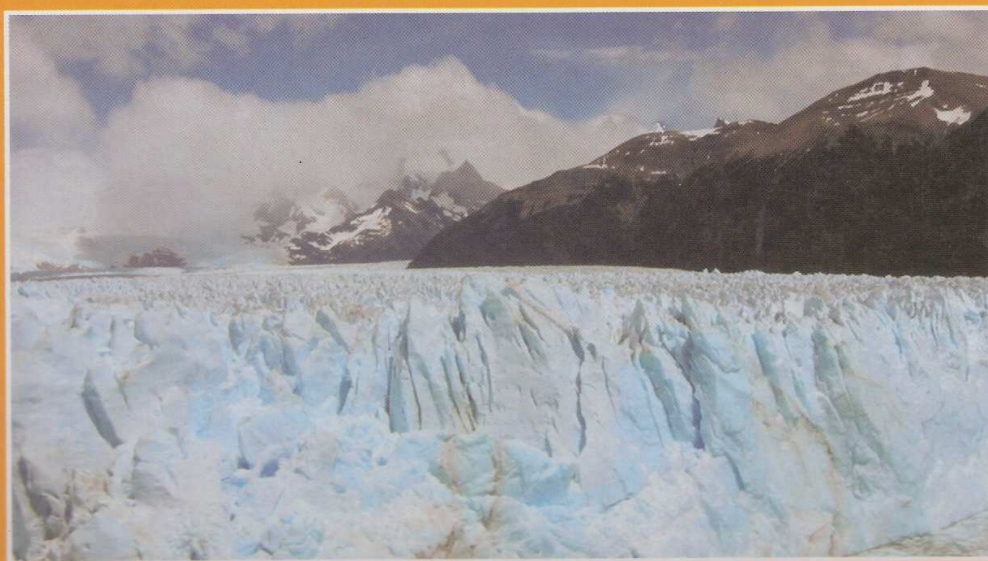


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THE LATE CENOZOIC OF PATAGONIA AND TIERRA DEL FUEGO

J. RABASSA



Late Cenozoic Geohydrology of Extra-Andean Patagonia, Argentina

Mario A. Hernández¹, Nilda González¹ and Lisandro Hernández²

¹ Cátedra de Hidrogeología, Universidad Nacional de La Plata, 1900 La Plata

² Cátedra de Fundamentos de Geología, Universidad Nacional de La Plata, 1900 La Plata

1. Introduction

Among the relevant characteristics of Argentine extra-Andean Patagonia, its arid to semiarid present climate should be mentioned. The scarcity of hydrological resources is one of the most significant consequences of these climates, particularly when compared with the Late Cenozoic paleoclimate of this region.

Contrarily to the situation along the Andean margin, where superficial and underground water is frequent, mostly related to the dominant snow régime, such lack of water resources in extra-Andean Patagonia has historically been a strong limitation to growth and development. It is a territory crossed by allochthonous streams with Andean sources, such as the Neuquén, Limay, Negro, Colorado, Chubut, Senguerr, Deseado, Santa Cruz, Coyle and Gallegos rivers. In this territory, when a location was away from these rivers, all intents of economic enterprise were forced to look for an underground water supply to make them viable.

The Native American itineraries across Patagonia were necessarily related to the distribution of springs or underground water outcrops, which would serve as milestones to travel and migration along large distances away from the streams.

Even during the historical trip of Hernando de Magallanes, the first reference of the Spanish conquest of Patagonia, underground waters were already mentioned. Around March 1520, his expedition made a stopover at Puerto San Julián, where they were able to get a good water supply from local springs. These springs would never be found again, though the site was visited by García Jofré de Loaisa in 1526, the legendary Francis Drake in 1577, Tomás Cavendish in 1591 and the Dutch explorer Narborough in 1670, among others. Most likely, these expeditions disembarked in winter or in the late fall, when these springs usually cease their flow (Hernández, 2000).

This chapter will focus on the part played by Late Cenozoic rocks and sediments of continental extra-Andean Patagonia in the geohydrological processes. They act not only as carriers of usable underground water, but mainly as participant in recharge mechanisms to other formations of older age as well as support for highly fragile ecosystems, such as the regional wetlands known as "mallines".

The geographical framework of this Argentine territory is given between the Andean Cordillera and its adjacent piedmont lands, the Río Colorado, the Atlantic

Ocean and its continental boundary with Chile, with a total area of approximately 700,000 km², roughly the size of Texas, or France and England together.

These huge dimensions are highly contrasted by the scarcity and the poor quality of the available geological information. In particular the hydrogeological data of low and irregular density and basically based on the exploitation of underground resources instead of on scientific research.

Thus, the most recent advances in its knowledge are due to the oil and gas and mining industries. The regional geology and stratigraphy studies are nowadays largely supported by the work of the Argentine Geological Survey (SEGEMAR), national universities and research centers, although in the first half of the twentieth century, the information was mostly provided by pioneer oil and coal explorers.

It is then understood that in the field of hydrogeology, the information is dispersed, with different levels of scale and resolution. This situation undoubtedly complicates the efforts of synthesis like the present one, forcing the use of case studies and spot examples as a means to approach comprehension.

2. Methodology

The *general* methodological concepts are basically deductive, making use of evidence provided by indicators to define the most accurate hypothesis. Consequently, it is a model in which the hypothesis that explains most of the evidence is the more plausible.

From a *particular* point of view, the work was oriented to identify the geohydrological conditions to ascertain the dominant regional characteristics. It comprised critical reviewing of existing information, pointing out the hydrolithological properties of the geological materials and the outcrop characteristics, in a geomorphological approach. It is herein intended to define their capacity of receiving, storing and transmitting water, as the underground circuit of the hydrological cycle.

Different physical conditions of the geohydrological system have thus been determined and, in this Late Cenozoic rocks and sediments, they play a significant role.

As stated before, the territorial dimensions in relation to information density forced to use representative case studies for the principal systems. However, the difficulty in extrapolating this information to the regional level is herewith acknowledged for most areas.

3. Limiting Geohydrological Factors

The limiting factors are, first of all, those related to the regional characteristics, which affect the availability, quantity and quality of underground water resources.

3.1. Climate

Two main characteristics are climatically highly significant: latitude, related to solar insolation and mean annual temperature, and the presence of the Andean Cordillera, with its influence on the precipitation régime. The against-trade winds coming from the Pacific Ocean ascend on reaching the Andes, while cooling

adiabatically and generating high precipitation on the western slopes, whereas the eastern side of the Andes is in the rain shadow, which generates true desert conditions. Exceptions are found in the lower portions of the ranges, mostly lacustrine basins of glacial origin. These depressions are gateways for moisture carrying winds, extending eastward the location of the 300 mm/yr isohyet, enabling the penetration of the Valdivian rain forest biotope.

While on Cordilleran summits, precipitation may reach up to 3000 mm/yr, in the extra-Andean regions it is reduced to 150 and 300 mm/yr, with a slight increase along certain areas of the Atlantic coast and in the southernmost sector through by direct oceanic influence (Fig. 1).

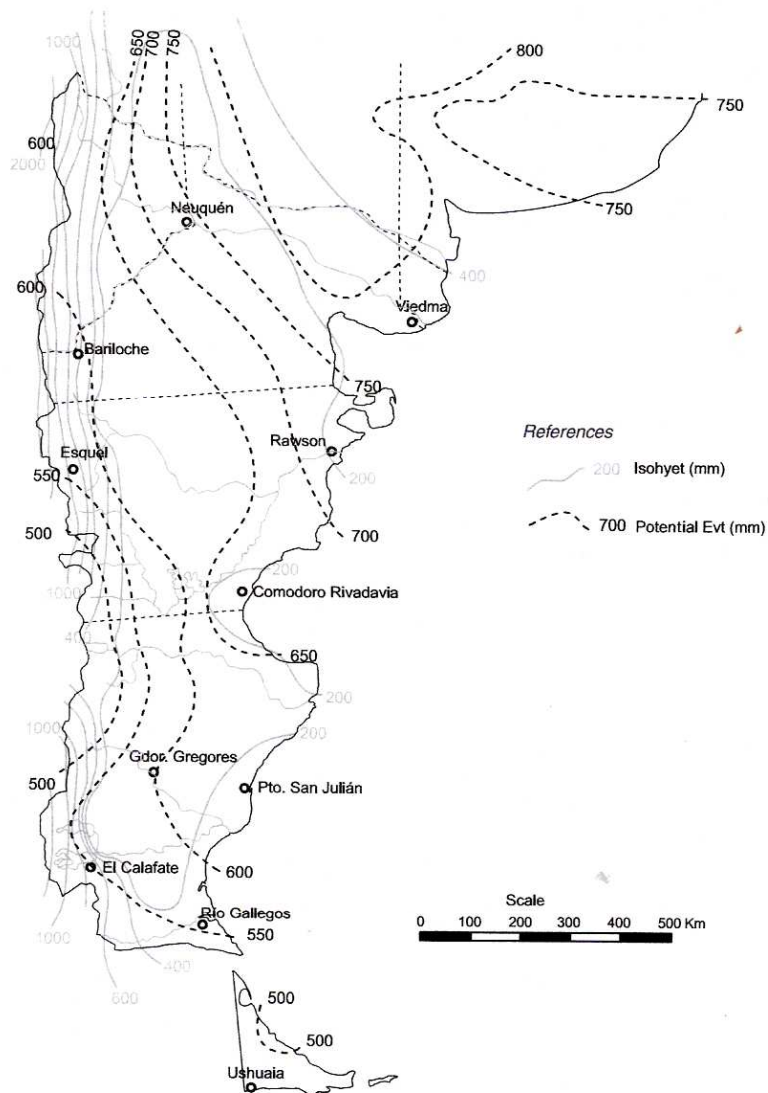


Fig. 1. Rainfall and potential evapotranspiration map.

Snowfall is very important in the eastern ranges of the Cordilleras and the adjacent piedmont area, as well as on the tablelands, due to its influence on the hydrological and geohydrological régime.

When comparing the mean annual precipitation with the average amount of mean annual potential evapotranspiration (600–900 mm/yr), a hydrological deficit of over 500–600 mm/yr becomes apparent. For this reason, in case the precipitation would be the exclusive source, aquifer recharge would be nonexistent, a condition which is not real, as there are other mechanisms which will be presented below.

The climate is cold-wet in the Andean zone, grading into temperate and cold-temperate eastward, from subhumid in the Andean slopes to arid and semiarid in most of the territory.

The mean annual temperatures range from 12–15°C in northern Patagonia to 6–11°C in the southern and western portions of the region, with frequent drops below 0°C in winter.

3.2. Vegetation

Within the Patagonian Phytogeographical Province, as defined by Soriano (in Paruelo *et al.*, 1992), four districts make up the continental environment: Sub-Andean, Central, Western and Golfo San Jorge (Paruelo *et al.*, 1992). These districts are shown in Fig. 1. The first one is characterized by a high cover, grassy steppe, extending along a narrow fringe following the Andean Cordillera between Futaleufú and Lago Buenos Aires and south of Lago Belgrano (though with interruptions), with its southern end south of Río Coyle. The Central district is the most extended in this region, represented by a low shrubby steppe or a very low cover, following the areas with lower precipitation. North of Lago Buenos Aires, the Western district follows as a very open, 50% coverage, shrubby steppe. The Golfo San Jorge district surrounds the gulf of that name, from Cabo Raso to Bahía Lángara, with dominant grasslands in the higher plains, locally known as “pampas” and shrubs on the slopes to the ocean and in the tributary canyons.

The ecological characteristic of relevant hydrogeological significance is the xerophytic nature of all plants, in which the stomas are replaced by certain specializations such as aphilia, thorns, hairs or coriaceous derma. This morphology reduces to a minimum the release of water vapor to the atmosphere, enabling infiltration, even with very low rain events.

An exception to this are the wetlands, locally known as “mallines”, with a Juncaceae, Cyperaceae and Gramineae vegetation, associated with valley bottoms and/or ponds with underground discharge and with generally clayey to silty-clayey channel sediments (Paruelo *et al.*, 1992). These are microhabitats used as stopovers for migratory birds, residence of other aquatic birds and drinking sites for the autochthonous fauna and sheep and cattle.

3.3. Hydrology

The rivers crossing extra-Andean Patagonia are of allochthonous character, with their heads in the Andean

Cordillera and snow or rain/snow régime, the first one with a main flood peak generated by spring melt and the latter characterized by winter rains.

The most important water courses are the Colorado (mean discharge of 148 m³/sec), Neuquén and Limay (forming the Río Negro, 858 m³/sec), Chubut (48 m³/sec), Senguerr (48.6 m³/sec), Deseado (transitory), Chico (transitory), Santa Cruz (790 m³/sec), Coyle (also known as Coig, 5 m³/sec) and Gallegos (34 m³/sec) rivers.

Most of these streams are permanent and all of them show a discharge deficit (with respect to the underground flow), which is very important with respect to underground water reserve recharge (Lerner *et al.*, 1990).

3.4. Geomorphology

Though there is a vast diversity of landforms and scales in such an enormous territory, from the hydrogeological (or hydrogeomorphological) point of view the *positive* ones must be noted, such as the eastern Cordilleran slopes (known as “Precordillera”), the high northern Patagonian and Deseado tablelands, the frequent hilly ranges (Sierras de Huantriacó, Auca Mahuida, Lipetrén, Piré Mahuida, Lonco Trapial, Taquetrén, Olte, Canquel, Chaira, San Bernardo, Cañada Grande, Cordón Alto, etc.), high erosion remnants, the tablelands and their terraced levels, pediments, volcanic structures and cones, dune fields and the glacial landscape.

The *negative* landforms are also important, such as stream valleys and associated features, glacial valleys, large lakes and ponds, endorheic basins (of structural, eolian or volcanic origin) and the “cañadones” or “uadis”, ephemeral valleys, usually dissecting alluvial plains.

The role of these landforms in the terrestrial phases of the hydrological cycle will be described later, when discussing the geohydrological phenomena and the system configuration.

3.5. Soils

Aridisols are dominant, particularly in the two eastern thirds of the region, with the presence of Entisols in many of the fluvial valleys and “cañadones”. Inceptisols and Mollisols are present in the western transitional areas and Alfisols in the northern sector of Neuquén and Río Negro provinces.

They are mostly high permeability soils with low specific retention, a circumstance that should be taken into account when analyzing the recharge process.

3.6. Geology

The geological aspects, such as lithology, stratigraphy, structure and geomorphology, are considered elsewhere in this volume. It is preferred to use a mainly hydrogeological approach to differentiate the two main media in which underground water circulates (porous and fissured) and their relationship with the material capacity to receive, store and transmit water (hydrolithology).

The porous media (primary porosity) is mostly represented by Late Tertiary and Quaternary deposits, among them the widely distributed marine deposits in the eastern sector, terraced aggradational levels, glacial and periglacial deposits, present and past alluvial accumulations (paleochannels), and colluvial, lacustrine, fluvio-lacustrine and eolian sediments.

Interconnected joint systems, columnar jointing and hollows in lava flows, open bedding planes in tuffs, schistosity planes and faults are the features characterizing the fissured media (secondary porosity) of this region, with a reduced share of spaces generated by solution (karst and pseudo-karst).

With respect to their hydrolithological specifically relative permeability characteristics, the following types are identified:

- (a) aquifer – materials that easily receive, store and transmit water;
- (b) aquiclude – those that receive and store water, but do not transmit it;
- (c) aquitard – those that receive and store water but transmit it with difficulty and only under certain conditions; and
- (d) aquifuge – those that do not receive, store or transmit water.

The fissured media is essentially aquifer, differentiating rocks according to their higher or lower permeability.

In this context, the Late Cenozoic deposits, although they are of wide extent in extra-Andean Patagonia (up to 600,000 km²; Lapido and Pereyra, 1999), they lack a significant thickness, thus making their role in the geohydrological cycle mostly that of a water transmitting element rather than that of an aquifer.

4. Porous Media

For the identification of those hydrogeological units acting like an aquifer, the geological units that fulfill this role have been grouped, independently of their stratigraphic assignment or nomenclature.

The hydrogeological concepts of Struckmeier and Margat (1995) are used in this chapter, which means that the identification of hydrogeological units is mainly based on hydrolithological criteria.

Under this denomination, units of varied genesis or different stratigraphy and age are often included or, inversely, different geohydrological characteristics are attributed to segments of the same formation.

Under these premises, units of porous media (primary or intergranular) are briefly identified as active parts of the geohydrological systems described below.

4.1. Late Cenozoic Gravel Deposits

The gravel and coarse sand deposits included in the "Patagonian gravels" are herein taken as a single unit, in spite of the recommendations of Panza (2002), who used geological and geomorphological concepts. This unit includes the terraced deposits of the tablelands, the

more recent fluvial terraces as well as the piedmont aggradation levels (Fidalgo and Riggi, 1970; Lapido and Pereyra, 1999). These deposits are very frequent in the western sector of the region.

Although with some variations, all of these units possess very important hydrodynamic features and offer moderate to high permeability, a mostly subhorizontal position and high continuity in the field.

Apart from the mentioned differences, including those related to grain size, sorting and mineralogical composition, the consolidation and cementation degree is highly significant (sometimes lowering rock permeability by one order of magnitude), as is the anisotropy of the deposit with respect to water transference.

These units are very common in extra-Andean Patagonia (Fidalgo and Riggi, 1970) and their participation in the geohydrological system is very important. In most cases, they are direct receptors of atmospheric recharge, are overlain by soils with very low specific retention or, eventually, they are not overlain by soil at all. These facts make them act as deep recharge generators toward underlying porous or fissured layers and providing springs or superficial sources along their basal stratigraphic contact with formations of lower permeability.

4.2. Glacigenic Deposits

These units are recognized along the western and southwestern margin of the region, and essentially composed of till, proglacial and glaciofluvial sediments of the Andean Cordillera and the piedmont areas, from Neuquén and Río Negro (González Díaz and Malagnino, 1984) to the southernmost end of Santa Cruz and Tierra del Fuego (Rabassa and Clapperton, 1990; Pereyra *et al.*, 2002; Rabassa and Coronato, 2002;).

These sediments are basically aquifers, with a very important lateral relationship with glaciers and streams of glacial origin which, due to their nature, provide huge volumes of water to the neighboring aquifer bodies. That is the case of the Santa Cruz, Coyle (Coig) and Gallegos rivers. The glacigenic deposits are also usually water-transmitting units to the aquifers nearby, both in porous and in fissured media.

4.3. Aeolian Deposits

These units are widely distributed in the region with many morphological types such as sand blankets, barchans, longitudinal dunes, coastal dunes, cover sand bodies on fluvial terraces and so on. Their occurrence has been favored by the arid climatic conditions dominating during most of the Quaternary and the availability of mobile material of fluvial, pyroclastic and glaciofluvial origin (Lapido and Pereyra, 1999). They are very little known from a geological point of view, particularly due to their physical instability. They have strong permeability due to the high degree of sand sorting, even though silt and clay dunes ("lunettes") or volcanic ash dunes may also be present. They do not have a large thickness, with perhaps the exception of a few sites, such as Ricardo

Rojas at Península Valdés. Their recharge is analyzed as a mechanism of fast infiltration in Section 6.2.

4.4. Modern Alluvial Sediments

These deposits are located in the present alluvial plains of the streams of the region, even in those of an ephemeral or transitory nature. They have a very high hydrogeological significance since they host enormous amounts of subbed water. These deposits show a large variety of grainsize types, from boulders and coarse gravels to silts and clays, but predominantly medium to fine gravels and sands. The hydrolithological behavior is naturally aquifer, generally overlying sediments of the same kind or aquiclude, aquitard or aquifuge, in the latter case referring to rocks without secondary porosity. Their development is highly variable both spatially, several kilometers wide in the lower Colorado, lower Chubut and middle Deseado rivers, down to a few meters width and thickness in narrow valley canyons. The exploitation of the subbed river aquifer is of great importance in the northern areas (valleys of the Negro and Colorado rivers) both for drinking water for rural population, as it is in the Chubut and Santa Cruz rivers for secondary recovery in oil production (Senguerr and Deseado rivers).

4.5. Mass-Movement Deposits, Colluvial Sediments and Slumping at the Edge of Volcanic Plateaus

These sediments and rocks are of an obvious varied origin. However, they are included in this section due to their similar hydrogeological characteristics: lack of sorting, large clast size, high permeability, reduced thickness and geomorphological position. They are located at the edge of structural plains, mountain ranges and the eastern Cordilleran slopes, allowing a fast concentration recharge mechanism (see Section 6.2).

4.6. Coastal Marine Deposits

These deposits are of very little regional significance, restricted to a 10 km fringe parallel to the present coastline (Lapido and Pereyra, 1999). These units are sandy string-like alignments, gravel accumulations, terraced ridges and shelly accumulations, whose larger influence on local hydrogeology is to form real lower salinity water lenses, bounded by fresh/salty water interphase toward both the sea and the arid continent. The latter salty waters are the product of the hydrochemical evolution in the zone of regional discharge. They form high permeability aquifers and their recharge is produced by the fast infiltration mechanism described in Section 6.2.

5. Fissured Media

This condition is achieved mostly by joints affecting different rock types of aquifer significance such as the extensive Jurassic volcanic and pyroclastic (ignimbrites and tuffs) rocks, open bedding planes (tuffs), columnar

joints in basalts of varied age and, to a lesser degree, solution cracks and channels in calcareous and gypsum rocks (Hernández and González, 2003).

The fissured Pre-Cenozoic rocks are also indirectly important in this aspect, because they form the basement of several geohydrological systems. The Cenozoic basalts are directly related because of their part in the recharge processes through their cracks and joints. These basalts are occupying, according to Lapido and Pereyra (1999), more than 120,000 km² along extra-Andean Patagonia, with larger surfaces in Neuquén and Santa Cruz provinces. Alkaline, olivine basalts, basandesites and leucocitic basalts are dominant. The most relevant hydrogeological unit is the La Angelita Basalt and its corresponding units, Laguna del Guadal, Cerro Piedra and Laguna Barrosa basalts, all of them located in Santa Cruz (Panza and Franchi, 2002). They are important both for the extension of their flows as well as for their subhorizontal position and the high density of columnar jointing, with up to 5 cm separation at Pampa de Cerro Rubio. The cracks and joints are, as discussed below, a basic element in the process of water transference toward the underlying, porous media aquifer beds (gravel units, Patagonia Formation sedimentary rocks) or fissured media (Bahía Laura Group, Jurassic) participating in the fast infiltration and delayed recharge processes.

Less frequent and important is the secondary porosity due to hollows in the lava flows, particularly because they are not always interconnected by water-bearing channels. The importance of these jointed lava flows is highlighted since they contribute to the definition of three of the models presented in Section 6.1.

6. The Geohydrological Systems

The distribution of the geohydrological systems in Patagonia presents a wide variety of elements and different acting mechanisms in the hydrodynamic cycle of Recharge-Circulation-Discharge. For this reason, case studies must be used. Nevertheless, it seems appropriate to start with a general characterization based upon the conditions sketched in previous sections, together with the relationship between units, to present a physical scheme which may explain the geohydrological phenomena.

The Non-Saturated Zone (NSZ) in a strict sense (its definition is usually offered for porous media) has a varied development, from more than 70 m in the tablelands between the Colorado and Neuquén rivers, lacking a capillary zone, down to a few meters nearby the waterloosing streams and the southern Santa Cruz lower coastal plains, and even zero thickness in the wetlands or "mallines".

Logically, the thinner the NSZ is, the more favored the aquifer recharge processes are, but there are lesser opportunities for natural mitigation of pollution. From a physical point of view, practically all materials mentioned in Section 4 are part of the NSZ. A remarkable condition is the frozen state of the upper portion of the NSZ during winter in many areas of the southern and southwestern parts of the region, particularly because of the delayed recharge processes.

In many sites, the porous media NSZ underlies a fissured media cover, particularly in the case of the more recent basalt flows (La Angelita, Lipetrén, Trayén Niyu and other basaltic units) affected by columnar jointing or high cavity density. It must be explained that the NSZ thus described does not extend to the topographic surface itself, but starts instead at the base of the flow.

Concerning the Saturated Zone (SZ) in geohydrological schemes, the phreatic term of the systems is the most relevant for this study, since it is better connected, directly or indirectly, to the Pleistocene rocks and sediments. The semiconfined units, and even more so the confined ones, are generally lying in Pre-Quaternary terrains.

The physical configuration of different models of systems identified in extra-Andean Patagonia is presented below, with representative case studies exposed in Section 7. Naturally, the occurrence of Late Cenozoic rocks or sedimentary deposits is closely related to the uppermost part of the schemes.

6.1. Geohydrological System Models

Different geohydrological models are herein proposed to understand the nature and distribution of groundwater resources.

A₁ Model: fissured rocks (columnar jointed basalts) overlying aquifuge or fissured rocks. The aquifer unit is included in the gravel beds (sometimes only transitorily) and in bedrock fissures.

A₂ Model: fissured rocks (columnar jointed basalts) directly overlying aquifuge or fissured rocks. In this case, the aquifer unit is the underlying fissured rock.

A₃ Model: fissured rocks (columnar jointed basalts) overlying thick clastic beds. The aquifer is in the porous media.

B₁ Model: gravel layers overlying fissured rocks. The aquifer bed may be located in the gravels and/or in the rocks with secondary porosity.

B₂ Model: gravel layers overlying aquifuge rocks. The aquifer is obviously located in the gravel beds, generally with transitory régime (seasonal in the Cordilleran areas).

B₃ Model: gravel layers overlying clastic deposits of medium to large thickness. The aquifer condition is generally located in both units, except where the gravelly cover is very thin or when the local climate imposes a deep phreatic surface.

C₁ Model: alluvial sediments in permanent, active stream valleys, with well-developed flood plains, overlying fissured or aquifuge bedrock. In these cases, the phreatic aquifer is located in the fluvial sediments, due to permanent nourishment from the feeding streams and depending upon the bedrock behavior, even in their fissures.

C₂ Model: alluvial sediments in permanent, active stream valleys, with well-developed flood plains, overlying clastic sediments. In these cases, a hydraulic continuum is observed in the phreatic layer, including both types of materials.

D₁ Model: alluvial sediments in inactive streams, overlying aquifuge or fissured rocks. These are aquifers located in the alluvial beds, of a transitory character, and in fissured rocks with a very deep phreatic surface.

D₂ Model: alluvial sediments in inactive streams, overlying porous deposits. The aquifer beds are generally contained in the underlying sediments, and in the alluvial deposits with a climate-regulated, transitory régime.

E₁ Model: very thick, glaciogenic deposits. The phreatic aquifer is of a non permanent, perennial régime, and basically regional flow, generating deep recharge.

E₂ Model: glaciogenic sediments overlying aquifuge of fissured rocks. The glaciogenic deposits permanently contain the phreatic aquifer and are transmitting the recharge into the fissured media.

F₁ Model: eolian formations (dunes or sand blankets) overlying gravel beds which are lying on sandy or pelitic clastic materials, or fissured rocks. These elements may or may not integrate a hydraulic continuum. It is possible that the dune formation would be only NSZ or become a transitory régime.

F₂ Model: eolian formations (dunes) overlying sandy or pelitic, porous materials. The main aquifer is generally in the dune formation.

G Model: heterogeneous colluvial deposits, frothy lava tablelands ("escoriales"), tillites or proximal apex of debris cones, overlying aquifuge or fissured rocks. According to their stratigraphic position, they may be only water transference or aquifer container elements.

H Model: sandy, gravelly or shelly ridges of the present coast, transmitting and containing lens-like aquifers of water relatively less saline than the surroundings.

This systematic classification, based upon local information and trying to achieve a regional overview, is based on physical systems. But, because of the restricted hydrological analysis, their behavior within the geohydrological circuit may be largely significant whenever the role of Late Cenozoic materials is highly relevant.

6.2. Hydrodynamics

As it has been stated above, the role of the Late Cenozoic rocks and sedimentary deposits is perhaps more valuable because of their participation in the Recharge-Circulation-Discharge cycle than for being aquifers of strategic or utility interest.

Within this cycle, the more relevant episodes are those related to the recharge and the discharge, since circulation is frequently limited by the reduced extent of the deposits and their peculiar hydrogeological characteristic.

Concerning the recharge, it should be noted that whatever has been the methodology for establishing the hydrological budget, it clearly emerges that there would be no possibility of water surplus charging into the underground, because the results are clearly showing a permanent deficit.

It has already been explained that the order of magnitude of the hydrological deficit is of 500–600 mm/yr (see Section 3.1). But the presence of underground

water reserves is confirmed, both in terms of quality and quantity, sometimes to unexpected levels.

There are particular mechanisms (Hernández *et al.*, 2002, 2004) that may explain this apparent contradiction between climate and recharge, a synthesis of which is presented below, following a plausibility analysis, as explained above in the methodological presentation.

- (a) *Fast infiltration.* This process takes place thanks to the relatively high permeability (sandy, gravelly sediments and jointed lavas) and the low specific retention capacity of the local soils. The largest portion of the net rainfall becomes gravity water, with up to 33.7% of infiltration of 172 mm/yr net rainfall for northern-central Santa Cruz and 58% of only >5 mm effective rain according to Hernández *et al.* (2002). It was also possible to establish the lack of or poor development of a capillary fringe, mainly because of supercapillary porosity. Recharge in dune formations belongs to this type.
- (b) Presence of *highly specialized vegetation* lacking stomas. These are succulent plants with different adaptations, such as thorns and hairs, with coriaceous derma or ephemeral types (Paruelo *et al.*, 1992). Among the most frequent species, *Azorella trifurcata*, *Azorella nucamentacea* ("piedra leña" or "llareta"), *Trevia patagonica* ("malaspina"), *Chillitrichum diffusum* ("mata negra"), *Berberis buxifolia* ("calafate"), *Accantholippia* sp. ("tomillo"), *Chusquea* sp. ("uña de gato"), *Nassauvia ulicina* ("colapiche"), *Poa linguaris* ("coirón") and *Stipa humilis* ("coirón") may be cited. Only the vegetation established in the wetlands ("mallines"), such as *Poa pratensis* ("pasto mallín"), *Trifolium repens* ("trébol blanco"), *Taraxacum officinale* ("achicoria"), among other species, does not need these specializations. The specialized vegetation together with fast infiltration eliminates or minimizes consumptive losses.
- (c) *Delayed recharge.* This is due to snow accumulation, frost or water freezing in the soil, particularly in the tablelands and sub-Andean regions, which melt during spring or on very sunny days. The resulting volumes of water are important, because the supply is almost instantaneous.
- (d) *Fast concentration:* Where sediments are exposed close to the mountain ranges in the Andean piedmont or in erosive landscape along the edge of the "pampas", superficial runoff is rapidly incorporated in the subsoil when flowing in a concentrated way over a steeper relief of a mostly aquifuge character.
- (e) *Supply by stream loss:* Rivers, creeks and even irrigation canals in extra-Andean Patagonia (valleys of the Colorado, Negro and Chubut rivers; CORFO irrigation systems, Río Colorado) show this behavior, providing important discharge to the river bed within the alluvial plain, and also toward the fluvial terraces. For example, the subbed flow of the Senguerr and Deseado streams are under strong groundwater exploitation for secondary oil recovery operations.

It is necessary to note that the aforementioned mechanisms are generally convergent, as it happens in wide sectors of the region, such as the central zone of Chubut and Santa Cruz provinces.

Because it corresponds to recent recharge, it should be mentioned that apart from quantity, these are low salinity waters, frequently less than 2 g/l, thus differentiating them from the surrounding water resources, where underground waters are salty or saline.

The *discharge* of these systems takes place toward the ocean, or inland in endorheic depressions, generally occupied by salt lakes and lacustrine fine sediments.

The underground supply, particularly in salt and dry lakes whose bed is below sea level, frequently merges with superficial runoff during high precipitation events to maintain the brines in salt lakes and other depressions. The high evaporation rate makes that, to a large extent, these bodies have a transitory régime.

A very frequent, particular way of underground discharge is by means of springs, very important to the regional economy, both for cattle and sometimes even for domestic use or as supply for the wetlands ("mallines") and grasslands fed on by cattle, sheep or the local fauna.

Although they occur in Tertiary formations, the springs that supplied the city of Comodoro Rivadavia (named as Manantiales Bher and Manantial Rosales) or those that still do so in Puerto Deseado and Puerto San Julián should be noted.

Most of the Patagonian "mallines" receives their supply from springs, thanks to which they maintain their ecological role hosting an important local and migratory bird fauna.

Springs of varied genesis are recognized (Hernández, 2000; Hernández *et al.*, 2004): (a) structural, (b) located at thalwegs, (c) of stratigraphic nature (the most frequent ones), (d) placed in fissures or in lava flows and finally (e) a few of karstic origin (northwestern Neuquén and central Santa Cruz provinces).

According to their régime, they are in general either of transitory or perennial, subvariable or variable nature. It is common that many springs which nourish the wetlands ("mallines") or small lakes are not observed directly because they are sub-aqueous, thus being identified only during extreme drought conditions.

The *circulation* of underground water, as the time between recharge and discharge processes, is constrained by the extent of the aquifers. In these particular cases, as it has been noted before, circulation corresponds to relatively short distances due to interfering local discharge (springs, discharge in wetlands, endorheic basins and micro-basins), thus implying a predominant active or local flow over passive or regional conditions.

The more extensive circulation cases are related instead to older aquifers, because the Late Cenozoic ones are of a smaller, thinner or shorter type.

7. Case Studies

Though it should be noted that it is inconvenient to assume regional behavior in such an extensive territory while lacking appropriate hydrogeological information, a series

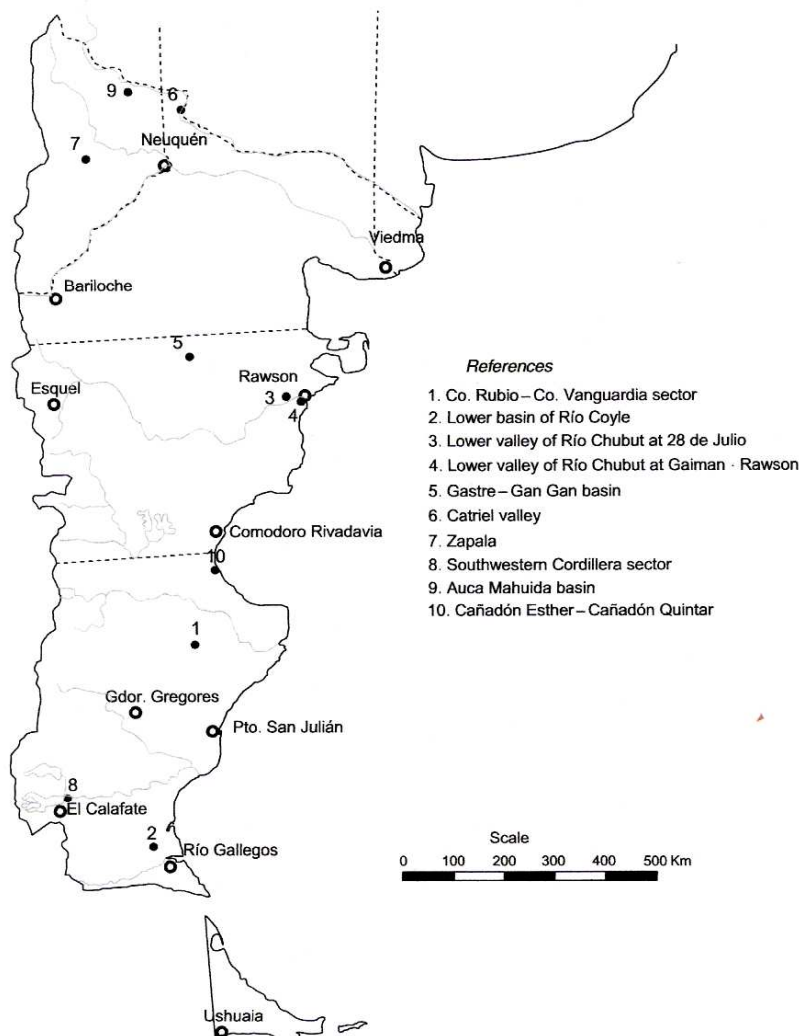


Fig. 2. Location of study cases.

of case studies is presented below, with the aim of demonstrating representative examples in a relatively wide area.

The location of the basins or sites cited in this section is presented in Fig. 2 and the graphic expression of system configuration in Fig. 3a, b and c.

7.1. Cerro Rubio–Cerro Vanguardia Sector (Santa Cruz Province)

This basin, located in the central part of Santa Cruz Province, is very significant (Fig. 2) because many of the models presented in Section 6.1 (A_1 , A_2 , A_3 , B_1 , B_3) and most of the recharge mechanisms are found here (Hernández, 2000; Hernández *et al.*, 2002, 2004; Hernández and González, 2003).

Starting with the La Angelita Basalt flows, which are highly jointed and of subhorizontal position, they encompass models A_1 to A_3 . When these flows directly overlie the gravel cover (La Avenida Formation or Pampa de la Compañía Formation), they act as quasi-instantaneous transmitters of the reduced rainfall supply to the gravels. Together they form an aquifer of medium thickness (3–7 m), which discharges through stratigraphic springs in the local channels and canyons.

If the gravelly cover overlies fissured rocks, such as the Bahía Laura Group (Jurassic ignimbrites and tuffs), it partly discharges into this aquifer, which is of regional significance. If it does instead overlie aquifuge rocks (such as the Bajo Pobre Basalt), it discharges directly in canyons or wetlands. In both cases, it corresponds to the

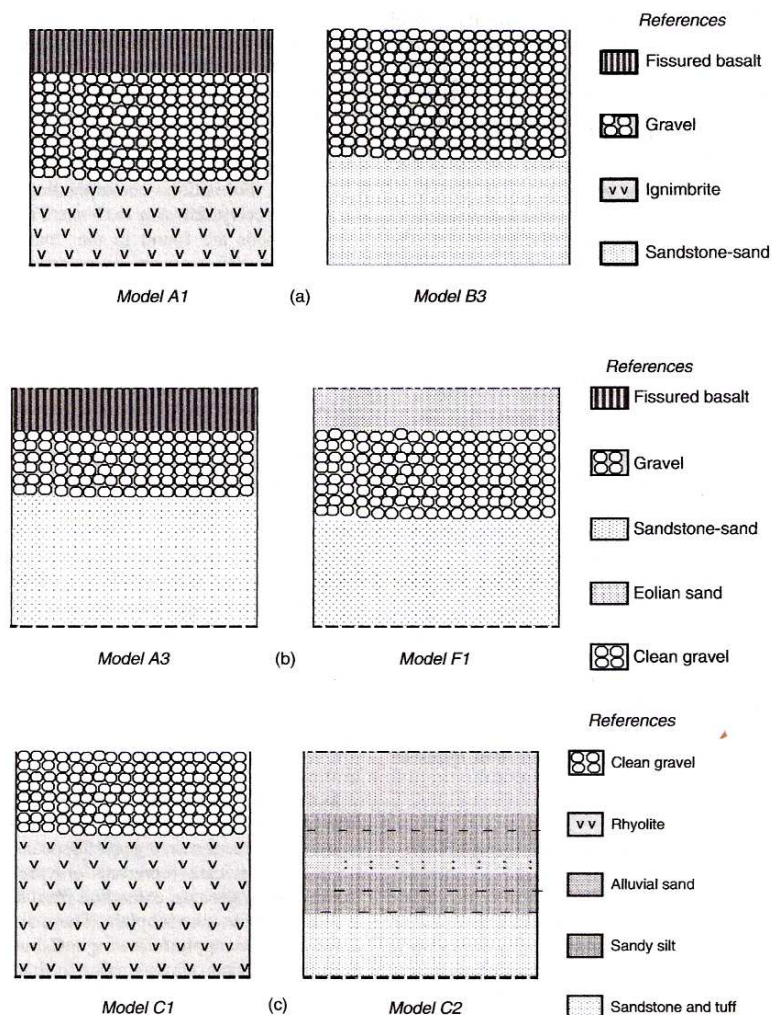


Fig. 3. Case studies (a) Cerro Rubio–Cerro Vanguardia sector. (b) Auca Mahuida basin. (c) Lower valley of Río Chubut.

A₁ model. The mechanism of fast infiltration is dominant, though delayed discharge occurs as well.

It may happen as well that the basalt covers the fissured Jurassic rocks directly, thus being responsible for their recharge (A₂ model), or if it overlies the marine sedimentary rocks of the Patagonian Formation in the eastern sector of this region, it has the identical function of recharging into the porous media (A₃ model).

In those cases where the lavas are absent, the B₁ and B₃ models may be observed. The first one corresponds to a moderate thickness (3 a 5 m) of the "Patagonian gravels" ("Rodados Patagónicos") on ignimbrites of the Chon Aike Formation (Jurassic), which has secondary porosity due to jointing, whereas the B₃ model occurs on sedimentary deposits of the Patagonia Formation, which is a low yield and saline water aquifer.

The aquifer contained in the gravels is thin and contains little but relatively good quality water.

In these systems we find several of the recharge mechanisms described in Section 6.2, such as fast infiltration, reduction of consumption losses by specialized vegetation and delayed recharge.

7.2. Lower Basin of the Río Coyle (Santa Cruz Province)

This case study is focused in the zone of Las Horquetas, close to the merging of the southern branch with the main Río Coyle, in southern Santa Cruz Province (Fig. 2).

It corresponds to Late Pleistocene sand and gravel deposits covering the youngest terrace of the Río Coyle valley (Fasano *et al.*, 2003), with a 6–7 m thickness, overlying a 26 m thick layer of green clays, and an even greater underlying thickness of silts, sandy silts and very fine sands of undifferentiated Tertiary age.

This would correspond to a B₃ model, but the clayey bed has an aquitard behavior and separates a transitory phreatic aquifer (mostly dry at the end of the summer) from another semiconfined one, both discharging into the alluvial plain of the Río Coyle. This stream also drains into this landform as a looser stream, thus corresponding to a C₂ model.

7.3. Lower Valley of the Río Chubut at 28 de Julio (Chubut Province)

This example is located in the uppermost part of the lower valley of the Río Chubut, between the sites of 28 de Julio and La Angostura.

The C₁ model is recognized here since medium gravel, alluvial deposits are overlying Jurassic volcanic rocks of the Lonco Trapial Formation. The clastic cover is bearing low salinity phreatic water, supplied by the influent stream, thus making this the dominant recharge mechanism. Discharge is consumptive due to agricultural activities (fruit crops and implanted grasslands) while underground loss downstream into the valley (Hernández *et al.*, 1983) occurs as well.

It is still unknown if the substratum is truly aquifuge or if it has secondary porosity.

7.4. Lower Valley of Río Chubut at Gaiman – Rawson (Chubut Province)

Downstream from the previous locality, the gravels of the alluvial plain are replaced by sandy to silty-sandy sediments, with a shallow phreatic aquifer supplied by the influent Río Chubut, with Tertiary sediments at the base (Patagonia Formation and Sarmiento Group). The latter also forms the higher terrace of the valley and their redeposited materials, locally known as “terrazza intermedia”. Below the phreatic level, there is a semiconfined aquifer which it recharges, the finer facies of the Patagonia Formation or the tuffs of the Sarmiento Group acting as aquitard.

It is a case of local recharge by direct input from the river, which was subjected to seasonal bank storage release before the regulation of the system by an upstream dam (Florentino Ameghino Dam) eliminated its effects. The Río Chubut presents a “yazoo” type morphology within the valley (Hernández *et al.*, 1983).

The physical configuration of the geohydrological systems clearly belongs to the C₂ model.

7.5. Gastre–Gan Gan Basin (Chubut Province)

This basin is localized in the Arroyo Sacanana valley, its tributary creeks and the neighboring tablelands, where

several models apply, which although having a reduced extent, they all merge to the supply of a large number of “mallines” on both sides of the Provincial Route N° 4. The zone is bounded by the Piré Mahuida and Talagapa ranges to the north and the Rosada ranges to the south.

These are gravel and sandy gravel deposits overlying aquifuge rocks, like the Permo-Triassic granites of the Lipetrén Formation, corresponding to the B₂ model, which is very thin (up to 3 m). Thinner, poorly sorted gravel beds are found in the “pampas” bounding the Sacanana valley, over pyroclastic rocks and jointed basalts of the Jurassic Cañadón Asfalto Formation, with a B₁ model, and terraced gravel beds that cover or are interbedded with modern, undifferentiated basalts on the lower “pampas” of Gastre and Gan Gan.

These sediments do not have any aquifer value, but they are essential for the rapid collection of rainfall that flow along the bedrock contact or through its secondary pores. They merge with small alluvial and colluvial fans (G model) to form the supply that feeds the wetlands and salt lakes of Pampa de Gastre, like the Grande, del Molle and del Pito saline depressions.

Though superficially restricted, eolian accumulation over granular materials (F₁ model) and supply from ephemeral creeks to a poorly developed subbed river, sometimes releasing water into fissured bedrock (D₁ model), is found as well.

7.6. Catriel Valley (Río Negro and La Pampa Provinces)

In this area (Fig. 2), two typical schemes can be found: the phreatic aquifer of the Río Colorado valley and water storage in the terraced gravel deposits.

The first case represents a typical condition of the Patagonian streams, extending from the river to the edge of the present alluvial plain. These are sands and gravels fed by river supply following a C₂ model.

The second one is similar to that presented in other examples: gravel beds that may be grouped as “Patagonian gravels” (Fidalgo and Rabassa, 1984), overlying the fluvial terraces and the clayey sediments of the Malargüe Group (Allen Formation), which act as aquiclude to the underlying confined aquifer (Neuquén Group).

These gravel deposits have a thickness of up to 10–12 m and the included phreatic aquifer has a mean saturated thickness of 5–6 m, with a flow direction toward the alluvial plain. The dominant recharge mechanisms (direct autochthonous) are those of fast infiltration and reduction of consumption loss due to xerophytic vegetation.

7.7. Zapala (Neuquén Province)

Carrica *et al.* (1997) described the hydrogeology of this zone, where an F₁ model can be found, with a sequence starting with thin eolian deposits overlying an up to 1 m thick gravels and jointed, vesicular basalts (Zapala Basalt, Pliocene), a set that covers the main aquifer under exploitation, the sediments of the La Bardita Formation of Late Miocene age.

The most important characteristics are that the eolian and gravel deposits and the lava flows are under unsaturated conditions, have high primary and secondary porosity and their role in the transmitting system is bringing the water to the first aquifer contained in the La Bardita Formation (gravels, coarse and fine sands and silts).

As presented by these authors, the main recharge mechanism is fast infiltration supported by xerophytic vegetation that minimizes the evapotranspiration effects.

7.8. Southwestern Cordilleran Sector (Santa Cruz Province)

The hydrogeology of this area is poorly known, mostly because surface waters are easily available. Some of our current knowledge derives from hydroelectricity projects (Turazzini, 2002) and oil and gas activities, though the latter are frequently subject to confidentiality agreements.

Glacial and glaciofluvial deposits of the upper basins of the Santa Cruz, Coyle and Gallegos rivers are part of the hydrological systems (E_1 and E_2 models), in which a phreatic aquifer is contained in glaciogenic deposits of high permeability, with permanent recharge thanks to meltwater and supply by stream loss.

Downstream, deeper, semiconfined (recharged by vertical infiltration) and confined (with allochthonous recharge coming from the upper portions of the basins) aquifers may be located.

These deposits may be filling the valleys or are found in higher topographic positions, on the terraces or their slopes (La Leona). In the first case, it corresponds to heterogeneous anisotropic systems with recharge by fluvial influence and lateral supply from the Andean ranges and piedmont areas. In the second one, the anisotropy is more strongly indicated by the convergence of mass-movement deposits, lacustrine clays, marine sediments, ancient alluvial beds and volcanic material (volcanic and pyroclastic rocks), where the phreatic surface has typical convex profiles of variable gradient.

7.9. Auca Mahuida Basin (Neuquén Province)

This area has a variety of the identified systems for the extra-Andean territory: the A_3 model applies to fissured Pleistocene basalts, covering gravel deposits (González Díaz, 1978), which overlie Tertiary clastic sedimentary rocks; the A_2 model corresponds to fissured volcanic rocks that overlie other units of similar characteristics; the F_1 model is valid for sandy accumulations overlying basaltic flows with secondary porosity or overlying clastic deposits.

There are also endorheic depressions and salt lakes that represent the active portion of shallower underground flow.

But the most important hydrogeological role of these systems in this basin is their participation in the recharge of an important aquifer contained in the Neuquén Group (Cretaceous) which, radiating from a virtual epicenter located in the Auca Mahuida volcano zone, achieves

confining conditions toward the east and southeast, due to the aquiclude characteristics of the Malargüe Group (Late Cretaceous–Paleocene), continental and marine sedimentary rocks that overlie it.

This aquifer is perhaps the most important in the extra-Andean region of Neuquén Province, both for its high yield and for the low salinity of its waters. It is widely used for water supply to secondary recovery operations of oil and gas.

7.10. Cañadón Esther–Cañadón Quintar (Santa Cruz Province)

This area, next to the city of Caleta Olivia, is taken as the prototype for a hydrogeological phenomenon in many of the ephemeral streams of the eastern portion of extra-Andean Patagonia, with their sources in the tablelands and discharging into the ocean (Hidroar, 2003).

Included in the D_2 model, they offer the singular characteristic of receiving the discharge of the springs originated along the contact between the terraced gravel mantle ("Rodados Patagónicos") that cover the tablelands and the shelly, calcareous beds included in the Patagonia Formation (Tertiary). These stratigraphic springs outcrop along the dry valley slopes and their discharge (together with the episodic activation of superficial flow) provides the recharge of the underlying multi-aquifer set (Griznik and Fronza, 1996).

Occasionally, the F_1 model is present when dune or sandy bodies occur on the tablelands.

8. Human Impact

Until the second half of the twentieth century, the main human intervention in the natural, regional ecosystems was by sheep farming, with significant soil damage due to overgrazing and with sediment mobilization enabling deflation.

Since 1940 and because of the oil production development in the Golfo San Jorge and Neuquén basins, a significant impact on the underground water resources started to be noticeable, due to the usual practice of releasing saline water with salt concentrations higher than 90 g/l onto the fields.

In later decades, the development of the Austral basin, the northward expansion in the Neuquén basin, as well as in the Río Colorado and Golfo San Jorge basins, this impact became more noted and increasingly worrying, including the hydrocarbon pollution of the underground stores. Only as recently as 1992, environmental protection laws concerning the oil and gas activities were passed at the national level.

The exploration phase operations, particularly those related to geophysical studies, have introduced significant changes in the landscape, with frequent alterations of the superficial flow during the flood season, which although not usually beyond the alluvial plains of the presently active channels may reach an abundant size during exceptional meteorological events.

More recently, and favored by an increase in the international price of precious minerals (mostly gold), an important mining activity has developed in the region, which may potentially introduce significant changes in shallow aquifer water quality due to pollution and a strong water demand.

Nonmetallic and metallic mineral mining in open pits may generate, if the environmental aspects are not efficiently protected, important negative effects if part of the NSZ is eliminated. This zone acts as a natural buffer against pollution, because oxidation, precipitation and co-precipitation, complex formation and aerobic degradation processes take place in it. In many cases, the sand and gravel resources under exploitation are included in formations with aquifers of good quality or local recharge.

In addition to the qualitative effects, there is a quantitative damage to the already scarce underground water resources, for the competition and subsequent conflict between several water uses (domestic, rural, urban, cattle and sheep raising, agricultural, mining, industrial, etc.) and the true impact on the wetland ("mallines") sustainability, as supply is diminishing as a consequence of intensive (for this specific region) aquifer exploitation. Further discussion about environmental damage generated by wetland destruction on the local and regional ecosystems seems to be obvious.

Though they are reduced in comparison with the physical size of the region, the fast expansion of urban areas, generally unplanned, should be mentioned, as it is the case of the cities of Neuquén, Viedma, General Roca, Comodoro Rivadavia, Trelew, Esquel, Caleta Olivia or Río Gallegos, as well as the inadequate agricultural land treatment in the upper and lower valley of the Río Negro and the lower valley of the Río Chubut, or sheep overgrazing at the Río Genoa valley.

The climatically imposed fragility of these territories results in a very significant environmental impact, as for example, the very slow, natural recovery of vegetation affected by mining or oil activities or the slowing down of the natural mitigation processes in oil-polluted soils and aquifers.

9. Conclusions

It is clear that the present-day characteristics of the region with respect to hydrogeological resources are important limiting factors to its growth, development and life and environmental quality.

Even though the hydrological budgets may numerically demonstrate the impossibility of natural infiltration processes, several mechanisms that explain the presence of high quality, underground water resources have been recognized.

The role played by Late Cenozoic rocks and sediments in these processes is fundamental and, actually, it is much larger than the importance as aquifers themselves.

The recharge mechanisms defined here are fast infiltration, xerophytic vegetation suppression of consumption losses, delayed recharge, rapid concentration and supply from feeder streams.

The physical settings of the different geohydrological systems have been defined on the basis of the hydrogeological characteristics of the Late Cenozoic (and underlying) geological materials.

Due to the difficulties in extrapolating hydrogeological behavior to such a vast territory (approximately 700,000 km²), mainly because of scarcity of specific information, case studies have been presented for the Santa Cruz, Chubut, Río Negro and Neuquén provinces, each with differently acting geohydrological systems.

The human influence in the region, limited only to sheep farming until the first half of the twentieth century, is increasing with the on-going expansion of mining, forestry, intensive agriculture, urban development and most importantly, both present day and future oil and gas exploration and exploitation activities. Then, its impact on underground water resources will become enormous and of serious, mostly unpredictable, environmental consequences.

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