareous levels and marine fossils. The Cenozoic sedimentary process ends during the Pliocene with continental clastic accumulations of fluvial origin and upper Pliocene (Puelches formation). Finally, quaternary Pampean sediments are deposited in angular unconformity over the Puelches formation. The stratigraphic column of Fig. 3 summarizes the filling of the basin.

## Hydrogeological features

According to the above geologic characteristics, the tertiary–quaternary sedimentary formations are most important

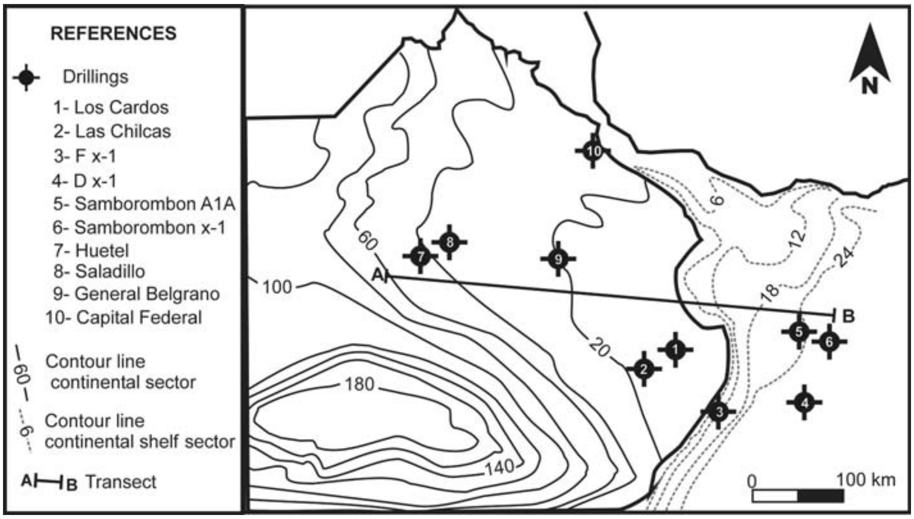


**Fig. 2** Topographical map with oil exploration wells. A typical hydrogeological profile along transect AB is discussed in the text [*Contour lines* (m)]

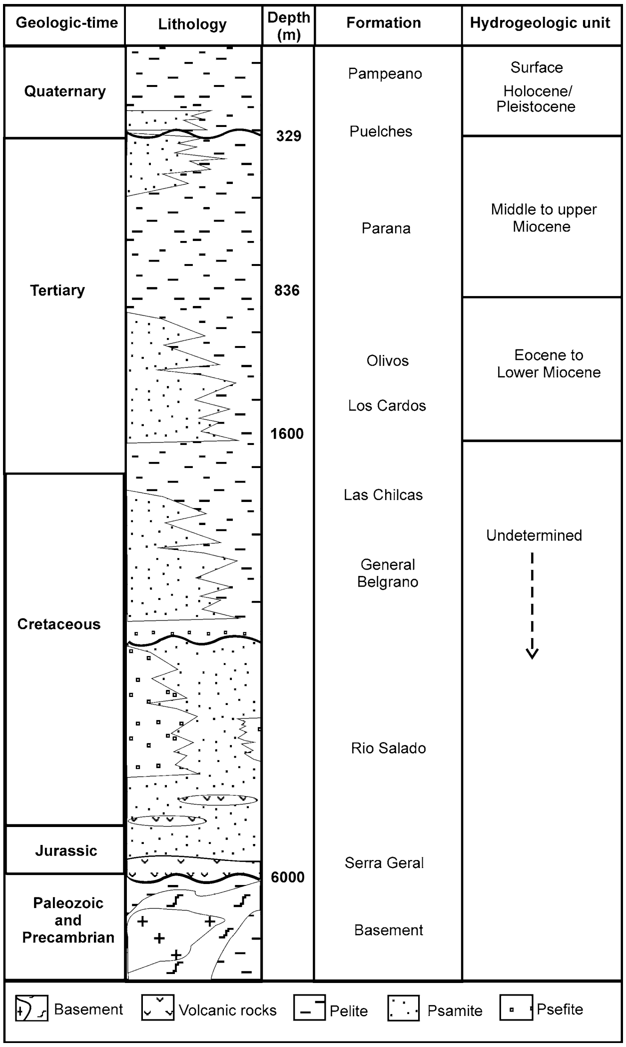


**Fig. 3** General stratigraphy of the Salado sedimentary basin

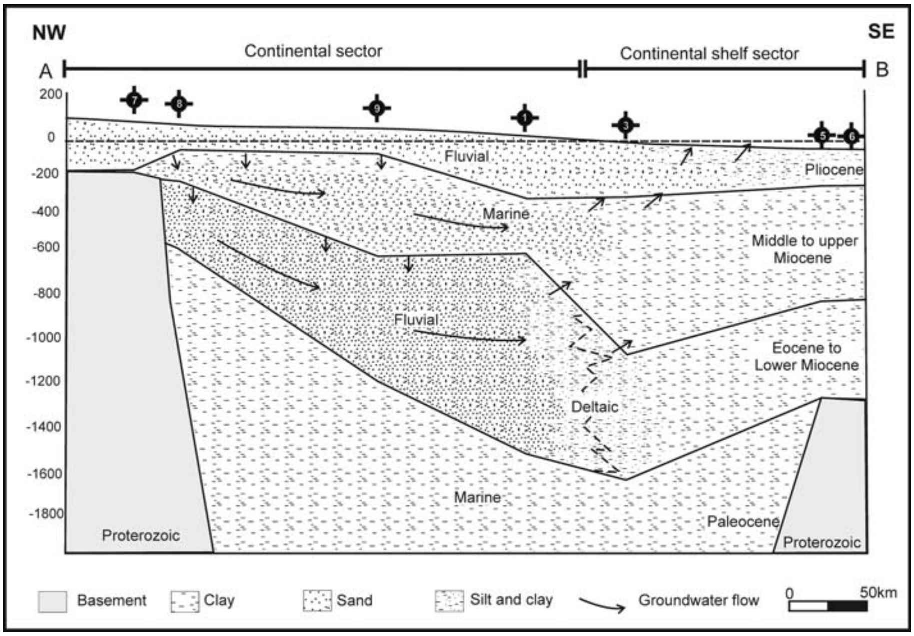
regarding environmental matters. The lithology and facies of these formations determine the hydrogeological units of the basin. The scarce deep drilling records available limit the regional knowledge of the pre-tertiary units.

Figure 4 shows a typical hydrologic profile along transect AB (Fig. 2) in the northwest–southeast direction. The uppermost hydrogeological unit develops over the whole basin and is composed of two layers: a lower one of sandy-fluvial Pliocene sediments with average transmissivity of 500 $m^2$/day, and an upper one of silty-loessic Holocene sediments with average transmissivity os 200 $m^2$/day (EASNE 1972). Loessic sediments are much eroded in the continental shelf sector, but fluvial sands outcrop in some artificial channels (Paterlini et al. 1993). On a regional scale, and neglecting local details, loessic and sandy-fluvial sediments form a multilayered aquifer recharged by rainfall. Groundwater depth is small, usually $<3$ m. Flux direction is towards the surface streams, the Rio de la Plata and the Atlantic Ocean, with low hydraulic gradients ($6 \times 10^{-4}$). Although the phreatic and topographic morphologies are similar, the phreatic morphology has a lower slope and shows a regional eastward seepage (Fig. 4). The salinity of water in this unit is low ($<1$ g/L), but increases towards the axis of the basin and also in the southern sector.

Downwards, the next hydrogeological unit is composed of marine sediments of middle to upper Miocene distributed throughout the basin. However, facial variations related to proximal and deep environments can be observed in the basin. The deposits in the continental sector are generally sandy in the bottom of the unit and silty at the top. The amount of sands is larger towards the axis of the basin, whereas silts increase towards the southeast. The continental shelf area exhibits silty facies that are typical of deep marine environments. The silty layers at the top of the unit and those associated with the deep marine deposits behave as aquiclude to aquitard, whereas the bottom sandy layers of the continental sector are predominantly aquifer. The regional transmissivity of the continental sandy sector ranges between 100 and 1,000 $m^2$/day (Hernandez et al. 1975), and is estimated to be about 50 $m^2$/day in the continental shelf sector. Piezometric levels are at 100 m over mean sea level (MSL) in the very west of the basin and decrease towards the east, with a hydraulic gradient of about $10^{-4}$. The regional groundwater flux discharges into the ocean, but there is an upward flux in the shelf sector because of the less permeable facies (Fig. 4). Water in this unit is $Cl^-$ to $SO_4^{2-}$ with an irregular chemical composition. The salinity ranges mostly between 10 and 30 g/L, with maxima over 100 g/L and minima from 2.5 to 3 g/L (Hernandez et al. 1975). These low salinities belong to wells under exploitation in the northeast zone of the basin.

Another hydrogeological unit formed by Eocene to lower Miocene sediments lies below (Fig. 4). This unit has fluvial characteristics in the west (continental sector) that pass transitionally into marine deposits towards the east (continental shelf sector). Red layer deposits composed of sandstones and red clays develop in the western sector of the basin. Psamites predominate in the lower half, with mostly clayed facies to the westernmost sector. Towards the east, these deposits pass transitionally into clayey-silty deltaic and marine deposits that become completely dominant before reaching the continental slope. The variations in the hydrogeological behavior are due to the presence of aquifer sections related to psamitic continental facies, and aquiclude to aquitard sections related to clayey-silty to clayey facies of transitional to marine character. The regional transmissivity of the continental sector is usually $<1{,}000$ $m^2$/day, with extremes of 100 and 5,000 $m^2$/day (Hernandez et al. 1975). Towards the continental shelf, and according to the lithologic characteristics, the transmissivity fall $<100$ $m^2$/day. Piezometric levels decrease

**Fig. 4** Typical hydrogeological profile along transect AB (see also Fig. 2)



gradually from about 100 m over MSL in the western sector of the basin, to nearly 0 m over MSL at the seashore. The regional groundwater flux is towards the ocean, but there is an upward move in the continental shelf sector associated with changes in facies (Fig. 4). This unit has aquifers of $Cl^-$ to $Cl^-–SO_4^{2-}$ waters, including $SO_4^{2-}–Cl^-$ waters, and salinities between 6 and 60 g/L (Hernandez et al. 1975, Bonorino 2005). Water temperature is estimated in the order of 35°C for wells between 800 and 1,000 m deep, which agrees with the natural geothermal gradient (Bonorino 2005).

## Hydrology and regional groundwater flux

The climate of the Salado sedimentary basin is humid temperate. The average rainfall for the period 1888–2007 is 918 mm/year, with extreme values of 1,450 and 430 mm/year. These variations of rainfall determine the existence of dry and humid periods. Figure 5 shows the evolution of annual rainfall, together with the curve obtained with a 10-year moving average, the average annual rainfall, and a trend line from filtered data. Periods with rains above or below the average are thus clearly identified, as well as a slightly increasing trend of rainfall (2 mm/year). According to the Thornthwaite and Mather (1955) method, the evapotranspiration is 770 mm/year.

The natural drainage network is poorly developed and lacks integration. The creeks are small and remain active because of the discharge of groundwater into them. Owing to this and the low topographic gradients, vertical water moves (evapotranspiration and infiltration) prevail over horizontal ones, thus making variations in the surface water and groundwater storages to be significant in the water budget. The natural morphogenic potential of the plain is thus reduced, thereby hindering the development of a suitable drainage network. Because of this and the numerous shallow depressions distributed all over the basin, temporary large floods often occur.

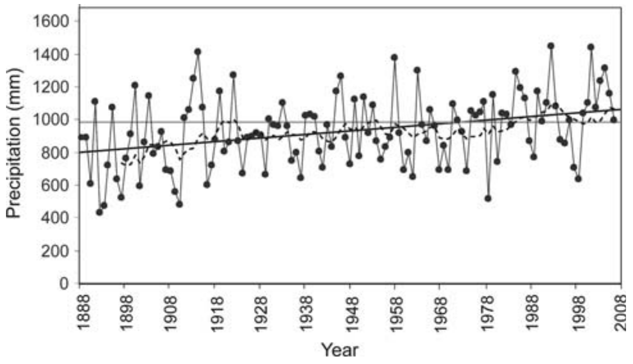


**Fig. 5** Evolution of annual rainfall (*solid thin line*) together with the curve obtained with a 10-year moving average (*dashed line*), the average annual rainfall (*gray heavy line*) and the long-term trend of rainfall (*solid heavy line*)

Groundwater flux has local and regional characteristics. The local flux appears in the uppermost quaternary hydrogeological units and refers to a seepage that is the basic discharge of those ponds and creeks in which it outcrops. The regional flux is a deep and very slow seepage in the tertiary hydrogeological units fed by the difference between inflow and outflow of local groundwater in the uppermost layers (Kruse and Laurencena 2005).

Although the information available to quantify the water budget in the Salado basin is scarce, the existing data from some subwatersheds allow the relative weight of the main

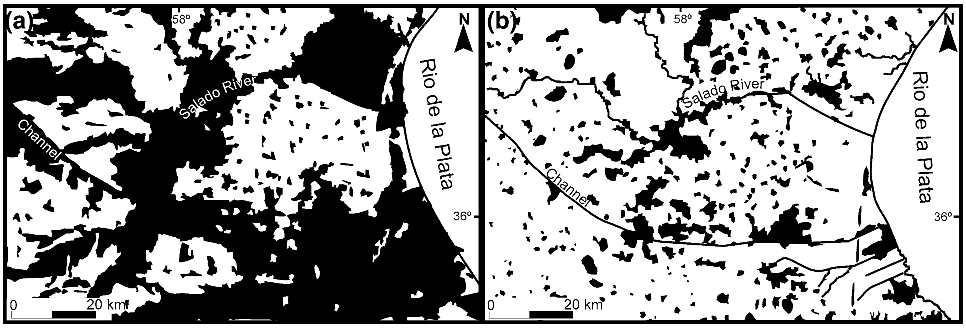


**Fig. 6** **a** Satellite image of the region covered by the severe floods occurred during the months of April and May 1980 (see Fig. 1 for location in the map). **b** Satellite image of how the basin was emptied during the autumn to spring months of May–October 1980. Flooded areas are in *black*. (Modified after Domínguez and Carballo (1983).)

hydrological components to be estimated. The available data for the Arroyo Azul (Azul creek) subwatershed (Fig. 1) gave a total infiltration of 88 mm/year for the period 1962–1985 (Kruse 1992), a little more than 10% of the average annual rainfall for the same period (838 mm/year). Streamflow is 31 mm/year, of which 14 mm/year correspond to baseflow. Actual evapotranspiration is 733 mm/year (Thornthwaite 1948), and regional groundwater flux has been estimated in 74 mm/year.

The average annual rainfall in the Arroyo Grande (Grande creek) subwatershed (Fig. 1) was 854 mm/year for the period (1967–1973). Streamflow is 37 mm/year, including baseflow and surface runoff. Considering that actual evapotranspiration is 717 mm/year, the contribution of infiltration to the regional groundwater flux has been estimated more than 63 mm/year (Sala 1977).

Owing to the lithology of its hydrogeological units, the Salado sedimentary basin has a hydrologic behavior that can be assumed to be continuous in time and space, although horizontally and vertically heterogeneous. The uppermost unit is recharged by rain infiltration. Because of the very low topographic gradient of the basin, the surface storage occurs over extensive areas, thus increasing the regional infiltration. The small difference in hydraulic head between surface and deep aquifers is balanced by the large area and time in which infiltration occurs, which leads to an indirect recharge.

The analysis of satellite images proved qualitatively the importance of infiltration processes in the Salado sedimentary basin. For example, between 20 April and 10 May, 1980, rainfall in the low-lying parts of the watershed (Figs. 1, 6) was 428.8 mm, which is 278 mm above the mean value for the region. This exceptional rainfall caused floods in a region of some 5,500 km$^2$ (more than 30% of the area shown in Fig. 6a). Satellite images show how the flooded area of the basin reduced to <2,000 km$^2$ during the autumn to spring months of May–October 1980 (Fig. 6b) (Domínguez and Carballo 1983). Furthermore, rainfall between May and October was 253.7 mm, whereas actual evapotranspiration for that period was only about 160 mm. This means that even with this rainfall excess, the flooded area was largely reduced. Owing to the low topographic gradient of the flooded region, it is not possible to attribute its nearly total drainage in such a short a time interval to runoff only. The explanation of this rapid drainage process during a low evaporation period (mainly winter months) can be found only in the infiltration of huge volumes of water towards deeper hydrogeological units, and the subsequent discharge into the continental shelf. Because of the small hydraulic gradient this discharge is slow, but as it takes place over the whole area of the basin, the transported volumes are large.

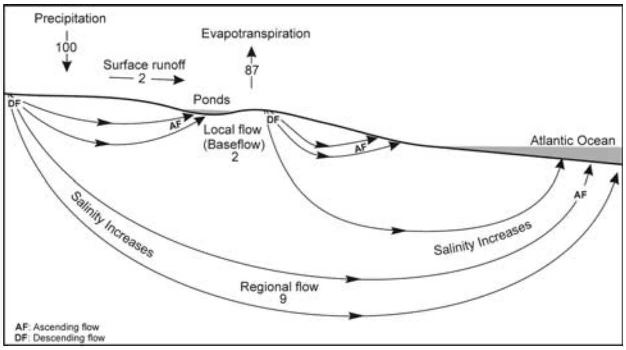


**Fig. 7** Distribution of 100 parts of rainfall to the components of the hydrologic cycle

According to the scarce data available, the characteristics of the hydrogeological units and the environmental conditions, it is possible to make an approximate assessment of the average values of the water budget terms. Of 100 parts of rainfall, 87 parts are lost to atmosphere by evapotranspiration, 11 parts enter the ground as infiltration, and the remaining 2 parts go as surface runoff. Of the 11 parts that enter the ground as infiltration, 2 parts correspond to local flux (baseflow) and the remaining 9 parts go as regional groundwater flux. The deep groundwater flux seeps into ocean by traveling long distances at a very low velocity due to the low hydraulic gradient (on the order of $10^{-4}$). These conditions favor the dissolution processes of minerals, thus making low-salinity water from surface units increase its salinity as it goes down into deep units, from where it finally seeps and discharges into the continental shelf as an ascending flux (Fig. 7).

## Concluding remarks

The connection between surface quaternary and deep tertiary hydrologeological units has a most significant role in the hydrological cycle of the Salado sedimentary basin. Because of the great area of the basin, vertical flux between surface and deep aquifers is not only an efficient mechanism for transporting large volumes of water, but also one of the main processes that sustain the hydrologic regime, which is responsible for the existence of the ecosystems of the basin. This flux is downwards in the continental portion of the basin and upwards in the adjacent continental shelf.

During wet periods, when extensive floods occur, the regional flux in the deep tertiary units contributes to empty large quantities of water coming from surface infiltration. Deep groundwater seepage flows slowly towards the discharge zone in the continental shelf. The kinetic interaction between surface and deep aquifers involves water, aqueous and non-aqueous matter and heat transport processes, and is accompanied by chemical interactions. The transported water increases its ionic content and salinity along its path towards the Rio de la Plata and the Atlantic Ocean. Yet, the low permeability of the sediments in the upper layers of the continental shelf does not allow the discharge to be large enough to change the chemical features of the water within the nearshore sectors of the estuary and ocean. It can be concluded that the deep hydrogeological units contribute to restore the surface ecohydrological balance of the Salado sedimentary basin in a short period of time. This could not be possible if runoff were the only discharge mechanism. Not only is this restoration to balance conditions crucial for the conservation of the numerous and well-developed ecosystems in the basin wetlands, it is also significant for the agricultural and cattle-raising activities of the region. These activities would be strongly affected if runoff were the only way of mitigating the floods due to heavy rains.

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