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Hydrogeology of Plains

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Abstract

This book defines in Sect. 1 the different type of plains and classifies them according to the processes involved in their genesis, and the dominant climate and hydrological balance in which they have developed. The lithological and geomorphological characteristics of all plains, either of alluvial, deltaic, piedmont, intermountain or marine nature, are described. Their hydrogeological behaviour is analysed with reference to their hydrodynamic and hydrochemical characteristics.

Section 2 deals with the coastal plains of Argentina, defining their characteristics and discusses the fresh water–salt water relationships.

In Sect. 3, the methods and techniques more frequently used in hydrogeological studies are discussed, mentioning their features and benefits: (a) topographical and geological maps; (b) aerial photographs and satellite imagery; (c) climatic data, such as rainfall and snowfall, temperature, evapotranspiration, stream discharge; (d) hydrological balance; (e) reports on surficial and groundwater; (f) descriptions and logs of drillings and wells, and (g) geophysical surveys.

Section 4 discusses the hydrogeological field surveys, indicating the tasks implied in these activities, such as measuring water level in wells and drillings, water sampling and steering pumping tests. It also debates about the hydrogeological exploration by means of geophysical methods, such as geoelectrical, gravimetric, magnetometric and seismic. The methods of geoelectrical prospection and the different drilling systems employed for water well building are herein described, indicating the advantages and disadvantages of each. The different kinds of hydrogeological maps and their utility for interpretation of the dynamic behaviour of groundwater are described and analysed. The reserves of the free and under confinement aquifers are defined and classified.

Section 5 refers to the chemistry of groundwater based on the origin and relationships of the ions in solution, the incidence of geology, geomorphology, climate and biota over their chemical composition, and particularly, the human effect. The salts generated by the different rock types and the ideal chemical evolution for regional underground flow are also mentioned.

In Sect. 6 the different definitions about water vulnerability to pollution, published by the most relevant researchers, are cited. The commonly used procedures to qualify and quantify vulnerability are detailed together with the mode to use them, proposing criteria to choose those most appropriated and comparing their capability. Finally, vulnerability is explained based on the results obtained in a regional research project on the Puelche and Pampeano aquifers, in the region of the city of La Plata, Buenos Aires Province, Argentina, including many descriptive maps.

All sections include figures and tables to help, in the comprehension of the text.

Keywords Groundwater · Hydrogeology · Hydrogeology of plains · Groundwater dynamic · Groundwater chemistry · Aquifer vulnerability · Argentina

Purpose

The purpose of this book is to present the behaviour of groundwater in the plains, because these landscapes have strong incidence both in their hydrodynamics as well as in their underground hydrochemistry. This is a consequence of the very low morphogenetic energy that characterizes the environment of plains, due to the very gentle topographic slopes that limit the lateral flow and force a predominant vertical. Another hydrogeological characteristic that is highly relevant to plains is the low velocity of the flows, due to the very low permeability and the small hydraulic gradients found in plains, which results in long periods of contact between the groundwater and the solid components of the aquifers. However, in those plains where wet climates are dominant, i.e. the precipitation is larger than the potential evapotranspiration, the existence of low salinity water is prevalent, especially in the shallower aquifers, whereas in those plains where the hydrological balance is negative, i.e. the potential evapotranspiration is greater than the regional precipitation, the situation becomes inverted and the shallow groundwater is predominantly brackish or saline.

Target

This book is oriented towards university students of different levels who are pursuing a degree in Hydrology, in general, and particularly in Hydrogeology or Groundwater Hydrology. It is also adapted to the needs of those professionals and researchers who are active in hydrogeological studies and/or exploration, mainly in plain environments.

Hydrogeology of Plains

1 Plains

In general terms a plain can be defined as a field of low relief, or marked with little unevenness, as opposed to mountainous areas or highlands, where the height differences are more accentuated. Despite its relative flatness plains are never completely flat, presenting elevations called watersheds and lowlands, known as depressions where water bodies (rivers, lakes, lagoons, marshes) are located.

It is difficult to establish the setting of topographic gradient magnitude to establish what a plain is, because it essentially depends on the position related to the orographic systems. However, it can be taken as common value limits slopes of 10/1000 and 0.5/1000. The first one is characteristic of piedmont plains, but it can grow up to 80/1000 in the proximal alluvial fans, whereas the second may fall below 0.2/1000 in depressed plains as the Río Salado Plain in the Province of Buenos Aires (Argentina).

The plains can be identified in different ways, depending on the process that generated it or the landforms that characterize it. Thus, from a genetic point of view, they can be classified into: **alluvial** plains, when they are derived mainly from fluvial action; **aeolian** plains, when the master builder agent is the wind; **marine** plains, carved by marine activity and **glacial** plains when the ice becomes the main formation agent. Normally, due to the extent of time it takes for the evolution of a plain (i.e., millions of years), they usually involve more than one natural process in its modelling. Thus, they are called **fluvio-aeolian, glacio-fluvial, glacio-marine,** etc., according to the agents involved.

Another way of classifying the plains, which is very commonly used in hydrogeology, is based on the climatic features. Following this criterion they are classified in humid plains, like those that record a certain water excess after a full hydrological year, this is the period covering the months of maximum precipitation (the rainy season) and those of lower precipitation (the drier season). Moreover, a plain can be classified as a wet plain when the water surplus should be the

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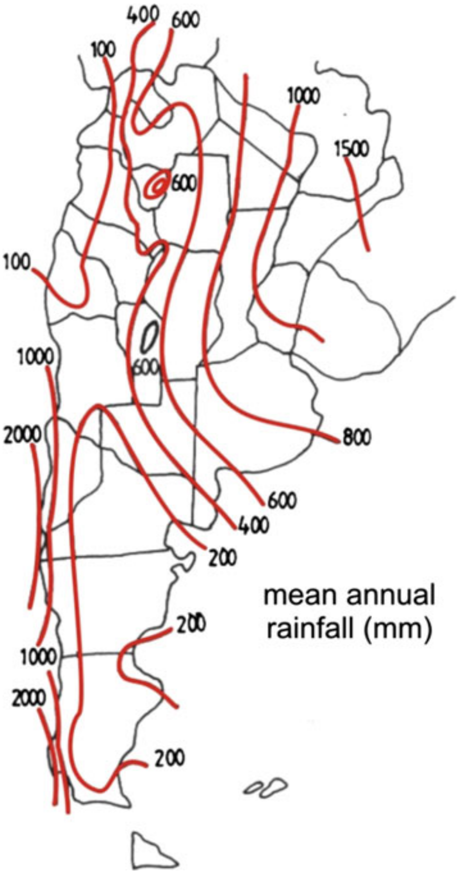
prevailing trend through most part of the considered years and the hydrological deficit, if any, being the exception to that rule. The excess of water is computed in relation to the annual rainfall.

The water surplus is computed in connection with the annual potential evaporation, which is the volume of water that the atmosphere is able to evaporate and that plants may transpire in a soil with an optimum moisture content. According to the above, if the precipitation exceeds the potential evaporation, water surplus exists and if it prevails over most hydrological years, the plain can be called a **humid one**. As a counterpart, when after the hydrological year water deficit exists and if this is the general trend over time, it is said that the plain is an **arid plain**.

Semi-arid plains are those that in some periods have a prevailing deficit and others when excess of water takes place, the first case being more frequent. In the **semi-humid** plains, excess and deficit of water are also produced, but the excesses are certainly more common in the historical series.

Figure 1 presents the annual isohyet rainfall in Argentina (following Burgos and Vidal 1951). In two regions of Argentina, annual rainfall is over 1500 mm/year

Fig. 1 Mean annual rain



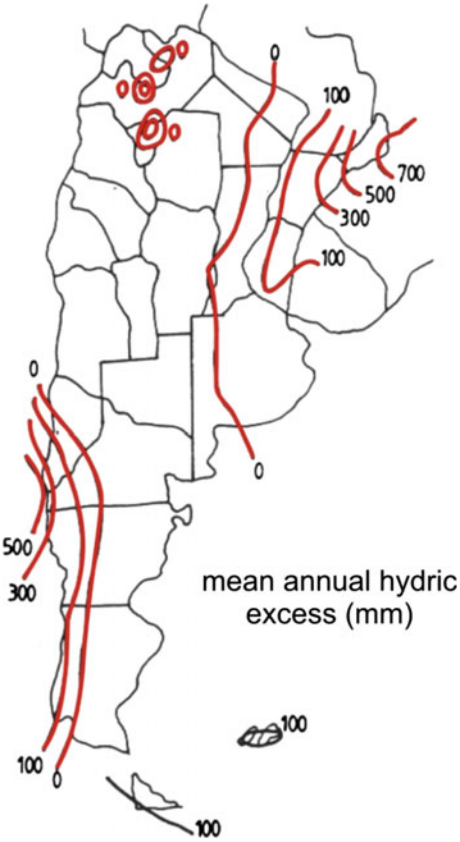


Fig. 2 Mean annual hydric excess

(mm/y). Firstly, in the northeast region of Argentina (NE), the field in question occupies the entire Province of Misiones, whereas in the southwest corner (SW), the area with very high rainfall covers an N–S trending, narrow strip that coincides with the Southern Andes, also known as the Patagonian Andes.

The region of lower rates of rainfall lies in northwest Argentina with less than 100 mm/y. In Fig. 2, the average annual water excess is represented by contour lines (Burgos and Vidal 1951). In this figure, there are two large areas with water surplus (NE and SW), which approximately overlap with those of highest annual rainfall.

Regarding groundwater dynamics, plains are characterized by a marked predominance of vertical movement with respect to lateral one, thus the processes of infiltration, evapotranspiration and oscillation of the water surface are predominant over lateral flow (Auge and Hernández 1984). With regard to surface water accumulation, areal types as ponds, marshes, lagoons and lakes, lead over runoff that is channelled through rivers and creeks.

1.1 *Alluvial Plains*

The alluvial plains are more or less flat surfaces generated by the action of rivers. Floodplains are landforms of accumulation or fluvial sedimentation unlike peneplains, which are forms of degradation or fluvial erosion. To understand the fluvial geomorphic processes, it is necessary to define some parameters or elements owned to or linked to rivers.

Discharge is the volume of water passing through a section of the channel in a certain time unit.

Capacity of charge or transport is the maximum solid charge that a water course can carry, for a given speed. If the solid volume transported exceeds capacity, the excess load is deposited. Conversely, if the solid volume is less than the capacity, the river erodes its own channel.

Base level is the level below which the rivers cannot erode its bed. The general base level of all rivers is sea level and its prolongation under the continents (Fig. 3).

Local base levels may be above or below sea level. Thus, a river that drains into a lake or a pond higher than sea level has this lake or pond as the local base level (Fig. 4). Closed depressions of lesser elevation than sea level, although much less

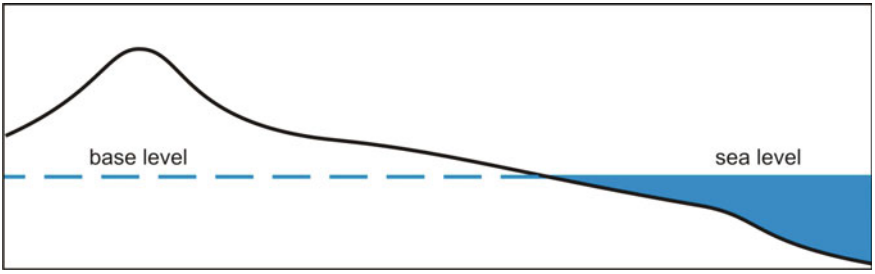


Fig. 3 General base level

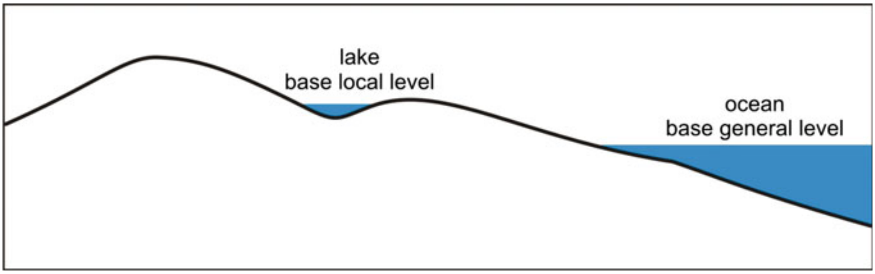


Fig. 4 Local base level

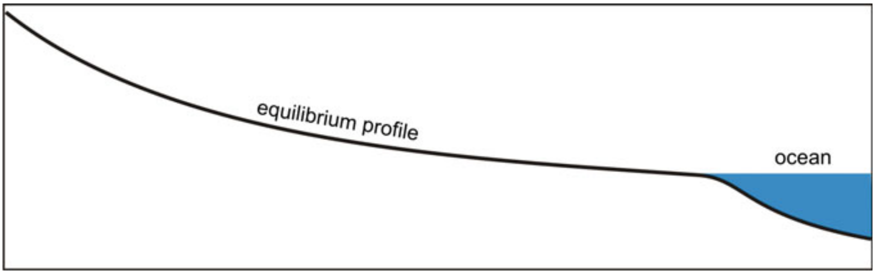


Fig. 5 Equilibrium profile

frequent, act also as local base levels (for instance, the Chasicó Lake in the Province of Buenos Aires, Argentina).

Profile of equilibrium is the form adopted by the riverbed in its longitudinal profile according to which, no erosion or sedimentation should occur. This situation rarely occurs in nature, although some rivers are relatively close to their equilibrium profiles. Schematically, equilibrium profile is a concave upward curve, steeper towards the sources and tangent to the horizontal towards the mouth (Fig. 5).

Erosion by a river begins in the lower parts of its bed and then rises up (headland erosion); the greater erosion activity is related with abrupt topographic slopes. Every river has a limit above which it erodes and below which it deposits its load. This limit is called the **neutral line** (Aubouin et al. 1980) (Fig. 6).

Fluvial accumulation occurs when the transported material weight exceeds the capacity of the river. The load capacity is directly related to the kinetic energy ($Kc = 1/2\ m \cdot v^2$); therefore, Kc increases linearly with increasing mass of moving water but in quadratic relationship regarding the speed of the stream. Therefore, when a mountain river enters its neighbour foothills, it generates characteristic landform of gravel and sand deposits called **alluvial fan** (Fig. 7), due to a hard reduction in its flow, caused by a decrease in the topographic slope.

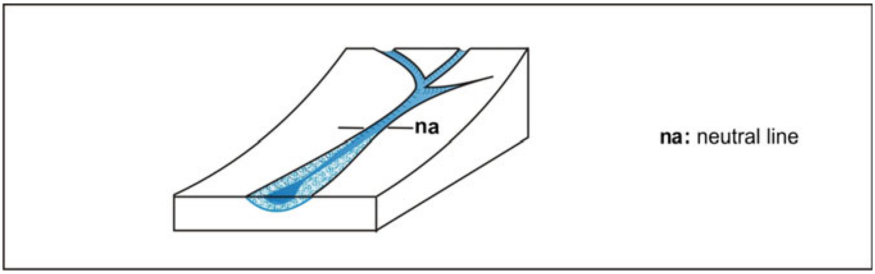


Fig. 6 Neutral line

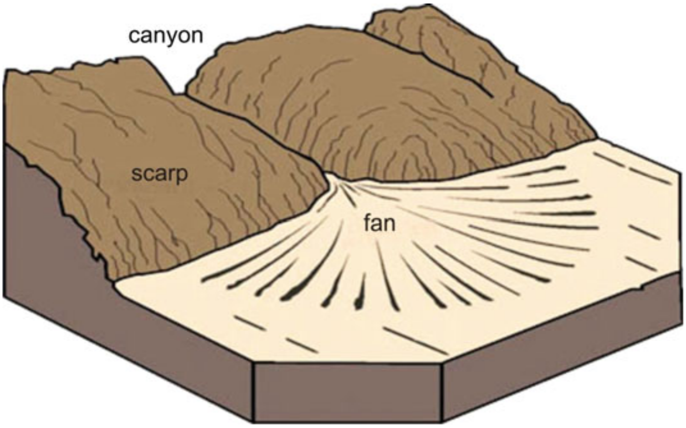


Fig. 7 Alluvial fan

Once inside the **alluvial-plain**, and as the distance increases away from the mountain body, the ability to transport water courses decreases, leading to a reduction in the size of their deposits (Fig. 8).

Therefore, as the observer moves away from the mountain area coarser deposits (such as gravel) are replaced by medium sized sediments (such as sand) to finally become fully substituted by finer sediments (silt and clay). On the same vertical position, however, it is common to find alternating materials of different sizes due to local variations in the capacity of the rivers (Auge 2008a) (Fig. 9).

It is understandable that during the period of flooding, the river will be able to drag more and larger sediments that during the drier season. Therefore, coarse sediment accumulations correspond to the rising and the finer deposits do so with lower or normal water level. The change in position of the baseline also results in a change in the carrying capacity of rivers. Thus, if a course near its equilibrium

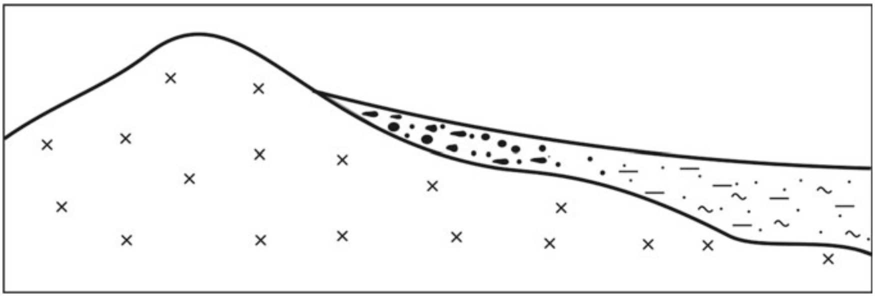


Fig. 8 Piedmont

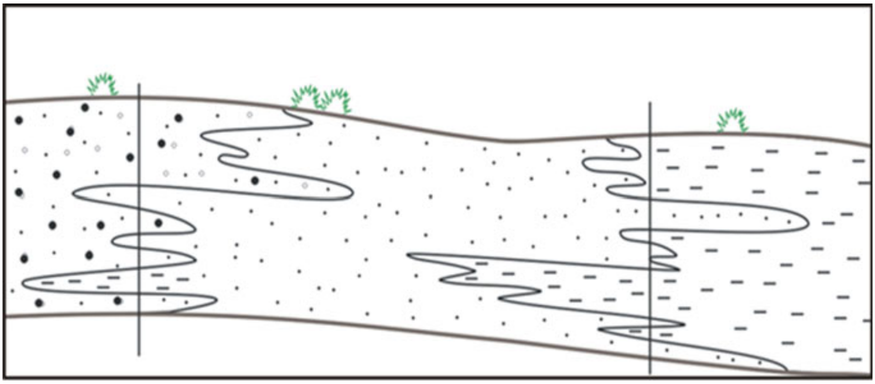


Fig. 9 Grain-size alternation

profile (lower erosion and deposition) undergoes a rise in its field headers or a lowering of its base level, as a product of the ebb of sea level glaciations, it modifies its hydrodynamic stability restarting erosive processes upstream of the neutral line and sedimentation downstream of it. River terraces are landforms derived from processes of accumulation and subsequent water erosion.

AA and BBB are river terraces. The oldest pair AA is at a higher topographic position that the most modern trio BBB (Fig. 10).

Alluvial-plains built by rivers near marine coasts were controlled in its activities by changes in the level of the oceans which occurred during the Quaternary. In the last 1.5 million years there were, at least, 5 major glaciations and another 5

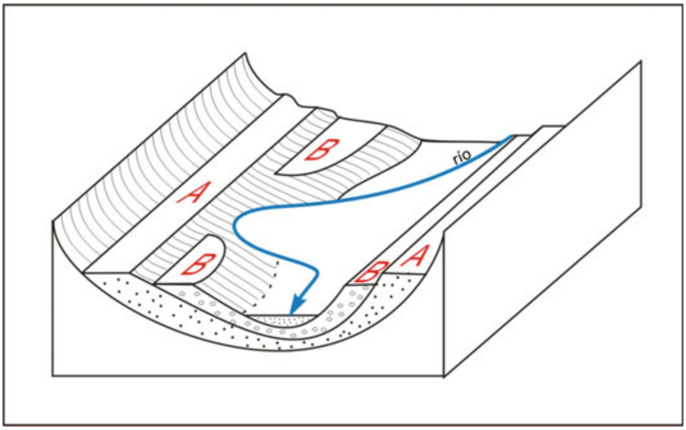


Fig. 10 Fluvial terraces

interglacial periods, the last of which currently elapses. Glacial periods generated a general decline in sea level, as the evaporated water that formed the ice masses on the continental areas did not return to the oceans. The lowering of the base level favoured the erosion and widening of the channels. In interglacial periods (warmer climates) base level rose leading to the accumulation of sediments in the channels which had been over deepened during the previous glacial period. The repetition of these cycles also resulted in the formation of river terraces in coastal areas, called **eustatic terraces**, as a result of the oscillation of sea level.

The tectonic uplift of the mountain environments results in a relative decrease of baseline and in the prevalence of an erosion period. The subsequent levelling of the relief and filling valleys and channels can be interrupted with a new uplift, a situation that also generates **tectonic terraces**. The terraces derived from alternating flooding (accumulation) and water level decrease (erosion) are called **climatic terraces**. The flooding of a river can respond to excessive rainfall on its basin, to the contribution of melt water in the summer months, or both processes.

1.1.1 Deltas

A delta is a type of floodplain which may be formed at the mouths of rivers in seas, oceans, lakes and estuaries. The deltas are more common in those seas enclosed or protected, where ocean currents are not too strong (for instance, the Mediterranean Sea). The Paraná River mouth into the Río de la Plata estuary gives rise to a significant delta (the Paraná Delta in Argentina). The word “delta” comes from the Greek letter of that name, for the similarity of the Nile River delta with triangular shape of the cited letter.

The material transported by a river is deposited when the current becomes slower in its mouth. In the near shore locations the coarser sediments (gravel and sand) build up, whereas the finer particles (silt and clay) are taken to greater depths and longer distances. The lithological constitution of a delta, involves three types of layers:

Bottom beds. They are composed of finer materials which are deposited in the sea, forming the bottom of the bay or estuary on which the delta is building.

Front beds. They are formed by coarser sediments representing the delta front as it progresses and makes up most of its volume.

Top beds. These layers are emplaced above the front beds, and they form an extension of the alluvial plain of the delta which then becomes the terminal portion (Fig. 11) (modified from Aubouin et al. 1980).

Meanders. In the fluvial geomorphic evolution, the meander corresponds to the stage of senescence or old age landscape. Gentle slopes, poorly marked topography and rambling rivers are responsible for the formation of meanders (which are wide and pronounced curves in water courses) (Fig. 12).

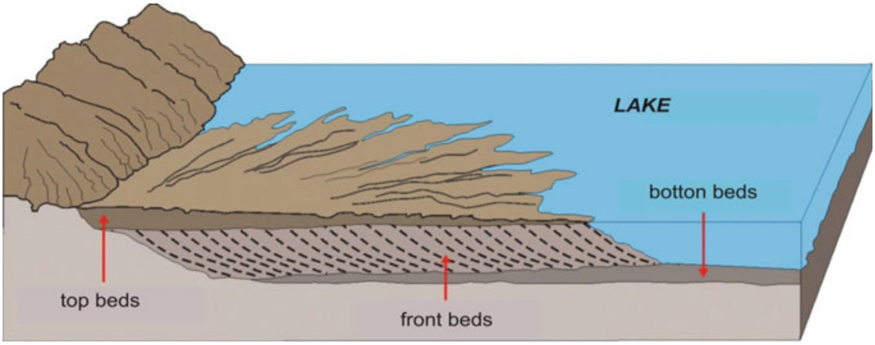


Fig. 11 Delta

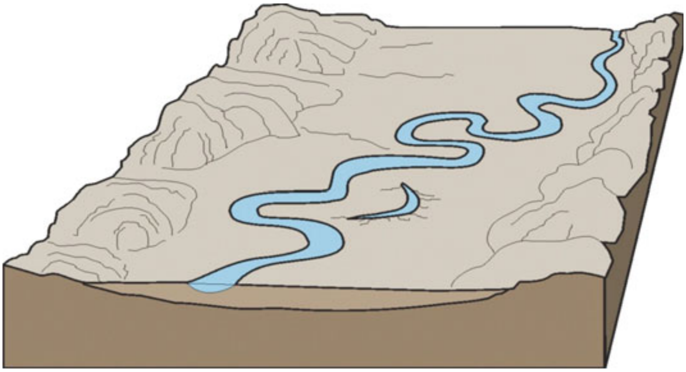


Fig. 12 Meandering river

1.1.2 Piedmont Plains

They are formed by lateral coalescence of several alluvial fans.

1.1.3 Intermountain Valleys

They are depressed linear landforms, limited laterally by highlands or mountain ranges (Fig. 13).

Most **intermountain valleys** are actually depressions of tectonic origin because their sidewalls are in contact with the positive elements, are bounded by faults (for instance, in Argentina, the San Francisco Valley in Jujuy Province, the Catamarca Valley, the Santa María Valley in Catamarca Province, the Fertile Valley in San

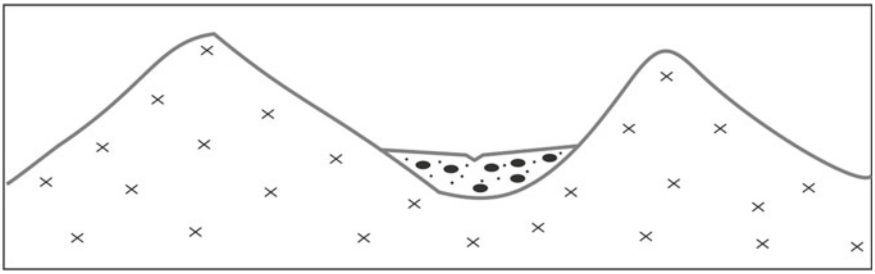


Fig. 13 Intermountain valley

Juan Province, and the Conlara Valley in San Luis Province). When these valleys occur as closed landforms, they are called “**pockets**”.

1.1.4 Marine Plains

The marine plains are formed by the action of the sea along the coast. The sea acts through the waves and currents whose origin in both cases, is due to the wind, in the outer portions of the ocean. The difference between waves and currents is that the first ones break near the beach and have an oscillatory movement. The currents move slower and usually in only one direction. According to its relative stability, the coast or shoreline can be classified into emersion, dipping and neutral. The emersion coasts tend to rise (the sea is removed); being the most common landforms the banks and coastal bars. The coasts of immersion tend to sink, because the sea is advancing over the continent; most commonly, they form cliffs. Dunes are of great hydrogeological importance in coastal environments, because they usually contain fresh groundwater.

1.2 Hydrogeological Behaviour

1.2.1 Alluvial Plains

Floodplains in its different types (piedmont, deltaic, channelled, ample, intermountain, etc.) and also those derived from the combined action with other (wind, ice, sea) agents, are the most important reservoirs of ground water. The hydrodynamic characteristics of aquifers located in flood plains (recharge, flow, hydraulic gradients, discharge, yields) depend upon their physical properties (porosity, permeability, thickness, lateral continuity, etc.), the shape and magnitude of the recharge and discharge, and the geomorphological characteristics that these areas have. Thus, in a foothill plain with significant topographic slope towards the surrounding mountains, where most recharge is generated, it is reasonable to expect the presence of aquifers with high pressure and flow, with common areas of flowing.

As the distance increases to the hilly area, topographic slope and grain size are reduced, generating the latter a decrease in permeability and thus in flow rates. The mineralogical composition of the skeleton of an aquifer affects the chemical quality of the water. Thus, the feldspar grains that are easier to weather than silica can give up substantial amounts of Na and K. The limestone aquifers, in turn, have carbonated water with calcium and magnesium.

Geomorphology also affects the chemical quality of groundwater. The strong topographic gradients (piedmont environments) result in important hydraulic gradients and flow velocities. In return, in flat areas with little topographic slope, hydraulic gradients and flow rates are low. In the first case the salinity of the water will be lower than in the second.

In zones with deep groundwater (arid plain), topographic depressions are areas of preferential recharge. However, if the bottom has fine material with low permeability, the infiltration is impeded and evaporation becomes easier. In environments with water table near the topographic surface, for instance shallower than 10 m (humid plain), the rivers and depressions (ponds, marshes, and swamps) are generally of the effluent type, that is upslope areas of groundwater discharge. In these areas recharge normally occurs in the topographically high or intermediate zones (Auge 2008a) (Fig. 14).

Groundwater quality depends upon the grain size of the layers through which the water circulates, its mineralogical composition, the length of the underground travel, the geomorphological characteristics and climatic conditions of the area. To this, human intervention should often be added, which generally causes deterioration in groundwater quality.

The aquifers formed by unconsolidated medium and coarse fractions of good permeability, provide circulation and decrease the surface contact time between

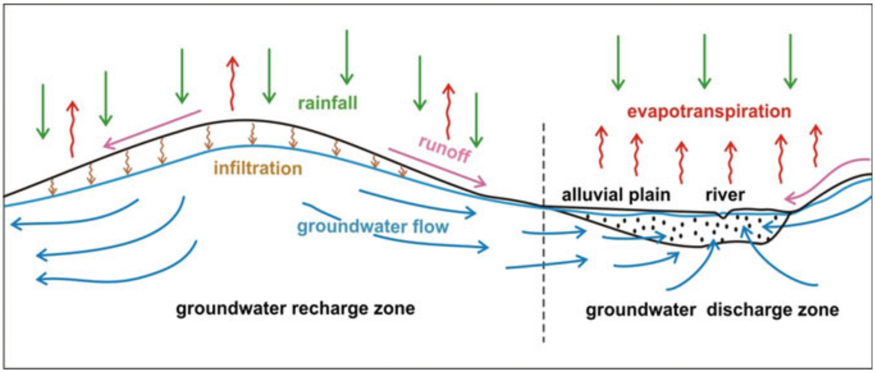


Fig. 14 Groundwater flow in humid plains

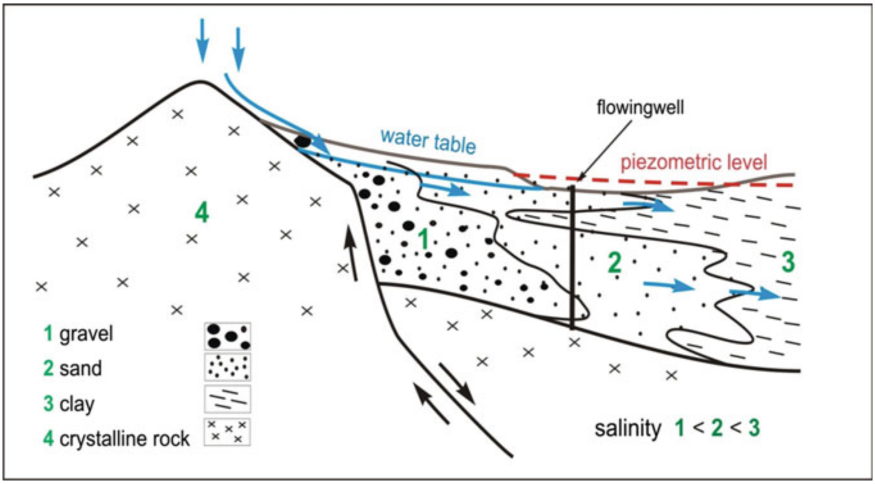


Fig. 15 Relation between groundwater flow and salinity

water and solid components, hindering the dissolution of minerals and results in a lower salt concentration. By increasing the travel distance, the water incorporates greater amount of salts in solution and its quality deteriorates. Therefore, in the recharge areas or nearby, groundwater has lower salinity than in the discharge ones (Fig. 15).

If aquifers are composed of finer materials (silt) or whether they form the matrix of other thicker (silty or clayey sands) beds, the flow velocity decreases, but the time and the contact surface and hence the salt concentration, increases.

Finally, the climate is another factor that controls salinity. Under arid and semi-arid climates, the groundwater salinity increases, primarily due to evaporation in shallow aquifers, and also due to lack of dilution.

From the foregoing, it follows that the dynamic and chemical characteristics of groundwater in alluvial-plains or floodplains are controlled by different factors.

The type of plain also regulates those characteristics. Thus, in the deltaic plains, which are the terminal portion of a floodplain, the volume of sediment accumulated is important and therefore it is so the stored water.

This situation takes place when the seabed or estuary where a delta forms suffer subsidence (i.e., sinking), thus allowing to maintain the balance between the sediments and the sinking process. If subsidence exceeds in magnitude vertical growth, the delta disappears below sea level (as it happens with the Amazon River Delta). If the relationship is otherwise and the ocean currents are not strong enough, the delta progresses offshore.

The Paraná River have fresh water, but the occurrence of clayey sediments of marine origin and with lower permeability at shallow depths underneath the Paraná Delta, makes brackish its groundwater (Fig. 16).

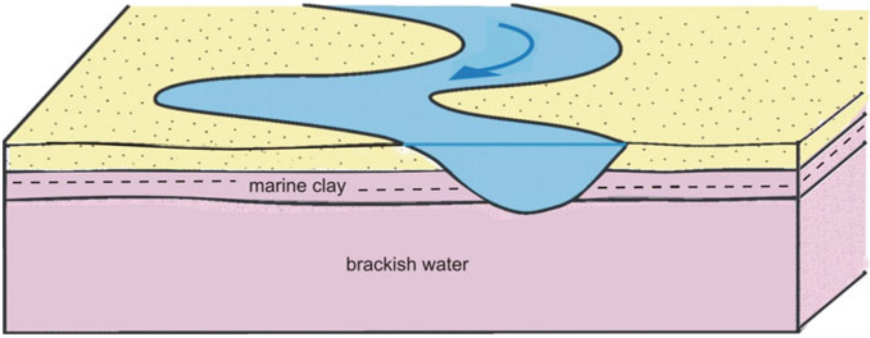


Fig. 16 Paraná delta

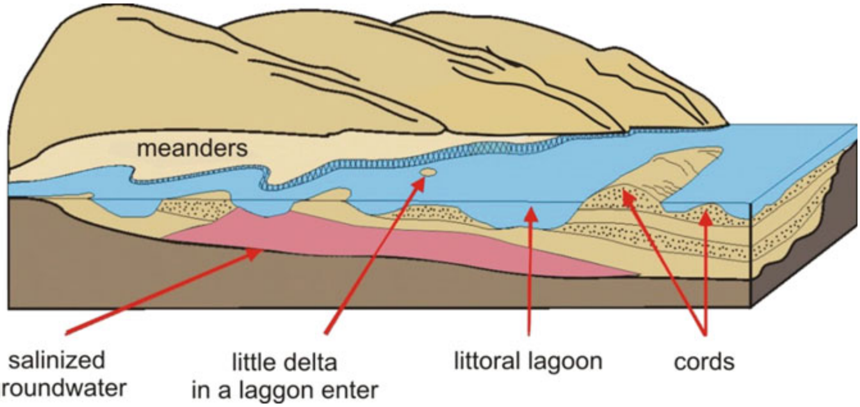


Fig. 17 Salinity on deltas

For this reason, the river also contributes finer deposits and organic matter, which becomes accumulated in secondary channels or outside of the main channels when they overflow. The wells drilled in the Paraná Delta have provided interesting yields but mostly of brackish water. In the deltas formed in marine coastal areas, the tide influence can reach several kilometres inland and produce an appreciable salinization of groundwater along the area of marine incidence (Fig. 17) (modified from Aubouin et al. 1980).

1.2.2 Great Alluvial Plains

As it has already been stated, the plains formation usually involves more than one modelling agent. The most conspicuous example in Argentina is the huge

Chaco-Pampeana Plain, with more than one million km^2, which is derived today from fluvial and aeolian processes, but in the past, during the Late Tertiary, it was shaped by the sea. The most interesting yields are obtained in the vicinity of the alluvial fans and piedmont plains as the Santiagueño-Tucumana and Chaco-Salteña basins and the eastern portion of the Sierras de Córdoba. Good yields have also been obtained also in the vicinity of major rivers (such as the Bermejo, Pilcomayo, Paraná, Uruguay, Salado, Tercero, etc.), where the alluvium is composed of medium and coarse sediments (i.e., sand and gravel).

Occupying an area of 92,000 km^2 only in the northeast portion of Buenos Aires Province, a sequence of fluvial sands, of Late Tertiary to Early Quaternary age (around 1.5 million years), with an average thickness of 30 m, lies underground at depths between 20 and 90 m. These sediments contain the most important aquifer of the region, according to its quality and productivity (the Puelche Aquifer). The average permeability of these medium to fine sands is about 30 m/day and the effective porosity is of 20 % (Auge et al. 2002). The average flow rates obtainable in well drilled wells vary between 40 and 150 m^3/h (cubic m/h).

In general, groundwater of the Chaco-Pampeana Plain, increase their salt content in relation to rising environmental aridity. Also, there is an increase of salinity with depth, due to the presence of marine clayey sediments of the Paraná Formation. Locally, an important increase in salinity occurs as well in discharge zones or bad drained areas, with prevalence of fine grained, silty clay sediments and water table occurring near the topographic surface (zones where lakes, marshes or wetlands are found), for instance Mar Chiquita Lake in the province of Córdoba).

Other sediments that usually form this vast alluvial plain are the Pampeano Loess units (silts and fine sands of aeolian origin), which have lower permeability (1 m/d) than that of the Puelches sands. The salinity of the groundwater contained within the Pampeano loess is normally controlled by the depth of the water table and the climate characteristics; in humid regions fresh water prevails and in arid regions, the water shows higher salinity).

The Pampeano loess contains the phreatic aquifer and sometimes, due to variations in both vertical and horizontal permeability, it may have one or more aquifers under pressure, forming semi-confined or multilayer aquifer systems.

1.2.3 Piedmont Plains

The Piedmont Plains are composed of alluvial fans, bajadas and playas. Alluvial fans, also known as alluvial cones, are accumulation landforms generated by a reduction in the carrying capacity of rivers, when they leave the mountainous, highland regions. Basically, its genesis, composition and geometry are comparable to those of a delta, but out of the water; i.e., they show coarser materials at their heads, vertically inter-bedded sediments of varying size, and the presence of an interconnected network separated by alluvial material (a braided stream). Alluvial fans are broad and extended landforms with gentle surface slopes between 1 and 5 degrees. Cones are less developed in terms of actual surface, but they are steeper, reaching slopes of up to 15°.

At the heads of fans and cones, there are usually thick and permeable materials (such as boulders and sandy gravels). Infiltration is very important, especially from stream waters coming down from the adjacent mountain areas. The steeper topography, with high permeability and lack of interceded finer materials, forces groundwater to behave like phreatic waters, although at much deeper positions (often more than 100 m).

At the head of these fans, very important yields of good quality water can be obtained, but their exploitation is limited due to the depth of the water table which increases the cost of pumping (200 m in the Mendoza River fan, at the foot of the Andes Ranges), but also due to the scarcity of large cities.

With increasing distance from the mountain region, the topographic gradient and grain size decrease, the material selection improves and groundwater is then located at shallower depths. In this area, known as the bajada, dominated by medium (sand) and coarse grained sediments (gravel) and inter-bedded finer materials such as silt and clay, good water quality is generally obtained in significant volumes, and also at available depths from a practical point of view (less than 100 m) (Fig. 18).

The piedmont hydrogeological behaviour can be summarized saying that recharge areas are located in fans, lateral flow dominates in the bajadas, and the discharge zones are located in the playas. The quality and performance of aquifers declines in the direction of flow, the bajada areas resulting, for all practical purposes, much more helpful to the exploitation and delivery of groundwater.

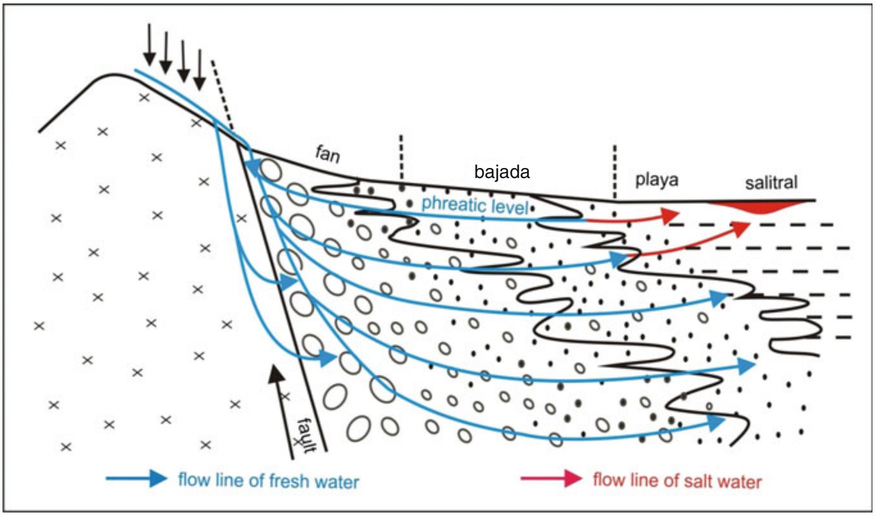


Fig. 18 Piedmont

Permeability is highly variable due to the strong vertical and lateral anisotropy, which causes that nearby wells, may provide very different flow rates. In order to obtain higher yields and reduce pumping costs, it is essential to make a detailed control of exploration wells including: lithological sampling, speed penetration, electrical profiles, and hydraulic tests (Auge 2005a, b). The both vertical and lateral grain-size variations may force that the number of productive layers can vary significantly in nearby positions, which justifies detailed checks on exploratory wells being made.

The following permeability values are provided with the purpose of having an order of their magnitude in different geomorphological foothills positions.

Piedmont	Permeability (m/d)
Fan	1.000 a 100
Bajada	500 a 25
Playa	100 a 5

1.2.4 Intermountain Valleys

The intermountain valleys are longitudinal depressions between hilly or mountain elevations. These valleys can be derived from tectonic activity (folding, faulting) or by erosive action (mainly fluvial), or by combination of both processes (Figs. 19 and 20).

Most intermountain valleys of the Pampeanas Ranges, of the Cuyo region and of NW Argentina, are of tectonic origin as the Fértil Valley in the province of Catamarca, the Tulum Valley in the province of San Juan, the San Francisco Valley in the province of Jujuy and the Lerma Valley in the province of Salta.

Faulting may sometimes be seen at the surface, on one or both edges bounding a depression, but in general the identification of fractures is not easy. Generally, the alluvial filling in a valley of fluvial origin does not exceed 50–100 m thick, whereas

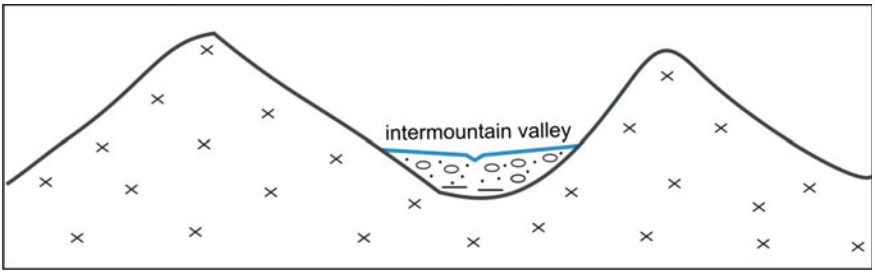


Fig. 19 Intermountain alluvial valley

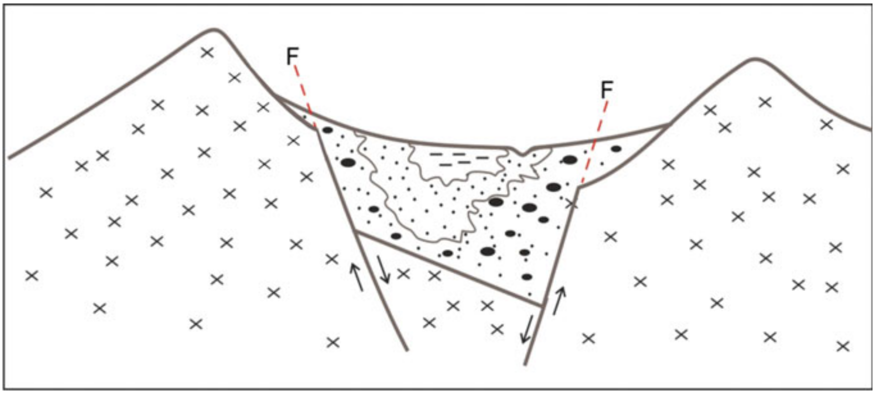


Fig. 20 Intermountain tectonic valley

another valley of tectonic origin, the sedimentary filling may reach from a few hundred to more than 1000 m thick.

The alluvial or river terraces are landforms of high hydrogeological interest associated with the intermountain valleys. The terraces are geomorphological units that represent the bottom of ancient channels. The stratigraphic system does not follow the principle of superposition, so the topographically higher terraces are older than the lower ones. Terraces are caused by changes in the position of base level for more or less uniform flows, or strong flow variations in stable geomorphological conditions. In relation to the above, terraces are classified as: **tectonic, eustatic, or climatic terraces**.

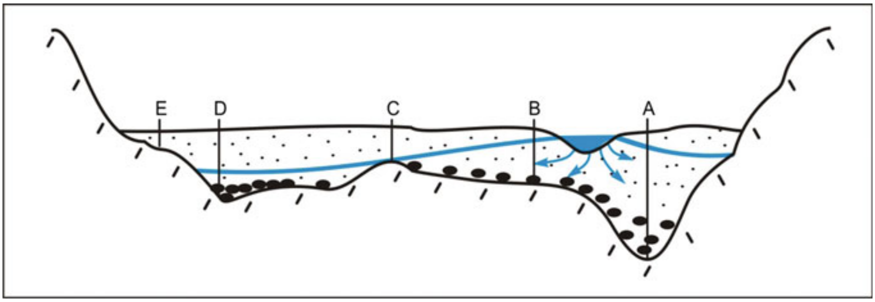
Tectonic terraces. Orogenic uplift increases topographic slopes, favouring the accumulation of stream and gravitational sedimentary loads.

Eustatic terraces. During glacial periods, sea level lowering resulted in dominant erosion processes in the middle and lower sections of rivers. During the interglacial events, rise in sea level lead to accumulation and in-filling of the channels which had been excavated during the glaciations.

Climatic terraces. In rainy or thaw periods, the volume of water transported by a stream increases and so does its capacity. This condition results in accumulation or sedimentation processes which become dominant. In times of lower or normal yield, stability or erosion with excavation of the channels prevails.

In intermountain depressions, the most hydrogeological favourable areas are those located where higher saturated alluvial thicknesses and effective recharge are present. The latter one ensures the replacement of part or all of the volume to be extracted. Normally, in arid and semiarid regions, rivers are influent to the water table, so the safer exploitation wells are generally chosen near its margins (Fig. 21; modified from Davis and de Wies 1971).

In the terraces, representing the channels occupied by the river sometime in the past, interesting flows are obtained when the saturated sedimentary thickness is



Relative yields: well A > B > D. Wells C and E will not yield water

Fig. 21 Favorable places for tapping

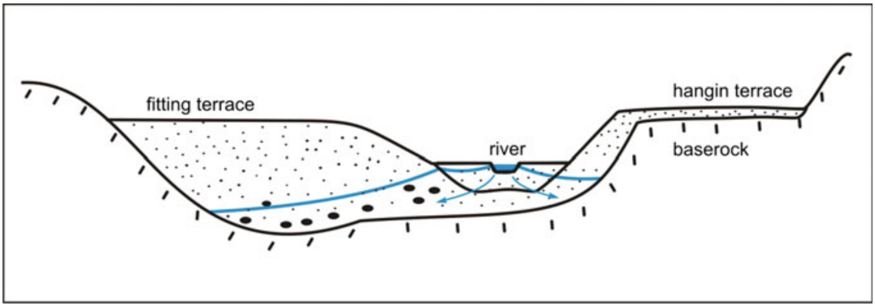


Fig. 22 Fluvial terraces

important. These terraces are called packed or nested terraces, unlike the hanging terraces, when the alluvial and saturated thickness is smaller and often they do not contain groundwater (Fig. 22) (modified from Davis and de Wies 1971).

In the intermountain depressions, it frequently happens that older alluvial thickness do not match the present channel of the river, because it has migrated laterally over time occupying other positions in the floodplain. Identifying these excavated places in bedrock, or the substratum where the alluvium is based is not really easy; therefore, to the use of conventional techniques such as geological and geomorphological surface survey, mapping and analysis of aerial views, the use of subsurface exploration methods such as geoelectric, seismic and exploratory drilling must be added. If the substratum component is compact and resistant to erosion, the presence of steep slopes and river banks on one of the sides of the valley is an indication that the river could eventually lie on the same bank (Fig. 23).

With regards to homogeneity and isotropy of alluvial components, fit for the intermountain depressions, the concepts are similar to those which have been mentioned for alluvial fans. Therefore, the aquifer skeleton observed a marked

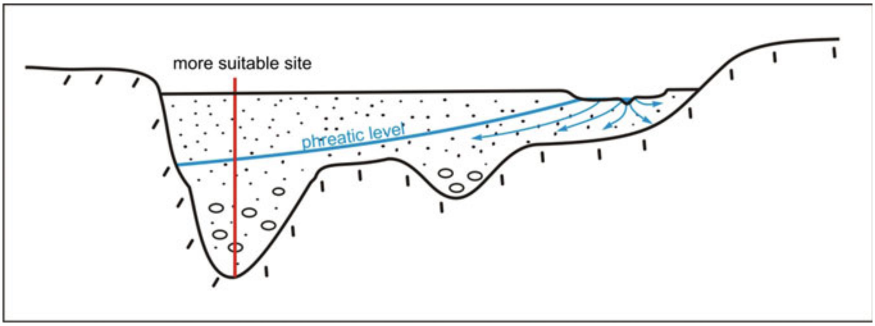


Fig. 23 Fluvial migration

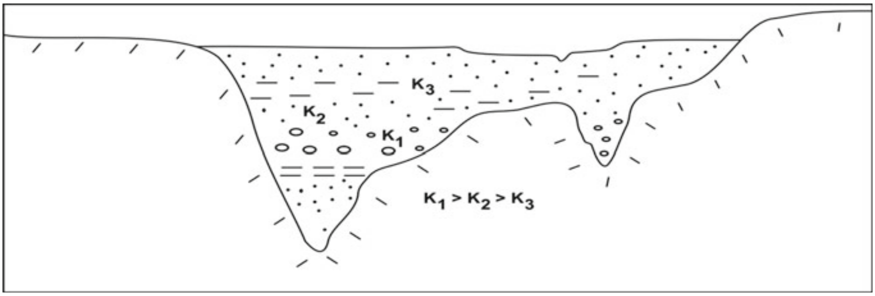


Fig. 24 Permeability—grain size relation

heterogeneity and anisotropy, both lateral and vertical, due to its genesis in rivers with substantial topographical slopes. The sediments that match the ancient stream beds are thicker and with lateral reduction in grain-size; therefore, they will have better hydrogeological prospects. Also, a vertically alternation of coarser and finer sediments is present accordingly with periods of flooding and low water, respectively (Fig. 24).

Permeability usually presents variations consistent with the anisotropy of alluvium with values frequently between 700 and 20 m/d for coarser deposits (gravel) and medium-sized (sand) sediments. Finer (silt and clay) deposits usually do not exceed 0.1 m/d.

Fluvial water quality controls the quality of groundwater when the rivers are influent. In these cases, if the river has freshwater, groundwater quality suffers a declination with increasing distance to the stream channel. If the river is effluent (that is, it receives water from the aquifer), it is common that its waters have greater salinity than remotely located groundwater due to increased salinity by evaporation and flow.

1.2.5 Channelled Alluvial Plains

The channelled alluvial plains have broadly the same hydrogeological characters than the intermountain depressions. In morphological, stratigraphic and structural terms, however, there are differences because channelled plains are entrenched in plateau or flat environments and they are laterally bound by river bank or cliffs of low altitude (from 10 to 100 m). This generates that the dominant contribution are fine grained (silt and clay) sediments from the flatter regions that surround them. Medium and coarse grain-sized units (sand and gravel) are provided by the mountainous regions located at the heads of the watersheds by transportation along the river channel. The alluvial thickness rarely exceeds 50 m, decreasing towards the heads and increasing towards the river mouth. If it occurs at sea level, it can generate mixing between the river and marine sediments.

Channelled alluvial plains are present in all rivers which cut across Argentine Patagonia (the Colorado, Negro, Chubut, Deseado, Santa Cruz and Gallegos rivers). These are rivers that originate in the Patagonian Andes and after traveling hundreds of kilometres eastward, they end into the South Atlantic Ocean. Its main contribution comes from rainfall and snowmelt in the mountainous area where precipitation is plentiful. Upon leaving the range environment, they enter the arid Patagonian Plateau, where rainfall is less than 200 mm/year.

The alluvial valleys reach substantial width, especially in their middle and lower sections (10–30 km), which is a clear evidence of significantly higher river flow in the past, during glaciations, because the present channels rarely exceed 300 m width and even in times of extraordinary floods, they only occupy a quite small portion of their ancient valleys.

Most of these rivers are influent and its water is of good quality, and so is the groundwater surrounding its channels. The water quality declines towards the escarpment or the lateral bounds of the valley, because there is usually underground supply from the surrounding marine terraces, carved in clayey sediments of the Patagonia Formation (Fig. 25).

Alluvium permeability varies according to grain size, selection, package and presence of matrix or cement. In general, the sediment is friable sandy gravel, with inter-bedded sand or sandy-silty-clayey levels. Grain size decreases from headwaters to the lower parts of the basin, creating a concomitant reduction in

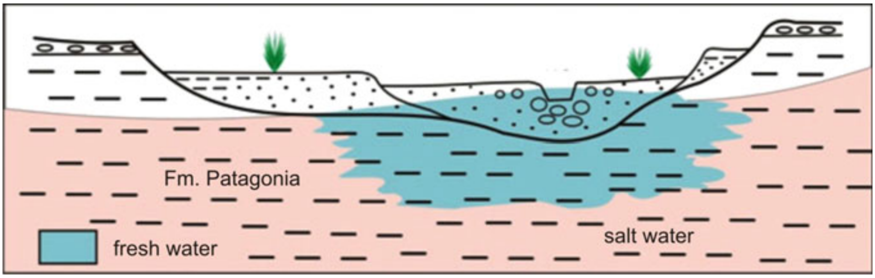


Fig. 25 Patagonic valley profile

permeability whose extreme values are between 700 and 10 m/d. In zones lacking coarser sediments, that is, those composed only of fine-grained deposits, permeability lowers to 0.1 m/d.

2 Coastal Plains

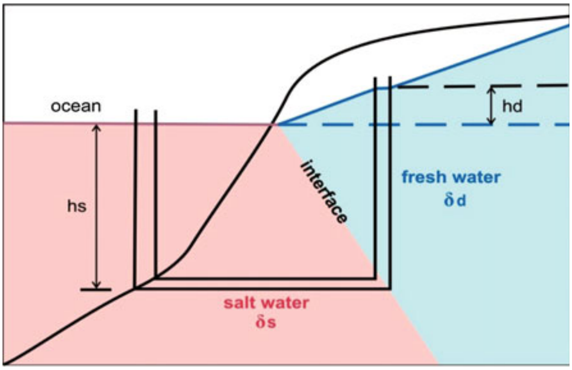
Virtually the entire Atlantic Ocean coast of Argentina is composed of different types of coastal plains. In the Province of Buenos Aires, the coasts are low, with wide sandy beaches. Farther south, the Atlantic Ocean coasts are restricted with cliffs and beaches composed of gravel and pebbles of the Patagonian environment.

Between San Antonio Cape and the southern portion of Buenos Aires Province, there is a coastal plain characterized by an almost uninterrupted belt of dunes of 30 m of maximum height. The dunes occupy a belt of up to 10 km wide and they are formed by well selected fine and medium siliceous sand, derived from the wave action of the sea on the sandy silts of the "Pampeano Sediments", also known as the "Pampeano Formation". The sandy dunes are home to an important unconfined aquifer that is the main source of water supply for most cities and seaside resorts of the region. Lack of cement and high sorting due to wind make up both the effective porosity (Ep) and permeability (K) of this sandy unit, reaching high values (Ep = 20 % and K from 15 to 100 m/day).

Groundwater is generally of good quality, because the recharge occurs in situ from rain. The underground flow is short and the siliceous component provides little opportunity for dissolution. Frequently, however, there are areas with higher content of iron in solution with pH neutral to acid waters, due to the presence of organic matter. Biological pollution and contamination derived from salt water intrusion of marine origin are the most serious problems affecting these aquifers. Biological pollution derives from the rapid infiltration of sewage and poor filtering process, provided by the sandy soils. The second type of contamination is a product of salty groundwater intrusion by declining water table levels, due to over-exploitation.

Fresh water keeps an elevation ratio to salt water, as a result of density difference between them (Fig. 26).

In an isotropic and homogeneous medium, this relation means that for every 1 m of fresh ground water located above sea level, there would be 40 m of freshwater below it. This equation, developed by Ghyben and Herzberg in the late 19th century, assumes a hydrostatic equilibrium, regardless the movement of groundwater, in a way the depth of the interphase thus calculated is somewhat less than the actual one, but it is easy to apply and generally gives good approximation for practical purposes. However, the deviation between the ideal and actual components requirements, in some cases makes that the equation loses applicability. These are the conditions in the Buenos Aires Atlantic Coast, where underneath the dunes there are fine grained sediments (silt and clay) of marine origin which significantly limit the available thickness of fresh groundwater.



$$hs.\delta s.g = hs.\delta d.g + hd.\delta d.g$$

$$hs.\delta s - hd.\delta d = hs.\delta d \qquad hs = \delta d/(\delta s - \delta d).hd$$

$$\text{if } \delta d = 1 g/cm^3 \text{ and } \delta s = 1.025 g/cm^3 \quad \mathbf{hs = 40.hd}$$

δd: fresh water density   δs: salt water density

Fig. 26 Fresh water—salt water relationships

3 Methods and Techniques for Hydrogeological Studies

The choice of methods, techniques and assessments used in hydrogeological surveys depends not only on the type of aquifer and environmental characteristics to be studied (intermountain valley, coastal plain, piedmont plains, etc.), but also on the amount, quality and density of the available information. For instance, the geophysical prospecting techniques are rarely used in those areas where the presence of numerous groundwater tapping makes possible the measurement of water levels, the sampling of water and even conducting pumping tests on already existing wells. As a counterpart, if the environment to study has not been widely drilled or if it has a limited amount of drilling done, underground exploration must have the support of geophysics studies and exploration wells executed for that purpose.

The following description is made with the purpose of providing an overview of the most frequently used method in the exploration and evaluation of groundwater resources.

3.1 Background Data Collection

This step refers to the identification, analysis and selection of existing information regarding the study area, including:

- mapping basis, both topographical and geological
- aerial photographs and satellite images
- rainfall, fluvial, snow and climate records
- geological reports

- surface and groundwater hydrology reports
- well logs
- geophysical surveys

3.1.1 Topographic Maps

The topographic maps allow the delimitation of the area, to locate the settlements and roads, establishing the identification of water itineraries and distances travelled. The maps also facilitate the vision of the major topographic features (mountain ridges, plains, valleys and rivers, estuaries, lagoons and marshes, piedmont slopes, etc.).

If the map has contour lines or isohypses, altitudes, height differences and topographic slopes can be established. In some cases, they show, if adequate symbols are used, the position of groundwater tapping as mills, dug wells, boreholes, dams, water intakes, etc., and the areas of natural discharge as springs, meadows, lakes and marshes.

The topographic charts provide the basis for hydrogeological mapping, because the bases to be used in the elaboration of piezometric, hydrochemical, structural and isopach maps are obtained from their information.

In spite of that, there are no unified criteria regarding the name that should be given to the hydrogeological maps based on the scale of the topographic maps. However, the following nomenclature is generally adopted (Auge 2003a):

Scale of the topographic map	Name of the hydrogeological map
1:500,000 and smaller	Regional
1:200,000–1:500,000	Reconnaissance
1:50,000–1:200,000	Semi-detailed
1:50,000 and greater	Detailed

Generally, for the purpose of field surveys, more detailed scales are used than those employed for the final elaboration of the hydrogeological map, in order to minimalize possible errors; it is advisable that the reduction of the map scale is at least twice. For example: field map of preliminary scale 1:50,000 and laboratory map or final scale 1:100,000. The above classification refers only to the final scale.

The surface geological maps result extremely useful for the work of the hydrogeologist, because outcrops of the geological formations are represented in them. A stratigraphic formation brings together a group of similar lithological units. Therefore, with the base of a geological map and a field survey to establish the hydraulic properties of such units, it is possible to identify hydrogeological environments at a glance.

The hydrogeologist is usually interested in learning about the behaviour of the exposed rock units according to their ability to store and transmit water. Therefore, a hydrogeological map may differ substantially from a geological map of the same area. Thus, the regional geologist may include into the same formation two

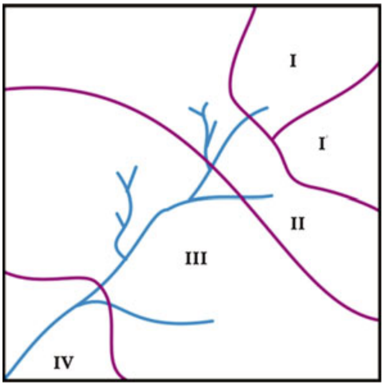


Fig. 27 Hydrogeological map. *I* Massif granite; *aquifuge*. *I′* Very fractured granite; it can storage and transmit moderate amounts of water; *discontinuous medium*. *II* Shales; *aquiclude*. *III* Clayey sandstones; their behavior can vary between *aquitard and aquifer of low permeability*. *IV* Conglomerates with silty sand matrix, in parts cemented by carbonates; *aquifer of medium to high permeability*

separated, superimposed lava flows, whether or not they have o have not alveolar structures and fractures or cracks.

The hydrogeologist, on the contrary, pay special attention to differentiate the units composed of massive volcanic flows, from those with cavities or alveolar holes, fractures and/or joints, which can give higher secondary permeability to the volcanic rocks, such as basalts.

Conversely, the geologist can distinguish stratigraphic units having the same hydrogeological behaviour; for example two sequences of clayey sandstones of different colour and age, separated by an unconformity, but with similar effective porosity and permeability (Figs. 27 and 28).

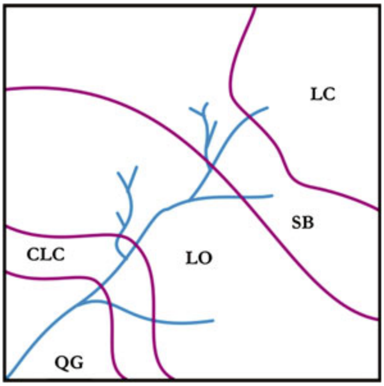


Fig. 28 Geological map. *LC* Los Cóndores Formation; Precambrian granites. *SB* San Bernardo Formation; Ordovician shales. *LO* Los Olleros Formation; Devonian clayey sandstones.*CLC* Cerro La Capilla Formation; Permian clayey sandstones. *QG* Quebrada Grande Formation; Tertiary conglomerates

3.1.2 Aerial Photographs and Satellite Imagery

These images are captured at different heights from the terrain surface, depending on the purpose of the work and scale needed, which is inversely proportional to the elevation of the obtained record. Using aerial photographs, relief or stereoscopic vision may be obtained, with a 30 % lateral overlap and 60 % in the direction of the flight (Fig. 29).

Satellite images are a very important contribution to the available remote sensing techniques. Landsat 7, a satellite for natural resources assessment, now in orbit at 705 km of altitude at the Equator, passes through the vertical position of the same place every 16 days, taking images of the Earth's surface, with a coverage that varies depending on the latitude, but which it is in the order of 32,000 km^2 in every image (generally 185 km by 175 km). The advantages of these images over the aerial photographs are the following (1) they cover a much larger area; (2) the elevation of the record virtually eliminates the possibility of obliquity deformation; (3) they may repeat the view of a certain place with time in a regular manner, to appreciate variations that the landscape may show in different seasons or under different climatic and hydrological conditions. In addition to Landsat, other presently orbiting satellites are SPOT (France), Cosmos (Russia) and ERS (European Community), all of them oriented to the assessment of natural resources and/or processes.

Using aerial photographs, the contacts between geological units may be accurately traced, for instance, the contact between surficial alluvial materials and crystalline rocks that make up the main body of a mountain, to stereoscopically distinguish different levels of alluvial terraces, or to identify structural features in the region such as folds, faults and joints. It also may be appreciated the drainage landforms and their characteristics, the areas of natural discharge, and any suitable environments for recharging, etc.

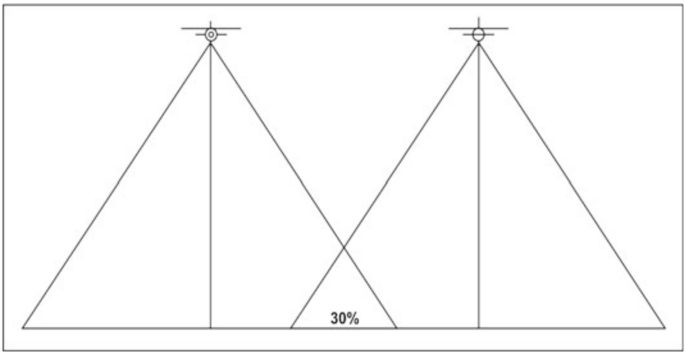


Fig. 29 Aerial photographs—overlap

Satellite imagery provides regional information thanks to their scale (1:1,000,000 or less). Therefore, they are most useful for the identification of large geomorphological, hydrological and structural features as mountain or highland chains, alluvial fans, rivers with its main tributaries, smaller streams, ponds, marshes, faults and major folds, etc.

3.1.3 Hydrological Balance

The records of rainfall, fluvial discharge and snowfall are useful to determine if there is surplus water in a certain region that can lead to groundwater recharge. The preliminary purpose of all hydrological study is to develop a **water or hydrological balance**. That is, to determine the flux in and the flux out of water in a hydrological system of known extension (surface watershed or groundwater basin, lake, wetlands, physiographical region, etc.) for a certain period of time. In the calculation, the net change in stored water should be included. In its simplest form, the water balance, governed by the basic principles of mass conservation, can be written:

$$I - E \pm \Delta S = 0$$

where

I Inflow (enter)
E Outflow (outlet)
ΔS Variation of stored water (+ if it increases, − if it decreases).

3.1.4 Geological Reports

Geological and topographical sections and petrologic, stratigraphic and structural descriptions, accompanying geological reports, are very useful for the interpretation of the underground hydrological behaviour of a certain region. The petrographic aspects have been mentioned above, when dealing with surface geological maps.

However, it must be noted that the ionic content of the groundwater depends largely upon the mineralogical composition of the geological units in which it flows. Therefore, knowing the ionic content is also important to understand the origin of the components in solution and to predict their changes in the future.

Groundwater in granite environments is usually rich in SiO_2, somewhat acid, low in salts and high in K^+. In basaltic environments it is common to find Fe^{++} and Mg^{++} and in calcareous areas, Ca^{++} and CO_3H^- dominate. In clayey sediments, waters are usually sodium chloride.

These considerations, however, should be taken only as indicative, as well as with lithology, since the type and ionic concentration of groundwater will be dependent upon climate, travel time, age and depth with relation to the surface.

The geological structure controls largely the underground hydrodynamic behaviour. Faults and folds can modify the hydraulic gradients and in some cases, they may even change or reverse the flow directions.

3.1.5 Hydrological Reports

The relevant importance of the underground environment is clearly understood. Surface data, especially with regard to maximum, minimum and mean stream flow, as also the variations between flow gauging stations, are of great interest because they may indicate discharge losses or gains, to or from the studied aquifer. Besides the river type (whether it is permanent, temporary or ephemeral) is highly indicative of the relationship between surface water and groundwater.

3.1.6 Well Logs

The well logs usually have a lithological description of the aquifer, aquitard and aquiclude, and include pumping tests with static and dynamic levels, water drawdown and chemical composition of the layers tested and those on exploitation. Data on grain size, mineralogy and electrical logs are not frequent. Either way, these logs are the most reliable information to interpret the underground hydrological behaviour, in both the hydrodynamic and hydrochemical aspects.

3.1.7 Geophysical Reports

The geophysical reports generally provide information about the sub-surface structure. Sometimes, if there is information about the lithological composition, it can help with the interpretation of the hydrogeological behaviour. Concerning prospecting, the geophysical methods most commonly used in hydrogeology are herein described.

4 Hydrogeological Survey

The hydrogeological survey consists of the identification, measurement and sampling of groundwater and the surface sources. In rivers, expeditious stream gauging is normally carried out by using floaters or current meters. These data allow the calculation of the velocity of the stream which, if the cross section at the site is known, provides the yield of the stream at the study locality. An expeditious stream gauging should be taken only as indicative, since the average, maximum or minimum flows may significantly differ from those recorded during the survey.

In groundwater tapping (wells or boreholes and dug wells) both hydraulic level and well depth are measured. The first value, after elevation is marked, enables the mapping with equipotential curves. This is essential to determine the direction of flow, the hydraulic gradients and overall dynamic behaviour of groundwater. The springs should be carefully surveyed, indicating its characteristics, amount, form and flow. They represent sites of natural groundwater discharge and thus they should be included as a factor in the development of loss of balance. It is also important to know the temporary stage of the springs (perennial or intermittent) and its temperature (thermal and non-thermal waters).

Samples of surface water, groundwater and springs, are used in the field, to determine pH, electrical conductivity and temperature.

Afterwards, samples are selected from field determinations, as the geological context and the position in the underground travel, for chemical and bacteriological analyses.

Another task carried out during the hydrogeological survey is to recognize and adjust the boundaries of the units mapped in the laboratory, using aerial photographs, satellite imagery and geological maps.

4.1 Pumping Tests

Customarily, the pumping tests are performed in existing wells. If there is planning to carry out exploratory drilling, one of its main purposes is precisely conducting pumping tests. The aim of these tests is to determine the magnitude of the hydraulic parameters of the tested aquifers, such as permeability, transmissivity, storage, effective porosity, and the behaviour of the wells (data on yield, drawdown, specific yield and efficiency).

The aquifer tests can be differentiated according to their dynamic, in tests of drawdown and recovery, and according to the stability of their yield, in constant and step-drawdown tests (Kruseman and de Ridder 1990).

There are theoretical requirements which the aquifers, the flow and the wells must satisfies, to provide appropriate test results, such as: homogeneity, isotropy, constant thickness, extension, laminar flow, negligible borehole size and efficient well. These conditions do not usually take place in practice, which ultimately produces a deviation between the actual and calculated values of the hydraulic parameters. However, the deviation is generally not accentuated and therefore the tests provide representative values (Auge 2008a).

The advantage of this methodology with respect as those used in laboratories (by permeameter or porosimeter) is that the tested materials are in situ and therefore do not undergo the inevitable alteration caused by sampling.

4.2 Hydrogeological Exploration

Hydrogeological prospecting can be done in several ways. Surface techniques have been already mentioned (such as geological and hydrogeological survey, aerial photographs, satellite imagery and water balance). Geophysical and drilling techniques are very useful regarding the accurate knowledge of the underground.

The geophysical techniques measure some natural properties such as magnetic susceptibility, density, electrical conductivity, potential, and elasticity. However, to get proper results some basic assumptions must be considered which derive from geological or hydrogeological knowledge and should also be a good control of the magnitude of the natural properties to be measured.

Wells provide more reliable data, but their biggest disadvantage is their very high cost. Nevertheless, the culmination of all hydrogeological survey should include the execution of one or more exploration drilling, whose location is chosen based upon surface studies and geophysical techniques. Unfortunately, the exploration drilling is rarely performed.

4.2.1 Geoelectrical

Are the most widely used techniques in geophysical prospecting of groundwater. Magnetometry and gravimetry, although cheaper, are of little use due to their lower resolution power. The seismic studies generally provide good definition, but they are expensive for hydrogeological investigation. Recently, microseismic techniques have been developed, with significantly cheaper cost. It is hoped that in a short time these techniques will be commonly used in hydrogeology research.

4.2.2 Gravimetry

It is based upon the measurement of variations in rock density for which three types of instruments, gravimeter, pendulum and torsion balance, are used. The prospections are quicker and cheaper and they are usually combined with the magnetometric methods, which provide adequate information about the deeper structure of the sedimentary basins. It is often used in oil exploration but it is still of little use in hydrogeological surveys.

4.2.3 Magnetometry

It's based upon the measurement of changes in the Earth's magnetic field. These are the faster and cheaper of all geophysical techniques. For determinations, a magnetometer is used. In general, it is applied in mineral prospecting. Its usefulness in combination with gravimetry has been noted. However, it is seldom used in hydrogeology.

4.2.4 Seismic

These are the most accurate and potentially most useful geophysical methods. Seismic techniques do not measure natural force fields, but the reaction of the geological units to vibrations which have been artificially produced. Definitively, these studies may identify variations of elasticity which result in higher or lower velocities of propagation of seismic waves.

Seismic methods are of two types: refraction and reflection. The refraction technique is the most widely used in hydrogeology. The reflection seismic prospecting is used for hydrocarbon exploration and it is much more expensive.

The vibrations produced with explosives, knocks or vibrators are detected by recorders (called “geophones”) located at different distances from the point of vibration. The record is the time that takes the wave to travel a given distance and therefore, it is related to its propagation speed. The consolidated materials (rocks) have higher propagation speeds than unconsolidated materials (sediments). Since consolidation usually increases with depth, the method is able to detect the position at which those changes occur.

Seismic refraction can identify the type of structure, the dip of the beds and the changes of lithological facies. It is particularly useful to locate the depth of the water table and to determine the thickness of the alluvial filling in foothills and mountain valleys. In the first case, it is due to increased propagation speed in saturated sediments related to non-saturated or sub-saturated materials. In the second case, it identifies the stark contrast between the speed of propagation in between bedrock and alluvial sediments.

4.2.5 Geoelectrical Techniques

This is the geophysical technique that provides most jobs in hydrogeological prospecting. Two types of electric potential can be measured. One is the natural potential difference between two points on the ground and the other the difference artificially produced by injecting an electrical current into the ground (resistivity). Both resistivity and spontaneous potential can be recorded with the same instruments.

Different electrode arrangements are used but the most employed are those of the Wenner and Schlumberger methods. In the first case, a constant spacing between the outer or current electrodes and the inner or potential ones remain. In the Schlumberger device, the distance between the potential electrodes is much smaller than that separating the current ones (Fig. 30).

The Wenner device provides a more direct relationship between the electrode spacing and the depth of penetration of the current. The Schlumberger device, for a given separation of the outer electrodes, allows a clearer definition of the sub-surface conditions.

The resistivity of the geological units varies over a wide range. Thus, for instance, massive granite can give values of 10^6 Ωm and a clayey bed saturated with

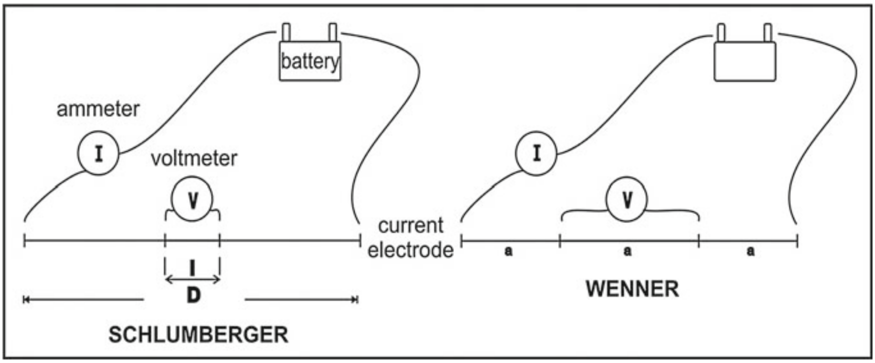


Fig. 30 The Schlumberger and Wenner electrodic devices

brackish clay only 1 Ωm. Generally dry rock or sediments have higher resistivity whereas if they are saturated, the resistivity markedly decreases, because the dominant current flow is conducted through the water. Therefore, the magnitude of the resistivity depends on the porosity of the material, its degree of saturation and the chemical composition of the saturating fluid.

The geoelectrical techniques have been successful in the detection of the saltwater-freshwater interface, the location of the base rock underlying the alluvial filling in intermountain valleys or in the piedmont and in the identification of gravel or sand paleo-channels carved in fine grained sediments.

The location of the water table below the ground surface is difficult to solve, due to variation in the degree of saturation which normally presents the aeration or non-saturated zone. In this regard, much greater accuracy is achieved by the seismic refraction techniques.

Electrical tomography is a technique recently developed, that uses 20 or more electrodes connected by an "intelligent cable", which allows to change electronically the layout and the distance between them (Auge 2008b).

4.2.6 Wells

As it has already been stated, the drills provide the most reliable data about the sub-soil hydrogeological conditions. Through them, proper information can be obtained about the behaviour of the traversed units in relation to their ability to store and transmit water and its quality.

Depending on their objectives, drills can be classified as **exploration** and **exploitation** wells. The former ones are for prospection and exploitation drills for the use of groundwater. Sometimes, exploration drilling can become later of exploitation or operational nature, if the hydrogeological conditions are correct and the construction characteristics of the borehole permit it.

The techniques more used to drilling are rotation and percussion. The combination of both (the roto-percussion techniques) gives good results in hard rocks (such as basalt, granite or rhyolite) and coarser alluvium (sandy gravels and boulders).

The characteristics of each technique are not detailed here; therefore, for information purposes only, it may be said that the **cable percussion** drilling allows a more representative lithological sampling than the hydraulic rotary technique. They are also highly accurate for identifying aquifers, allowing an adequate water sampling and an appropriate record of their static levels. The main disadvantages of the cable percussion system are that it is very slow and the need of using large section lengths and varied pipe diameters, most of which cannot be recovered later on, after drilling completion. All this leads to a relatively higher cost.

The main advantage of the **hydraulic rotary** drilling is its rapid advance, particularly in moderate resistance sedimentary rocks (siltstones, shales, sandstones, limestones) and their unconsolidated equivalents (silt, clay, sand, calcareous crusts). The most obvious disadvantage of this system is that the well needs to be filled with liquid to allow drilling. This is called drilling fluid and sometimes it contains artificially added clays (such as bentonite) and other materials. It also may have clays which have been naturally incorporated from the drilled terrains. The presence of liquid fluid makes it extremely difficult to identify the productive layers during drilling and this identification needs to be done indirectly by the lithological characteristics of the samples, which are known as the **cutting**.

The cutting drill is crumbled by the bit due to which is less representative of the natural lithological characters. As an example, it may be mentioned that the appearance of sand at the well head is a preliminary indication of the existence of a productive layer. Another drawback of this technique is that the drilling fluid or injection can invade and cause serious damage to the penetrated hydrogeological units. When bentonite is used, it forms a plaster or mud-cake on the wall of the borehole reducing significantly the permeability of the invaded zone. The plaster usually is hard to remove and it is quite common that the aquifers significantly reduce their yield and in some cases, it may inhibit exploitation. Removal of mud-cake, cleaning the invaded zone and removing formation fines, that is, the development, are the foundations of a successful hydraulic rotary drilling with respect to its efficiency

Rotary-percussion system uses compressed air for driving a bottom hammer (like jackhammers for the settlement of the streets), which hit and tour. The crushed material is dragged to the well head by the air stream in its upward return. The system loses efficiency when the hydraulic load in the background is greater than 10 $\mathrm{kg/cm^2}$ (100 m below the water table). The samples are of poor quality, because they have been crushed. This method allows a precise identification, but only of the position of the water table. Progress is significantly higher than the rotary and percussion techniques in compact rocks, gravels and boulders, but the rig is much more expensive because it needs the use of larger compressors.

The following records must be completed in all drilling techniques, but those of the rotary system are used as a model, because they are the most widely used in hydrogeological prospecting (Auge 2005a):

(a) **Lithological sampling (cutting)**: one sample is obtained per each meter drilled and all lithological changes are usually sampled. This is one of the main indicators of the underground hydrological behaviour. It allows differentiating aquifers from other units which in principle are not obvious, such as aquitards and aquicludes.

(b) **Advance speed or timing**: the advance speed determines the rate of penetration of the drilling tool. Normally, the time it takes to penetrate 1 m is recorded in the log. It is the first indication that a change in the sub-soil characteristics is received at the surface.

(c) **Sampling injection**: the electrical conductivity of the injection or drilling fluid is measured at regular intervals; to unify this with other records every 1 m of drilling. A noted change (either an increase or a decrease) indicates the presence of a layer with water more or less saline compared to the injection.

(d) **Weight of the drilling tool**: it is very useful technique if the rig has a tensiometer to measure the weight of the suspended drilling column because, by difference, the load at the bottom of the drill can be estimated. This technique is used to adjust the advance speed.

(e) **Rotation speed of the rotary table**: This speed has influence also on the velocity of advance of the drill bit; therefore, it is used to keep the rotation speed as uniform as possible.

(f) **Return speed injection**: This parameter is important for the lithological sampling and injection itself, because increasing depth also increases the time that takes injection to reach the well head. It is generally determined by calculating the speed depending on the useful diameter of the well and the flow injected by the injection pump. Sometimes, rice is used as a physical indicator of the movement.

(g) **Electrical logging**: There are different types of logs that are made in the wells. Some of them are obtained from natural or artificially induced currents and others by natural or artificial measured radiation, sound propagation, etc., but, usually, the set is grouped under the name of electric logging. Although they are commonly used in drilling for oil, they are much less frequent in water drilling, which essentially records spontaneous potential and resistivity; the gamma rays log is much more rear.

The Spontaneous Potential method, also known as “self potential”, may allow the appreciation of the position of the sandy beds and in very widespread layers, variations in its permeability. With the resistivity technique, the changes in the salinity of the groundwater may be ascertained. The log of gamma rays provides the limits of the clayey layers.

Both conventional and electrical logging, as it has been previously mentioned, should be analyzed together and not in an isolated manner, because an interpretation with a lesser chance of error is that one which arises from the use of the largest possible number of simultaneous records.

Finally, water sampling and pumping tests should be cited, usually performed after isolating layers with high salinity. Although it is convenient to place filters on the tested sections, the cost of this procedure and the time it takes to its handling make the tests frequent in open holes (without filters). This procedure results in reduced flow and it must increase the risk of collapse of the well. The pumping tests are of the type referred to in Sect. 4.1.

4.3 Hydrogeological Mapping

Hydrogeological maps derived from data obtained in the field survey, but the development is made in the laboratory. In general they are used to spatially characterize the hydrodynamic and hydrochemical properties of the underground water system.

From the maps depicting hydrodynamic characteristics, those maps with equipotential curves are the most important. For its construction, it is necessary to refer to the same reference plane the water levels in all measurement sites. The reference plane generally used is the average sea level. Other reference planes as levelling points are used in each country; for instance, in Argentina the zero of the National Geographical Institute (IGN), the zero of the Riachuelo tide-recorder in the city of Buenos Aires, the zero of the Peristyle of Buenos Aires Cathedral, etc.

Equipotential curves allow the identification of the position of groundwater recharge and discharge areas and to establish preferential flow directions and hydraulic gradients. The morphology of the water table or piezometric surface is clearly established and can also determine the relationship between groundwater and surface water (effluent, influent and isolated rivers). If the transmissivity (T) is known, the flow rate can be estimated through a selected section and if permeability (K) and effective porosity (Pe) are known the effective speed (Ve) of groundwater flow may be calculated.

The equipotential lines arise from the intersection of equidistant horizontal planes and the phreatic or the piezometric surface. In the first case they are also called isophreatic curves (Fig. 31) and in the second case, they are known as isopiestic curves (Fig. 32). Ultimately, they reproduce the shape of the groundwater surface, similarly to the contour lines which represent the topography landforms.

The combination of equipotential curves and prevailing direction of groundwater flow, which are represented by arrows perpendicular to the equipotential surface, is called the flow net. Interpretation of the flow net can be establish directly: recharge, discharge and flowing areas; flow directions; hydraulic gradients; shape of the actual hydraulic surface (phreatic) or virtual (piezometric).

Indirectly, if T, K, Pe and the saturated thickness are known, it may be determined: groundwater yields, flow speeds, changes in permeability, transmissivity, section of passage and structural behaviour.

Regarding its shape in plan, hydraulic surfaces (phreatic or piezometric) can be classified as: (1) flat or plane (Fig. 33), (2) cylindrical (Fig. 34) and (3) radial, and the latter as convergent (Fig. 35) and divergent (Fig. 36). The profiles are classified into (1) linear (Fig. 37), (2) parabolic (Fig. 38) and (3) hyperbolic (Fig. 39).

Flat forms rarely occur in nature as the medium for their presence should be homogeneous, isotropic, of constant thickness and uniform movement of

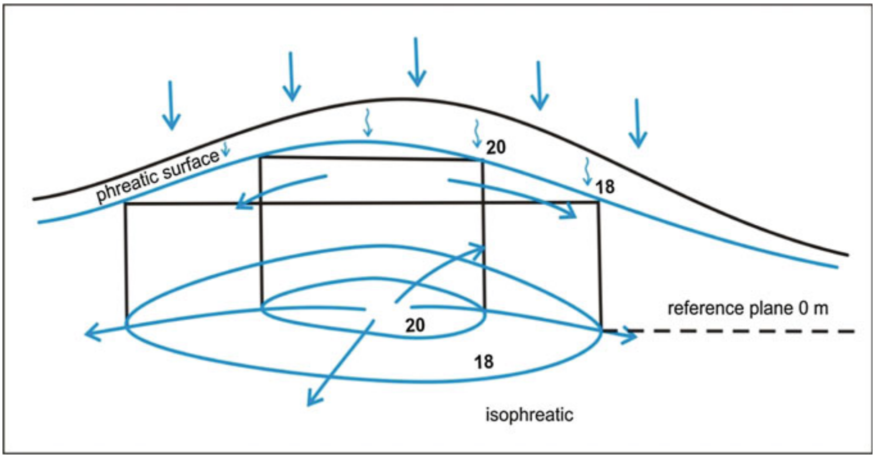


Fig. 31 Profile and phreatimetric map

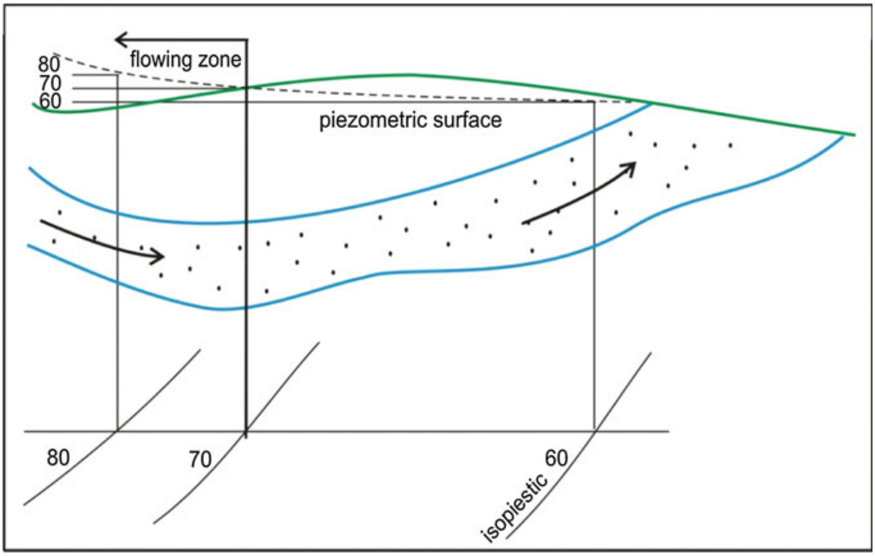


Fig. 32 Profile and piezometric map

groundwater. These forms appear in restricted sectors of larger areas, where hydraulic surface as a whole has another behaviour, essentially of the radial or cylinder-shaped types.

Fig. 33 Flat hydraulic surface

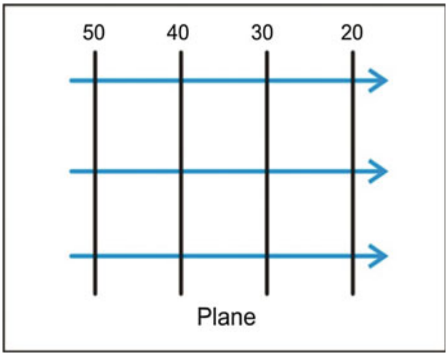


Fig. 34 Cilindric hydraulic surface

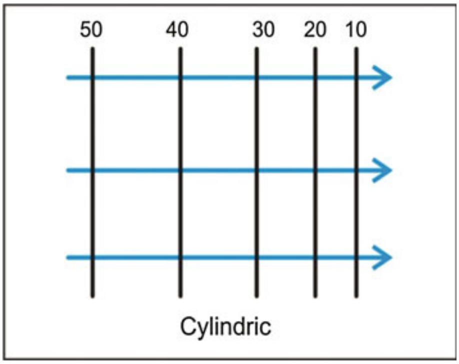


Fig. 35 Radial-convergent hydraulic surface

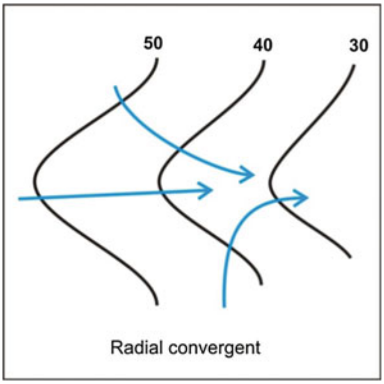


Fig. 36 Radial-divergent hydraulic surface

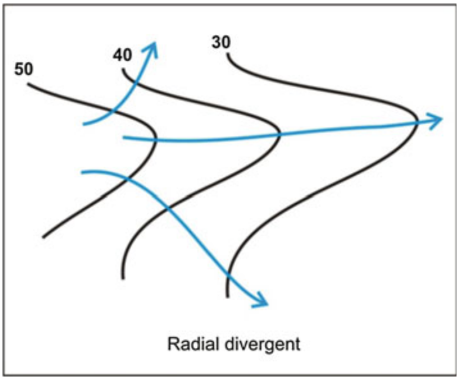


Fig. 37 Linear hydraulic profile

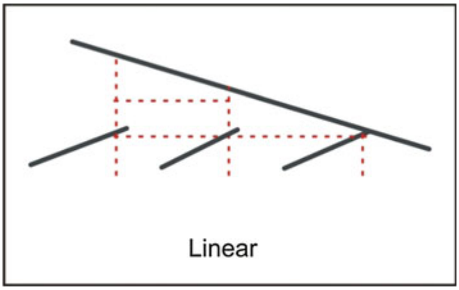
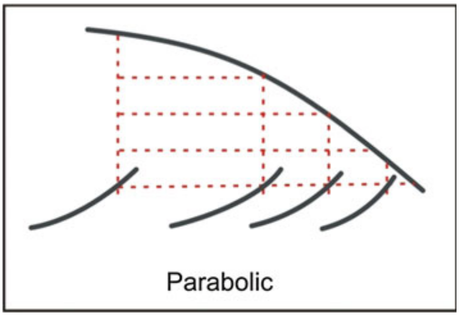


Fig. 38 Parabolic hydraulic profile



The most common **cylindrical shapes have a parabolic profile**, but also they are rare in nature and are linked to free aquifers, with reduced transmissivity in the direction of flow, or the presence of lineal discharge areas. As in the previous case they typically represent local behaviours which evolve regionally to radial forms.

Radial forms are the most common forms in nature because the groundwater is recharged in environments of preferential infiltration, from where it migrates

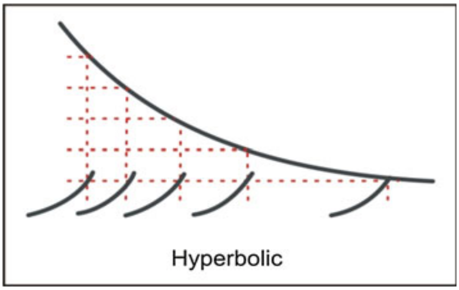


Fig. 39 Hyperbolic hydraulic profile

laterally to discharge sites. **Diverging radial shapes** indicate recharge areas or dispersion and areas of **convergent radial flow** depict discharge or concentration of groundwater flow.

Parabolic or hyperbolic profiles derived from various causes. If the flow is more or less uniform along the path, an increase gradient in the flow direction (parabolic profile) results from a decrease in transmissivity. This may be due to a decrease in: permeability, the saturated thickness, the passage section, or a combination of all, one, or some of these parameters. Under the same regime of uniform flow, **hyperbolic profile** is a product of increased transmissivity due to increases in: permeability, saturated thickness, or transient section, individually, or in combination.

Figure 40 represents the **flow net of water table or phreatic aquifer**; a recharge zone, a discharge zone and the main directions of groundwater flow are indicated. The recharge area is radially divergent with hyperbolic trend. The discharge, which coincides with the river, is radial convergent, but of the parabolic type. The latter may be due to increased yield in the flow direction and longitudinal reduction in passage section. Flow net also shows that the river is effluent (that is, it receives input of groundwater).

Another utility map in the interpretation of the underground hydrodynamics is that it reproduces the **depth of the water table** (Fig. 41). In areas of natural discharge the water table is emplaced at shallower depths than in recharge, and in the flow ones, is located in an intermediate position. Isodepth contours of the water table also indicate the thickness of the aeration, non-saturated, or sub-saturated zone.

If the aquifer is free or of the phreatic type, the **saturated thickness map** is derived from the comparison between the **map with equipotential contours** and those maps with **isodepth of the bottom of the aquifer** (Castany 1974).

Usually, it has more information on the position of the water table than to the floor or bottom of the aquifer. Therefore, sometimes, for saturated thickness or isopach of a free aquifer, an approach depth to its floor is assumed. This map allows, together with the effective porosity value, to set the volume of the effective reserve. For example, if an aquifer with a total volume of 20,000 hm^3 comes from the thickness map it possesses effective porosity of 15 %, the volume of stored water drained by gravity could theoretically amount to 3000 hm^3. In practice, not all the stored water can be removed due to technical limitations and natural

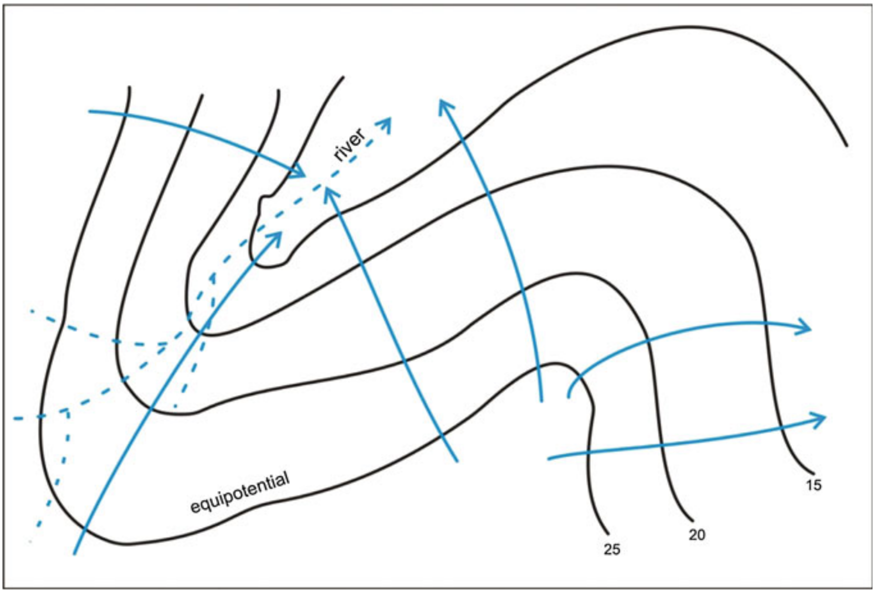


Fig. 40 Groundwater flow net

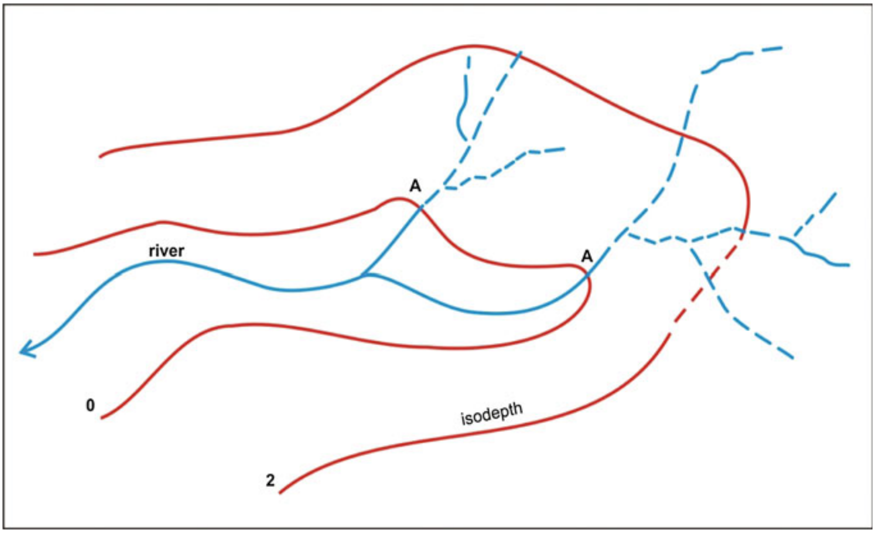


Fig. 41 Water table depth

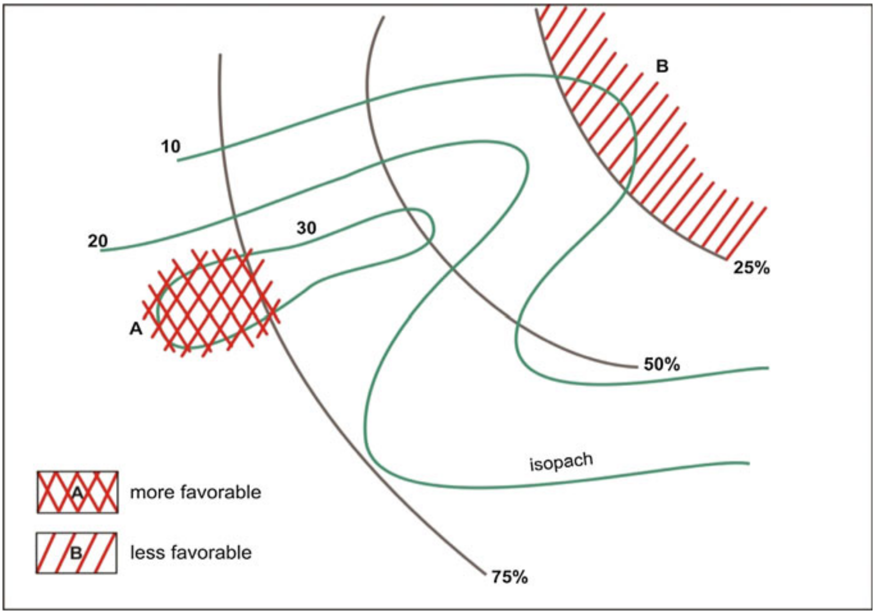


Fig. 42 Saturated thickness and facies maps

hydrodynamics. Generally, these limitations reduce by 50 % the volume of the exploitable reserves, with respect to the effective reserve. Thus, in the case of this example, only about 1500 hm^3 may be usable. When reserves are calculated, it is very important to know the amount of the recharge, if it actually occurs. For information purposes, it may be noted that in extreme cases the volume of recharge in a hydrological year, can reach up to 50 % of the effective reserve.

On a **map of groundwater facies** (Fig. 42), generally the percentages of medium fractions (sand) and coarser sediments (gravel) are represented, related to the total thickness of the formation (Auge 2006). Therefore, it is a map of grain size relationships, where the loose or friable state generates an aquifer behaviour (gravel or sand), compared to the fine-grained (silt or clay) of the aquitard or aquiclude behaviour. Based on facies maps, favourable sites can be identified to obtain higher yield rates. These sites generally coincide with the highest percentages of sand or gravel in the area.

A transmissivity map (Fig. 43) marks more accurately than previous parameters (as thickness and/or facies), areas with higher and lower water transmission capacity. It can be prepared from transmissivity values obtained from pumping tests, or combining their permeability with saturated thickness, because transmissivity is the product of permeability and the saturated thickness.

In practical terms, it is difficult to have sufficient pumping tests to develop transmissivity contour maps. Therefore, the most common is that transmissivity

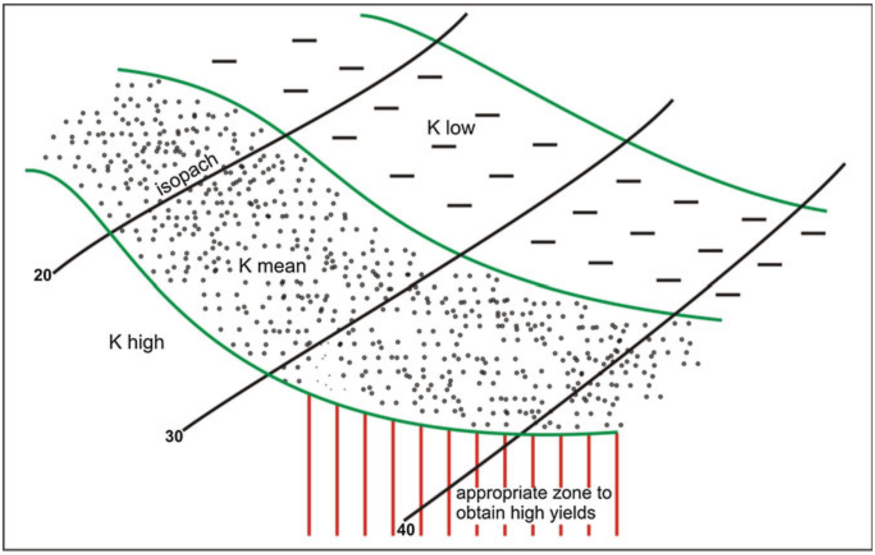


Fig. 43 Permeability and saturated thickness maps

maps are drawn from the thicknesses recorded and the descriptions made in the boreholes. A technique that gives good results is to assign relative permeability to the lithology units as high, medium, low and very low, in correspondence with gravel, sand, silt and clay. This allows, combining these skills with the thickness map, to identify areas most suitable to achieve good yields.

It is important to note that not always the best hydraulically areas are the most favourable for tapping. Technical limitations in some cases, such as distance between capture and consumption site, in other chemical conditions like highly saline water, or problems arising from pollution, force that the choice of locations for tapping should be made also considering these factors.

To set the variation of the **volume stored in a free aquifer**, it is necessary to know the fluctuations of the water table. This, coupled with the effective porosity and the area where the fluctuation occurs, allows the determination of the variation in the amount of stored water.

In a **confined aquifer**, since the storage coefficient is a function of the elasticity of the solid component and also of the water, the oscillation of the piezometric surface does not reflect changes in the volumes stored. In this case, fluctuations are caused by variations in the pressure transmitted over the aquifer or through wells.

In a **semi-confined aquifer**, the fluctuation may be due to a combination of both processes (change in storage volume and in transmitted pressures).

Returning to free aquifers, a map of significant importance is the variation of the spatial position of the water surface (water table) in function of time. This is made

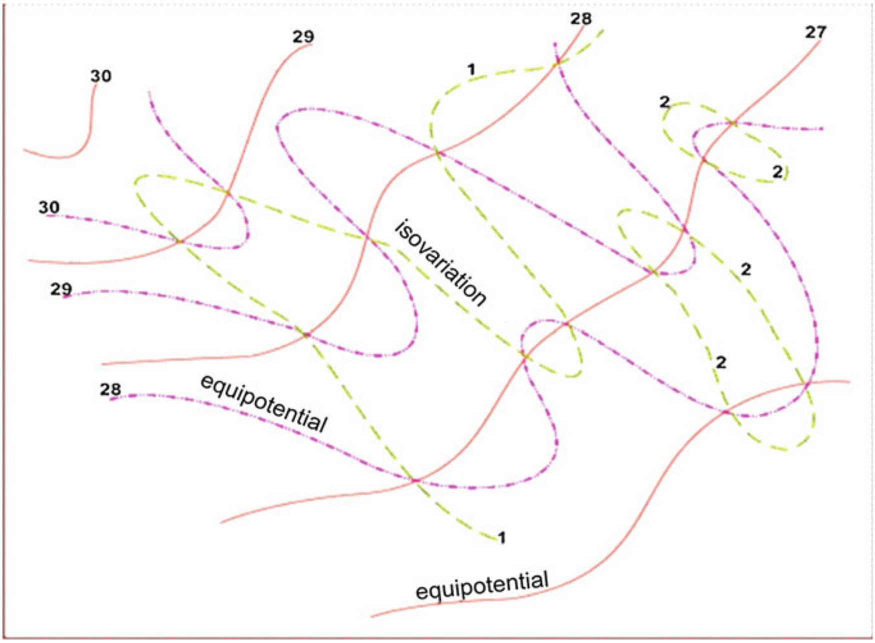


Fig. 44 Equipotential and water table oscillation maps

with contours of iso-variation, from maps with equipotential curves produced at different times.

In Fig. 44, one of the maps was built with hydraulic potential values for the deficit period (minimum height). The other map was prepared with dimensions measured in the period of water excess (maximum height). The residual variation map indicates the hydraulic height difference between the two periods.

Since it corresponds to a general rise between the initial and the final measurement, the water volume has increased and the iso-variation curves have a positive sign. If the variation would have corresponded to a decline, the stored volume would have decreased and curves would have a negative sign. To estimate the change in stored water, in this particular case called the **fluctuating reserve**, it is necessary to multiply the affected area by the effective porosity and by the average height of the fluctuations. In the case of Fig. 44, the surface between the iso-variation curves of 1 and 2 m is 450 km^2 and the average effective porosity of 12 %, the stored water increase is:

$$450\,\text{km}^2 \times 0.12 \times 1.5\,\text{m} = 81\,\text{hm}^3$$

5 Hydrochemistry

Another aspect of great interest in groundwater hydrology refers to the hydrochemistry. Knowledge of the characteristics and evolution of groundwater chemistry is a contribution to clarify its hydrodynamic behaviour. Thus, a similar chemical composition between aquifers located at different depths is an indication of its likely hydraulic communication.

The lateral chemical evolution toward chloride waters generally coincides with the direction of the groundwater flow, whereas in areas of recharge or preferential infiltration bicarbonate-type water dominates.

The chemical composition of ground water derives from the mineralogical components of the sediments or rocks in which it flows, climate, depth, morphology and modifying processes (oxidation, reduction, ion exchange, etc.). Human activity often generates changes to the original chemical composition of groundwater, as regarding salinization by over-exploitation in coastal and in many inland aquifers, nitrate pollution in agricultural regions or in urban areas, salinization due to water table rise by excessive irrigation, metal contamination product of industrial activity, etc.

The most common ions in groundwater (CO_3H^-, Cl^-, $SO_4^=$, Na^+, Ca^{++} and Mg^{++}) are the most used for cartographic elaboration and hydrochemical interpretation. Besides individual maps, that may be prepared with contents expressed in ppm (parts per million), mg/L (milligrams per litre) or meq/L (milliequivalents per litre), it is useful the representation of ion ratios, but in this case the concentrations should be expressed in meq/L.

As stated before, it is accepted in general terms that, in the recharge area, the water is predominantly bicarbonated and towards the discharge area, it tends to be chlorinated, particularly if the flow is of the regional type. In driving or circulating areas, sulphated water may predominate, although this depends on the presence of sulphur compounds on the solid components of aquifers.

From the above, it follows that the Cl^-/CO_3H^- relationship tend to increase in the direction of groundwater flow. However, the mineralogical composition of the materials through which the water flows can change this and other general principles. Thus, if the material is calcareous, calcium bicarbonate waters will predominate and whether there is high proportion of gypsum, calcium sulphate waters will predominate.

The extension of the underground travel is another factor controlling chemical characteristics of water. If the travel is short (short distance between areas of recharge and discharge), water may or may not evolve bicarbonate to chlorinated.

In calcium bearing waters, CO_3H^- is less soluble than $SO_4^=$ but if the water is sodium rich, bicarbonate is much more soluble than sulphate. If water is calcic, the first to leave the solution is the bicarbonate because with a slight increase of it, it will precipitate as $CaCO_3$. Subsequently, if there is still Ca^{++} in solution, it will precipitate sulphates as $CaSO_4$. Chlorides, because of their high solubility index, rarely precipitate and therefore they are more stable at a soluble state. To precipitate

Cl^- it is necessary that the waters reach an ion concentration of brine, several times higher than that of seawater.

Another relationship of interest is that one that links Mg^{++}/Ca^{++}; in sea water this ratio is about 5, but in groundwater it is reversed, giving values less than 1 (typically 0.2–0.6), due to the higher proportion of calcium respect to magnesium minerals in continental sediments. High ratio in coastal aquifers values is an indication of the presence of seawater. The Mg^{++}/Ca^{++} relationship also tends to grow in the direction of groundwater flow, due to the greater solubility index of Mg^{++}.

The chemical composition of groundwater can be changed by biological or physical-chemical action.

In the first case it is quite common reducing the $SO_4^=$ by bacterial action, a situation resulting in negligible content of sulphates in solution. Still much more common, it is the ion exchange water with minerals forming the solid skeleton of the aquifers (or base ion exchange). For example, calcium bicarbonate water can transform into sodium bicarbonate because the dissolved Ca^{++} may evict the Na^+ present in many clayey sediments. Calcium is fixed in the structure of clay and sodium goes into solution. It may be also possible, though less frequent, that the reverse happens, depending on the relative concentration of both in water and sediment.

5.1 Drivers of Groundwater Chemical Composition

Geology. The mineralogical composition of the solid material containing groundwater often prints its chemical property. Thus, flowing through limestone, the water is usually hard due to the presence of calcium and magnesium; the water contained in clays is usually chlorinated whereas that associated with quartz sands has high contents of silica. However, groundwater may also have a different chemical composition of the solid through which flows. The existence of a well-developed soil horizon implies the presence of abundant organic matter and strong biological activity, with production of large amounts of CO_2 which, when combined with water, generates $CO_3H^- + H^+$. This produces bicarbonate water, without influence of mineralogical composition of the soil (Guymon 1994).

Geomorphology. Morphological accidents also affect the chemical composition of groundwater. In humid regions, depressions are discharge sites and therefore the water has higher salinity (for instance, the river valleys of the Humid Chaco-Pampeana Plain). In arid regions, depressions often act as recharge areas and underneath them, the groundwater salinity is the lowest in the region (for example, the river valleys of central and NW Argentina).

Climate. Climate directly affects the water balance, with deficit in arid regions (Evtp > P), which favours the concentration by evaporation and ultimately results in water with higher salt concentration and of the chloride type. In humid regions (P > Evtp), there is excess in the balance and groundwater is generally less saline and of the bicarbonate type.

P precipitation
Evtp potential evapotranspiration

Biotic. Some plants can influence the chemical composition of water; legumes easily fix nitrogen from the air, which causes the associated groundwater to present higher contents of nitrates. *Sporovibrio desulfuricans* bacteria act as sulphate reducing by using oxygen present in the composition of $SO_4^=$ for their biological activity.

Man. Human activity is a factor that tends to alter the chemical composition of water. The processes of pollution from domestic, industrial, urban and rural (agricultural, livestock) discharges, are good examples. Another common process is the salinization of coastal aquifers by overexploitation (for instance, the seashore city of Mar del Plata, Argentina) or continental aquifers with fresh water in the upper section of the profile and salty waters at the bottom (western portion of the Buenos Aires Province, Argentina).

5.2 *Salt Provided by the Rocks*

Igneous rocks. The most common rocks are **granites** among the plutonic rocks and **basalts** among the volcanic ones. The dissolution of the silicates is faster in acid than in alkaline waters, which is favoured by CO_2. The reaction products may generate clays that fixed previously dissolved K^+ (Hem 1959). The water linked to granites is generally little saline and predominantly rich in CO_3H^-, Na^+ and Ca^{++}; SiO_2 may appear in concentrations of 20 to 100 ppm. Normally rNa > rCl and total salt concentration does not exceed 500 ppm. Water related to basalts has less silica than granites (less than 60 ppm), but more Fe^{++} and Mg^{++}. The pH is usually higher due to the alteration of olivine (Custodio and Llamas 1976).

Metamorphic rocks. The water contained in these rocks has chemical characteristics intermediate between those of igneous and sedimentary rocks. The water flowing through schists, quartzites, phyllites and marbles has low tenors in SiO_2 (<30 ppm). The marbles usually generate calcium bicarbonate water.

Sedimentary rocks. The composition of the associated water depends upon the type of rock. Because they have greater porosity than the crystalline rocks, generally they yield water with higher salt concentration.

(a) **Resistites**. They consist of minerals that originate (quartz, mica, resistant silicates). Typical representatives of these rocks are sandstones, sands, conglomerates and gravels. The composition of water can resemble that of the cement or the clasts (grains).
(b) **Hydrolysites**. These rocks (clays and shales) are formed by particles derived from hydrolysis of other rocks. These are rocks of lower permeability and higher total porosity, which generally have brackish or salty water. They abound in Cl^-, $SO_4^=$ and Na^+, but may also have Ca^{++}, Mg^{++} and SiO_2.

(c) **Precipitites**. These are the product of chemical reactions, which lead to insoluble salts (limestones and dolomites). Limestones produce CO_3H^- and Ca^{++}, according to the amount of dissolved CO_2. Dolomites generate CO_3H^- and provide equivalent amounts of Ca^{++} and Mg^{++}; thus, the ratio rCa^{++}/rMg^{++} approximately equal 1.

(d) **Evaporites**. These rocks are formed by the precipitation of easily soluble salts (from minerals such as gypsum, anhydrite and halite), due to evaporation. Associated groundwater has higher salinity. Gypsum and its anhydrous variety (anhydrite) give waters with higher contents in $SO_4^=$, Ca^{++} and frequently Na^+, Mg^{++} and Cl^-.

(e) **Carbonaceuos and bituminous rocks**. The reducing environments contribute to the formation of higher salinity waters with higher concentrations of Fe^{++} and $S^=$. Sulphates are missing or present in very low concentrations, but the higher proportion of CO_2 facilitates dissolution of other minerals such as calcium carbonate and silica, resulting in water with higher contents in CO_3H^- and SiO_2.

5.3 Evolution

In general, the regional groundwater flow (extensive flow), evolves from bicarbonate water in the recharge zone, to sulphated on circulating water and finally to chlorinated, in the discharge zone. Regarding the cation content, evolution is from calcium to magnesium and finally, to sodium.

Figure 45, taken from Custodio and Llamas (1976), shows the hydrochemical ideal evolution of regional groundwater flow.

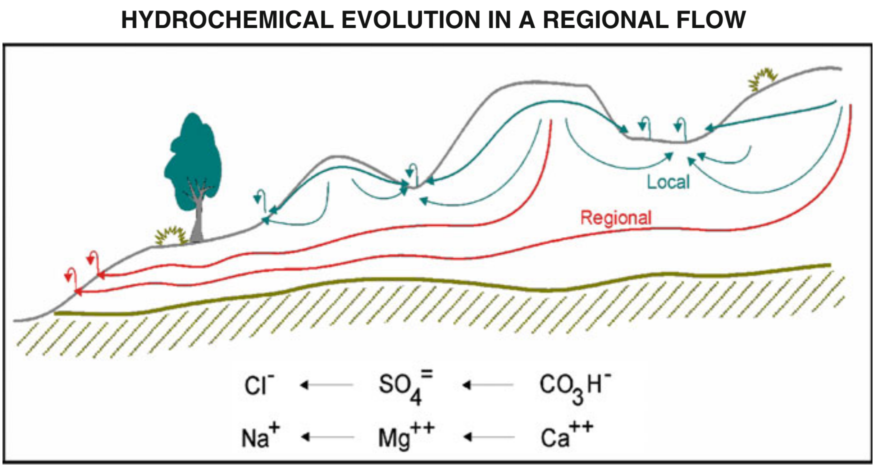


Fig. 45 Hydrochemical evolution in a regional flow

6 Vulnerability

Since Margat (1968) introduced the term “groundwater vulnerability to pollution”, there have been numerous definitions, ratings and methodologies related to it, often aimed at the mapping procedure. To date, however, no consensus has been reached on the scope of the term and, in this sense, there are two major groups.

One of these groups is represented by researchers who consider vulnerability as a property referred exclusively to the environment (such as aquifer type and coverage, permeability, depth, recharge, etc.) without taking into account the pollutant impact. This is known as intrinsic vulnerability. In the other group, those researchers that give, in addition to the behaviour of the environment, the type and importance of the pollutant load (specific vulnerability) are grouped.

There are also differences regarding the usefulness of cartographic representation and whether the vulnerability must be kept in a qualitative framework or move to another quantitative mode. In this respect the IAH (International Association of Hydrogeologists) 29th Congress, held in Bratislava in 1999, opened a sharp dispute between the German and Czech schools, arguing firstly the need to adapt new methodologies to transform the vulnerability into a quantitative variable. The Czech scholars favoured the preservation of the qualitative scope of the term, due to the problem of assigning representative magnitudes to components and processes that affect the aquifer vulnerability.

A brief reference is herein made about the definitions, components and the most widespread methods to characterize the vulnerability of groundwater for contamination and propose two new methods, one for unconfined and another for semi-confined aquifers (Auge 2005b).

6.1 Definition

Vrba and Zaporozec (1994) defined vulnerability as “an intrinsic property of the groundwater system that depends on its sensitivity to human and or natural impacts”. From this definition, it follows that the authors included in the same analysis, both underground system and contaminants, in this last case both artificial and natural.

Foster and Hirata (1991) stated that “the aquifer vulnerability to pollution represents the sensitivity to be adversely affected by a contaminant burden”. In this case, citing an imposed contaminant load, these authors seemed to refer only to pollution of artificial origin.

Custodio (1995) stated that “the vulnerability to pollution expresses the inability of the system to absorb disturbances, both natural and artificial”. Natural or artificial processes occur here again as potential generators of the alteration.

Carbonell (1993) defined vulnerability to pollution as the tendency of the contaminants to be located in the groundwater system, after being introduced over the shallower aquifer. In this case, this author considered only the action of pollutants.

EPA (1991) referred the underground vulnerability to a pesticide, such as the ease with which a contaminant applied on the surface can reach the aquifer depending on agricultural practices used, the characteristics of the pesticide and the hydrogeological susceptibility. This definition, in addition to environmental conditions, incorporates the properties of the contaminant and crop practices (specific vulnerability).

Another concept closely associated with the **vulnerability** is the **risk** of contamination, but it also generates differences in definition, utility and mapping techniques.

Some authors (such as Foster 1987) defined risk as danger of deterioration in the quality of an aquifer, for actual or potential contaminants existing in their environment. Other authors (like Vrba and Zaporozec 1994) assimilated to the specific vulnerability, which refers to the risk of groundwater contamination by one pollutant, or a family of contaminants with similar characteristics and behaviours (nitrates, light or heavy hydrocarbons, pesticides, phenols, metals, etc.).

In the understanding of the subscribed, **intrinsic vulnerability** is more useful in the work of planning land and water uses, particularly regarding the preservation of the quality of the resource, in places where it is not affected, no practices are made such as fertilization, pesticide application, irrigation, concentrated livestock or domestic activities, urban or industrial.

The **specific vulnerability** partially includes the concept of risk, since it refers to the danger of pollution in relation to specific contaminants.

In order to clarify this problem, a simple example has been cited:

(a) Assume a deposit with doors unlocked, located in rural areas, which is very vulnerable due to easy access; however, the risk of theft is low, because in the region there are not vandals.

(b) Then, another deposit in the urban area is taken into account and it is provided with strong locks, padlocks and barred windows. Therefore, it is little vulnerable but it has a higher risk, due to the supposed presence of criminals in the urban environment.

6.2 Methods

The most commonly used methodologies for the qualification and vulnerability mapping are cited here.

6.2.1 DRASTIC

It was developed by Aller et al. (1987) to EPA, in order to assess the intrinsic vulnerability of aquifers. It is a method of widespread use, both for qualification (qualitative assessment) as for mapping and based on the allocation of indices ranging from 1 to 10, according to the characteristics and behaviour of the variables considered in the acronym DRASTIC: **D** (Depth of water table), **R** (Recharge), **A** (Aquifer lithology), **S** (Soil type), **T** (Topography), **I** (Impact due to lithology of the sub-saturated section), and **C** (Hydraulic conductivity of the aquifer).

Index 1 indicates the minimum vulnerability whereas 10 is the maximum.

Apart from what has been expressed, for each variable a certain relative weight is assigned, according to their influence on vulnerability. For the weighted values, indexes between 1 and 5 are used. The cited authors adopted the highest (**5**) for water depth or water table depth (**D**) and lithology of the sub-saturated section (I) and the lowest (**1**) for the topography (**T**).

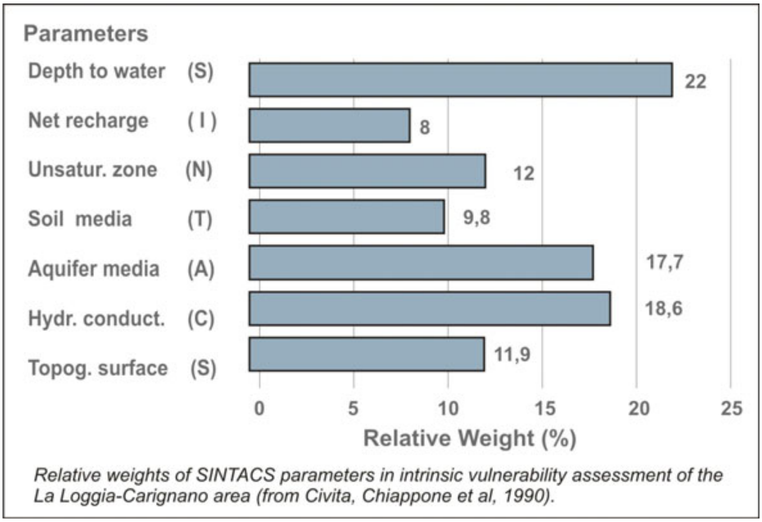
Both indexes are multiplied and then add 7 results to obtain a final value or vulnerability index, where the extremes are 23 (minimum) and 230 (maximum), although in practice the dominant indexes vary between 50 and 200 (Custodio 1995).

DRASTIC also considers the impact of agricultural activities, particularly of pesticides. Therefore, this and the other methods mentioned here qualify vulnerability in a qualitative manner and the most useful aspect is that they allow relative comparisons within the same region or between different regions.

6.2.2 SINTACS

This method is a derivation of DRASTIC, developed by Civita et al. (1990) to suit the diversified hydrogeological characteristics of Italy and the requirement of a more detailed mapping program. The acronym SINTACS (in Italian language) comprises: **S** (Soggiacenza—water depth), **I** (Infiltrazione—infiltration), **N** (Non saturo—sub-saturated section), **T** (Tipologia della copertura—soil type), **A** (Acquifero—hydrogeological characteristics of the aquifer), **C** (Conducibilità—hydraulic conductivity), and **S** (Superficie topografica—topographic surface).

Since DRASTIC has a complex structure, both in the input and the output, SINTACS operation is performed by software specially prepared for the method. To the aforementioned variables, influencing the intrinsic vulnerability, others may be added such as surficial water incidence and the use of the land. In Fig. 46, taken from Vrba and Zaporozec (1994), the relative weights given in percentage of the intrinsic variables are indicated for the region of La Loggia—Carignano, Italy. As it can be seen, the greatest impact on vulnerability is the **S** parameter, the depth of the water table (22) and the lowest is **I**, the net recharge (8).



Relative weights of SINTACS parameters in intrinsic vulnerability assessment of the La Loggia-Carignano area (from Civita, Chiappone et al, 1990).

Fig. 46 Sintacs vulnerability

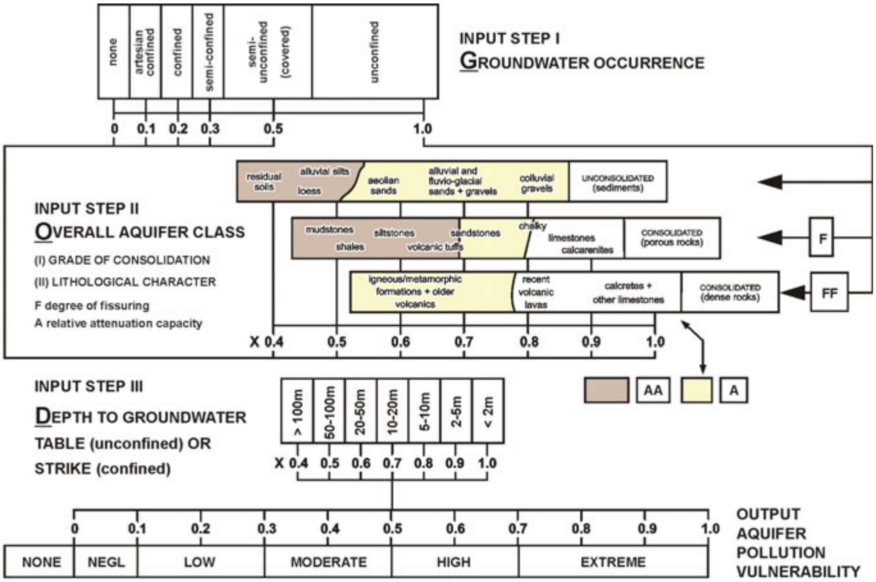
6.2.3 GOD

This method was proposed by Foster (1987), based upon the assignment of indexes between 0 and 1, to three variables nominating the acronym: **G** (Ground water occurrence—type of aquifer), **O** (Overall Aquifer class—cover lithology), **D** (water or aquifer depth).

Figure 47 (from Foster and Hirata 1991) is a diagram to qualify the vulnerability of an aquifer to contamination. The three indexes are multiplied together, and they are placed at one end (output diagram) that can range from **1** (**highest vulnerability**) **to 0** (**minimum**). Similar to the methods described here, but less known and rarely used, other methods have been developed by Fenge (1976), Zaporozec (1985), Marcolongo and Pretto (1987), Sotorníková and Vrba (1987), Schmidt (1987) and Villumsen et al. (1983).

6.2.4 EPIK

This is a parametric method developed by Doerflinger and Zwahlen (1997) for karst aquifers. The acronym stands for: Epikarst (**E**), Protective cover (**P**), Infiltration conditions (**I**), and Karst network (**K**), which are four unequaled characteristics for flow and transport through karst. The epikarst is an area of intense karstification and higher permeability near the surface (Tripet et al. 1997), in which three values have been assigned: **E1** corresponds to the typical karst network (dolines, depressions, cavities, caves, etc.); **E2** when surfaces of weakness in the matrix field generated



GOD empirical system for the rapid assessment of aquifer contamination vulnerability (from Foster, 1987).
Editorial note: Corrections received from the author
Step I: substitute "overflowing" for "artesian confined"; Step II: title should be "Overlying Lithology"; Output: omit "none".

Fig. 47 God vulnerability

alignments (dry valleys, dolines alignment, etc.) and **E3** absence of epikarst geomorphology.

The **Protective cover** is formed by the soil and other materials such as glacial deposits, loess, alluvial silt, scree, etc. For this parameter four values have been assigned (P1 to P4), depending on the cover thickness.

The **Infiltration** parameter is more difficult to estimate. The parameter **I1** has been applied to regions with accessible pathways to direct infiltration; I2 and I3 are used for areas with topographical slopes between 0 and 25 %. Contrarily to other parametric methods, vulnerability increases with increasing slope, which favours the concentration of runoff in more karstified places.

The **Karst network** parameter merits the assignment of three values: **K1** for a well-developed karst network, **K2** for poorly karstified areas and K3 for karst aquifers with discharge in porous media or presenting subordinate cracking.

The method includes four weights (α, β, γ, δ), applicable to each parameter (EPIK), to assess their relative weight in the calculation of the **index of intrinsic vulnerability**. This vulnerability index, also called the **protection factor** is:

$$Vi = (\alpha \cdot Ei) + (\beta \cdot Pi) + (\gamma \cdot Ii) + (\delta \cdot Ki)$$

where

Vi vulnerability index in the area i
Ei, *Pi*, *Ii*, *Ki* relative values of the parameters EPIK
α, β, γ, δ weighting factors corresponding to the EPIK parameters.

The relative values for the EPIK parameters are:

1	2	3	1	2	3	4	1	2	3	1	2	3
E			P				I			K		

Unlike most other methods, EPIK provides growing vulnerabilities with decreasing relative values of the parameters considered, because the method aims to define the **factor of protection** for groundwater, rather than the **vulnerability**.

Regarding the weighting factors, Zwahlen and Doerflinger (1997) proposed:

$$\alpha = 3\,\beta = 1\,\gamma = 3\,\delta = 2$$

Considering relative values and the weighting factors, it appears that the index of vulnerability or protection factor of a karst aquifer may vary between extremes of **9 (more vulnerable)** and **34 (less vulnerable)**. The same authors recommended the use of the following categories:

high vulnerability (9–19)
intermediate vulnerability (20–25)
low vulnerability (26–34)
very low vulnerability, when there is a debris soil coverage of at least 8 m thick, with low hydraulic conductivity.

6.2.5 AVI

AVI is the acronym of **Aquifer Vulnerability Index**. This method was developed by van Stempvoort et al. (1992) for mapping groundwater vulnerability of the Prairie provinces in Canada. The method is based on the relationship between the thickness of the sub-saturated zone (**d**) and its vertical permeability (**K**). Through this relationship, these authors defined a parameter called **hydraulic resistance** (**c**) which is equal to:

$$\mathrm{c} = \Sigma \mathrm{d_i}/\mathrm{K_i} \text{ for a number of layers from 1 to i}$$

According to the ratio, **c** is expressed in time units (usually in years), **d** is distance (usually expressed in meters), and **K** in m/year.

Table 1 AVI vulnerability

Hydraulic resistance	Vulnerability
<10	Very high
10–100	High
100–1000	Moderate
1000–10,000	Low
>10,000	Very low

The magnitudes for the vulnerability qualification are (Table 1):

To reduce the temporal values, it has been suggested to work with their decimal logarithms, thus the values of very high vulnerability would become <1 and the very low one to >4.

6.2.6 EKv

Auge (2004) considered that vulnerability "is a qualitative concept, which in general refers to the degree of natural protection of an aquifer with respect to pollution. For this reason, it is also known as natural protection or defence". In relation to the free aquifers, Auge (2004) developed a classification based upon the depth of the phreatic surface (**E**) (Table 2) and the vertical permeability of the sub-saturated zone (**Kv**) (Table 3), both parameters also considered by the AVI method. For these parameters indexes ranging from 1 (less vulnerable) to 5 (more vulnerable) are assigned, where **Kv** is the mean vertical permeability and **E** is the thickness of the sub-saturated section. Both values are added, providing a final index, with extreme values of 2 and 10 (Table 4).

For indexes of E + Kv between 2 and 4, the vulnerability is low, between 5 and 7 it is considered as medium and from 8 to 10, it is estimated as high.

Table 2 Vulnerability EKv—sub-saturated zone thickness

	Sub-saturated zone thickness (E in meters)				
m	>30	>10 to 30	>5 to 10	>2 to 5	<2
Index	1	2	3	4	5

Table 3 Vulnerability EKv—vertical permeability of the sub-saturated zone

	Vertical permeability of the sub-saturated zone (Kv in m/day)				
m/day	$<10^{-3}$	$>10^{-3}$ to 0.01	>0.01 to 1	>1 to 50	>50 to 500
Index	1	2	3	4	5
Vulnerability	Very low	Low	Mean	High	Very high

Index
5: Kv from 50 to 500 m/day (median to coarse sands, sandy gravels and gravels)
4: Kv from 1 to 50 m/day (silty to very fine sands, fine sands, and median to coarse sands)
3: Kv from 0.01 to 1 m/day (silt and silty sands)
2: Kv from 0.001 to 0.01 m/day (silts and clayey silts)
1: Kv < to 0.001 m/day (clays and silty clays)

Table 4 Vulnerability EKv—phreatic aquifers diagram

Kv	**1**	6	5	4	3	2
	2	7	6	5	4	3
	3	8	7	6	5	4
	4	9	8	7	6	5
	5	10	9	8	7	6
		5	**4**	**3**	**2**	**1**
		E				

Very little has been done with respect to the vulnerability of partially confined or semi-confined aquifers.

It is herein presented a preliminary essay prepared for the CYTED network of aquifer vulnerability (Auge 2001).

6.2.7 ΔhT′ Semi-confined Aquifer

The vulnerability of this type of aquifer is controlled by the physical and geometric properties of the aquitard that forms its top (vertical permeability, porosity and thickness) and also for the hydraulic potential difference when compared with the superposed free aquifer. Such difference in generally small under conditions of lack of anthropic intervention (a few centimetres to a few meters), is highly magnified in the media under exploitation, where it can reach tens or even hundreds of meters.

In Fig. 48, a natural hydraulic relationship with Δh1 positive to the free aquifer is indicated, which defines the recharge section of the semi-confined aquifer and Δh2 positive to the latter, which typifies the discharge sector.

The semi-confined aquifer may be contaminated by the free aquifer only in the recharge sector.

In the case exposed in Fig. 49 the water extraction generated a new hydraulic relationship between the two aquifers, whose more significant consequence with

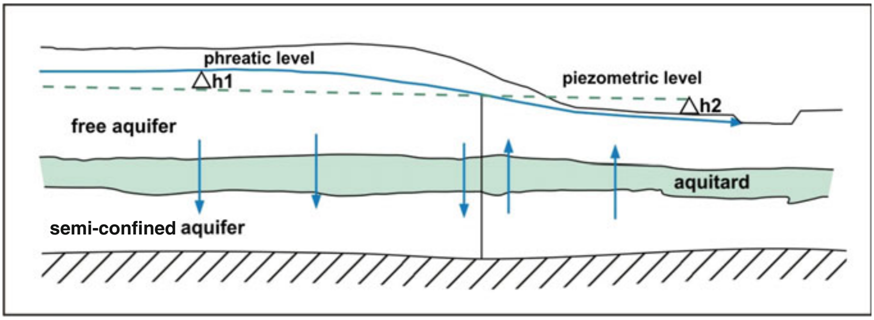


Fig. 48 Natural hydraulic potentials—free and semi-confined aquifers

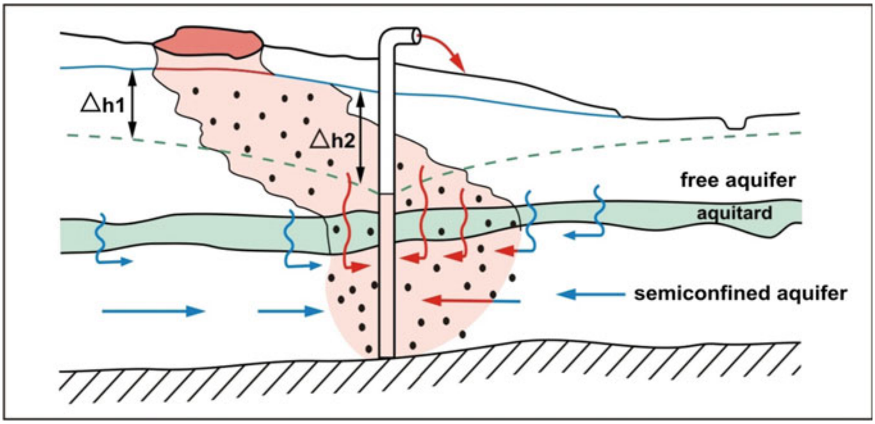


Fig. 49 Pollution due to pumping in a semi-confined aquifer

respect to the vulnerability of the semi-confined aquifer is the lowering of its piezometric surface with the subsequent hydraulic overcharge of the free aquifer at the top of the aquitard, that facilitates the descendent vertical filtration and the access of the polluting materials to the semi-confined aquifer.

The vertical permeability of the aquitard (K′) and its vertical transmissivity (T′ = K′/e′) are not easily determined. One possibility of doing so is by means of hydraulic tests, but these may provide values which are much higher than the real ones, particularly when the essay drillings lack a proper insulation between the free aquifer and the semi-confined. It is more representative to compare the phreatimetry with the piezometry in the same zone and to obtain a residual map, with the differences on hydraulic potential between the phreatic and the semi-confined aquifer and, starting from the latter one and knowing the flow through the partially confined aquifer, estimate the value of T′ (Auge 1986).

Magnitudes of T′ between 10^{-3} and 10^{-6} per day are typical of semi-confined aquifers, whereas those smaller than 10^{-6} indicate a higher degree of confinement and those larger than 10^{-3} day^{-1} suggest free or semi-free aquifers.

A value of $T' = 5 \cdot 10^{-4}$ day^{-1} means that for each meter of hydraulic potential difference between the partially confined aquifer and the phreatic one, the amount of $5 \cdot 10^{-4}$ m^3 (0.5 litres) will pass through 1 square meter surface of the aquitard after 1 day. This magnitude may seem negligible, but when the environment considered reaches natural proportions (hundreds or thousands of km^2) it becomes highly significant.

The relative hydraulic potential of the hydrogeological units involved are fundamental, because they set conditions for the vertical flow. If the levels are similar, the vertical flow through the aquitard will become seriously limited (Fig. 50), but the vertical dynamics will be highly noted in artificial alteration conditions (Fig. 51).

From the analysis of these figures it appears that the less favourable situation for the partially confined aquifer protection occurs when its hydraulic potential is less

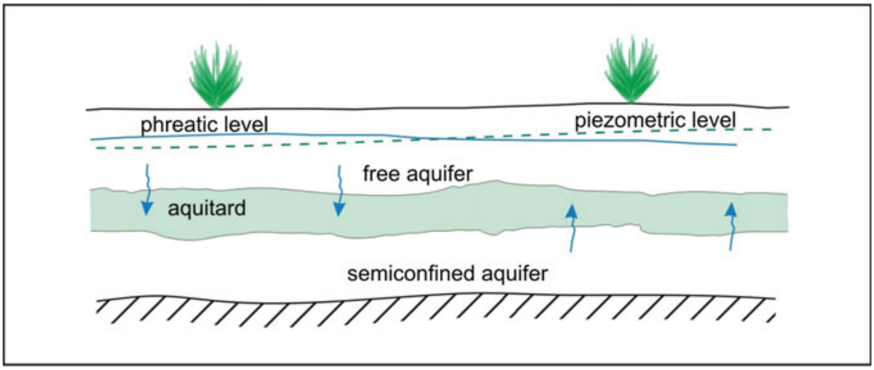


Fig. 50 Flow across the aquitard—natural hydraulic potentials

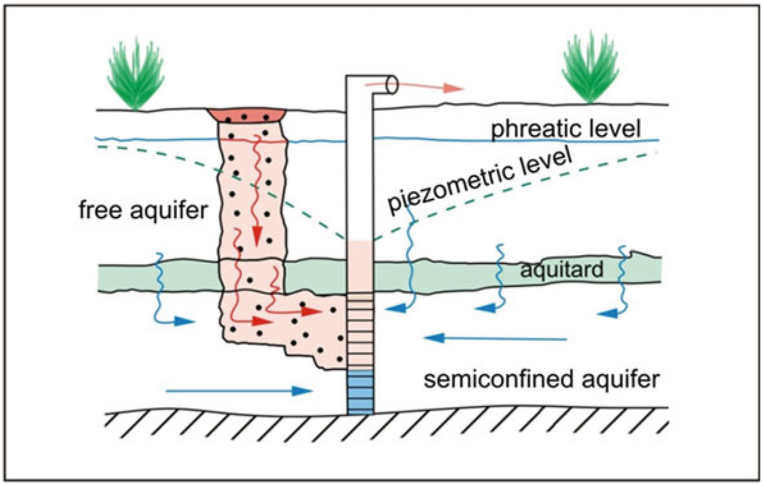


Fig. 51 Flow across the aquitard. Man-made hydraulic potentials

than that of the phreatic one; that is, a negative vertical hydraulic gradient develops with depth.

Another factor with incidence on the hydraulic communication is the area and lithological continuity of the sealing bed because the facies changes often notably modify its capacity with respect to the water transmission (Fig. 52).

Considering both variables (hydraulic potential and vertical transmissivity) three degrees of vulnerability (high, middle, low) may be established, primarily determined by the vertical gradient of the hydraulic potentials and secondarily by T′. If H1 is the hydraulic potential of the free aquifer and H2 is that of de partially confined one, then the following relationships are obtained (Table 5): It may be

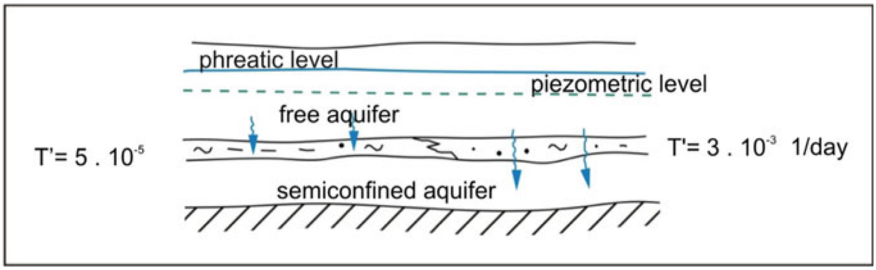


Fig. 52 Flow across the aquitard due a variation in its vertical transmissivity

Table 5 Semi-confined aquifer vulnerability

H2 > H1	Low vulnerability
H2 ≈ H1	Mean vulnerability
H2 < H1	High vulnerability

Hydraulic potential related to the associated phreatic aquifer

Table 6 Semi-confined aquifer vulnerability with respect to the vertical transmissivity of the overlapping aquitard

Day^{-1}	Vulnerability
$T' < 10^{-5}$	Low
$10^{-5} < T' < 10^{-3}$	Mean
$T' > 10^{-3}$	High

added to this, the hydraulic resistance offered by the sealing bed to the vertical passage (Table 6):

It is very important to indicate that the hydraulic potentials may vary, both by natural causes (periods of water excess or deficit) as due to a man-made origin (extraction, irrigation) and that may modify the direction of the vertical flow. For these reasons, the spatial and temporal evolution of the hydraulic potentials should be periodically monitored.

In Table 7, the described methods and the parameters used by each of them to evaluate vulnerability are indicated.

6.3 How to Choose the Appropriate Method

With the exception of EPIK, which has been used for karst aquifers and ΔhT', which is useful for semi-confined aquifers, the rest of the methods have been especially developed for detrital free aquifers. In this sense, only GOD contemplates partially the type of aquifer, regarding to its hydraulic behaviour and its degree of consolidation.

Table 7 Methods for aquifer vulnerability evaluation

DRASTIC		GOD		SINTACS		EPIK		EKv		AVI		ΔHT′
D	Water table depth	**G**	Ground water occurrence	**S**	Water table depth	**E**	Epikarstic characteristics	**E**	Subsaturated zone thickness	**A**	Aquifer	Hydraulic potential difference between phreatic and semiconfined aquifers
R	Net recharge	**O**	Overall aquifer class	**I**	Infiltration	**P**	Protective cover	**Kv**	Subsaturated zone vertical permeability	**V**	Vulnerability	Aquitard vertical transmissivity
A	Aquifer lithology	**D**	Water table or aquifer depth	**N**	Subsaturated zone	**I**	Infiltration			**I**	Index	
S	Soil type			**T**	Soil type	**K**	Karst network					
T	Topography			**A**	Aquifer type							
I	Subsaturated zone lithology			**C**	Hydraulic conductivity							
C	Hydraulic conductivity			**S**	Topography							

The selection of the method to evaluate the groundwater vulnerability in a certain region depends upon several factors, among which the following should be considered:

- **Knowledge and geographical distribution of the methodology**

There are countries, regions and even continents in which some of the methods are better known and which have been more widely used.

In North America, the most used method is DRASTIC, because it was designed in the U.S.A. and that it was one of the first ones in becoming popular (1987) to qualify vulnerability. In the Latin American countries DRASTIC is also applied, but in more or less equal conditions with GOD, which was also presented in 1987. In Spain and Great Britain GOD is utilized, whereas in the rest of Europe, SINTACS is preferred.

In karst aquifers, such as in the Mediterranean Sea coasts and the Caribbean, EPIK, of a more recent launching (1997) is employed, whereas the methodology for semi-confined aquifers is still under development (the CYTED Project).

- **Available information**

The evaluation of vulnerability in a certain region usually ends with its cartographic representation. Commonly, the evaluation is done, at least in its preliminary phase, using existing available information. In these regards, the situation gets more and more complicated as the amount of basic information needed to develop the method grows. DRASTIC and SINTACS require 7 parameters for their methodological development, whereas GOD is based upon 3 and AVI and EKv do so only on 2. Reasonably, when the number of considered parameters decreases the evaluation is simplified, although some degree of definition is lost.

- **Scope of the evaluation**

The detail degree of the evaluation depends upon the foreseen objectives. In semi-regional (scales of 1:100,000 to 1:500,000) and regional (scale of 1:500,000 and smaller) studies, which are usually aimed to the planning for preservation and adequate use of natural resources in relatively extensive areas (thousands to millions of km^2), the methods that require less parametric values (such as GOD, AVI and EKv) are preferred, whereas in the semi-detailed studies (scales 1:25,000 to 1:100,000) and the detailed projects (scales larger of 1:25,000), a better definition of vulnerability is achieved with the DRASTIC and SINTACS methods.

Since EPIK is practically the only available method specially prepared for karst aquifers, it is used regardless to the obtainable scale.

- **Validation of results**

The consistency of the vulnerability studies may be checked in those environments in which degradation of groundwater due to pollution takes place. In these cases, the specific vulnerability should be added to the type of the pollution load, so as to obtain a risk map.

Therefore, to validate the reliability of the vulnerability charts different methodologies may be applied to the polluted sites, to verify which of them is the most adequate, to use it afterwards, to be utilized with the objective of forecast pollution. In certain cases, however, none of them is representative, especially in urban and/or agricultural rural environments, in which the depth of the water layer is important. In these cases, places with high pollution with NO_3^- may appear as slightly vulnerable, due to the incidence of this parameter. In such circumstances, it becomes unavoidable the joint use of the vulnerability and risk maps, or even those of specific vulnerability.

The greater dependability of one or other method in unspoiled environments is very difficult to establish due, among other things, to the very low speed with which the contamination processes in underground hydrological systems take place, particularly in those that have inter-grain porosity.

6.4 A Comparison of the Methods

The advantages and disadvantages of the described methods are herein synthetically analyzed.

DRASTIC is a more robust method than GOD, because it uses a larger amount of variables (7), but this may become inconvenient if the values of any of them are unavailable. DRASTIC has also been criticized concerning the repetition in the reach of some parameters such as **R** and **C**, both related to the water renovation in the aquifer, and the poor incidence that others such as **S** (soil) have in relation to vulnerability (see Table 7).

SINTACS is a derivation from DRASTIC, thus presenting its same advantages and disadvantages, with the additional complication that it requires the use of the pertinent software for its operation. This is also of dual utility; on one side, it simplifies the input of new information such as phreatic level records, which allows to rapidly up-date the resulting cartography, especially if it is used within a GIS program, on the other, the lack of access to the software limits the use of this method.

GOD has as a greater advantage the simplicity of its operation and the scarce number of required parameters for its usage. This, at a time, results in less clear definitions than DRASTIC and SINTACS. Another shortage of the method is not to consider the soil incidence, which is a factor of great importance as a natural filter for pollution. Moreover, its output provides lower vulnerability values than those derived from each individual stage, since numbers smaller than unity intervene in the products.

EPIK presents as a favourable attribute to be the only method specifically designed for karst aquifers and as greater disadvantage the lack of definition of some parameters as **K** and **I** (see Table 7).

AVI is a simple method of easy application because it uses only 2 variables (the thickness of the sub-saturated zone and the vertical permeability of its components), but this also diminishes its precision. Furthermore, it is rather complicated to assign representative values to the sub-saturated zone permeability, because Kv, in addition to the lithology, depends upon the degree of saturation.

EKv has the same advantages and disadvantages of AVI.

ΔhT′ is a method used for semi-confined aquifers and it is in process of development.

6.5 Cartographic Representation

The synthesis of every investigation about the natural resources is its cartographic representation. This expression is applicable to hydrogeology in general and to the groundwater vulnerability in particular.

It is appropriate to accompany the vulnerability maps with others currently used in hydrogeological studies, such as flow network, water depth, chemical content, etc., so as to improve the understanding of the vulnerability maps.

It has been mentioned before that scales vary for different degrees of detail in the vulnerability studies. These magnitudes are usually adopted in relatively extensive countries and with scarce available information, such as those of Latin America; for these reasons these scales are not appropriate for other countries of much more reduced extent and greater basic information, as in Europe. The scales are adopted in function of the needed detail and they are indicated in Table 8.

The regional maps are used at a reconnaissance level and they cover several provinces or states within one country, or the whole country and even several countries, with extensions up to hundreds of thousands and even millions of square kilometres. These maps are aimed to present a general overview of the groundwater vulnerability, to contribute in the planning of the sustainable use of the resource, along great territorial areas. They are generally applied to the management of shared aquifers: inter-provincial, inter-state and across international boundaries.

The semi-regional maps are used to evaluate the groundwater vulnerability at the level of hydrogeological environment, which may be defined as “a region which presents distinctive characteristics or behaviours regarding its groundwater.” The term “distinctive” implies a repeated expression and/or easily detectable peculiar characteristic and, therefore, it does not necessarily involucrate a homogeneous behaviour. The factors that exert a larger influence on the underground hydrological behaviour are: geology, morphology, climate and biology (Auge 2003b).

These maps are applied to environments which occupy from tens of thousands to hundreds of thousands of km^2.

Table 8 Scales classification

Higher than 1:25,000	<of 1:25,000 to 1:100,000	<of 1:100,000 to 1:500,000	Lesser than 1:500,000
Detail	Semi-detail	Semi-regional	Regional

The semi-detail maps are employed in the study of hydrogeological basins or individual aquifer units, when its extension does not surpass a few thousands of km^2.

The detail maps are utilized in the evaluation of specific environments such as urban zones, agricultural and cattle-raising regions, industrial districts, etc. Generally, the studied extension covers from a few hundreds of hectares, to hundreds of km^2.

The vulnerability maps are sometimes named as “traffic lights” because most of them use greenish, yellowish and reddish colours. In this respect, Vrba and Zaporozec (1994) suggested the following colours:

Colour	Vulnerability
Green	Low
Yellow	Mean
Red	High

In the case that the classification accepts a grading of these parameters, dark green will apply to very low vulnerability and light green will do so to low vulnerability; likewise, a pinkish colour will represent high vulnerability and darkish red will consider very high vulnerability.

Figures 53, 54, 55, 56, 57, 58, 59, 60, 61, 62 and 63 represent part of the cartography included in the first year report of the “Vulnerability to pollution by nitrates of the Puelche Aquifer, La Plata, Argentina” Project (Auge et al. 2004).

The Puelche Aquifer extends boundless throughout the sub-surface of northeast Buenos Aires Province, Argentina, occupying an area around 92,000 km^2 (a size comparable to Portugal; Auge et al. 2002). For the development of this Project, a smaller area of 1000 km^2 was chosen, with centre in the city of La Plata (Fig. 54),

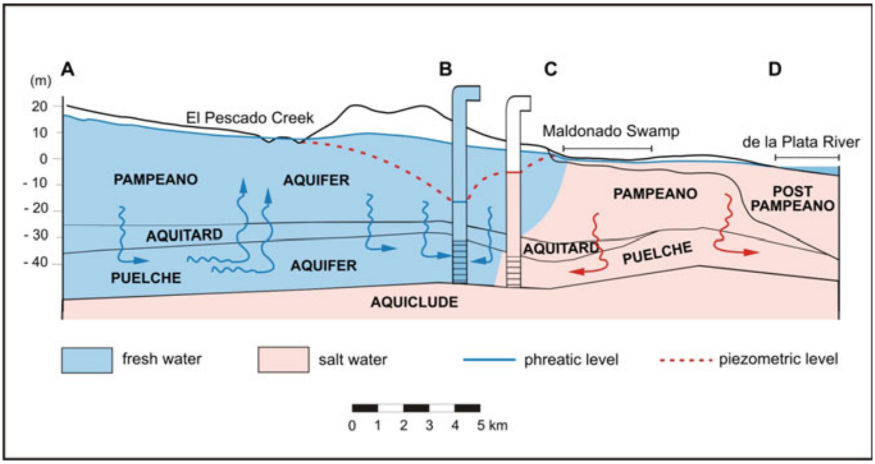


Fig. 53 Hydrogeological profile

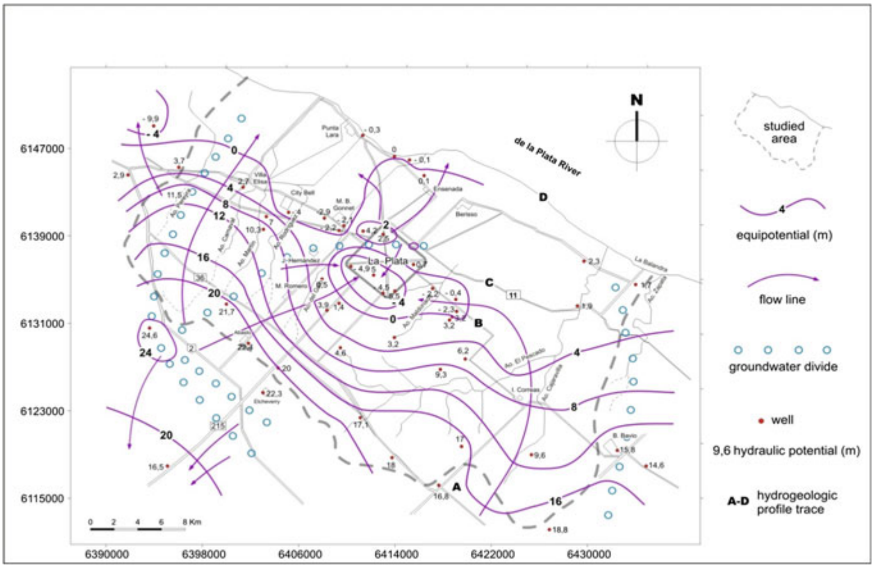


Fig. 54 Puelche Aquifer flow net

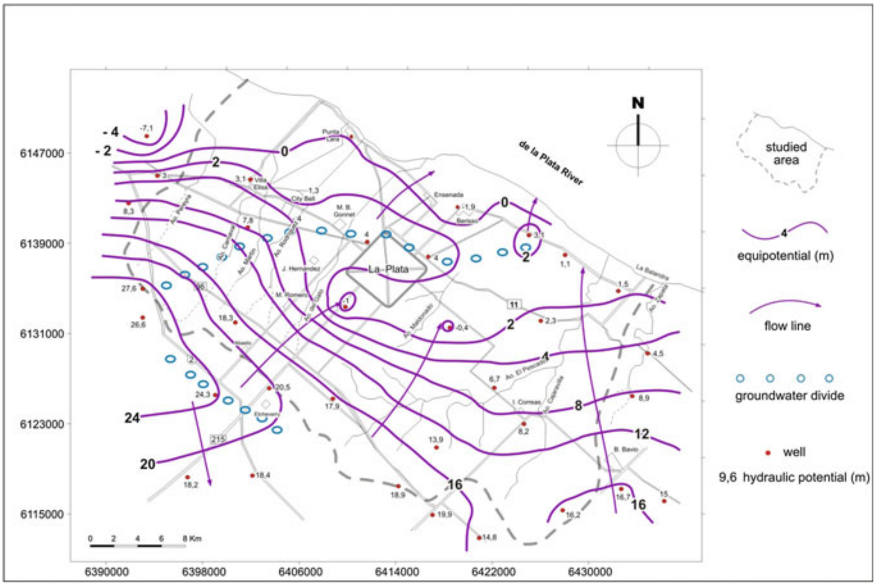


Fig. 55 Pampeano Aquifer flow net

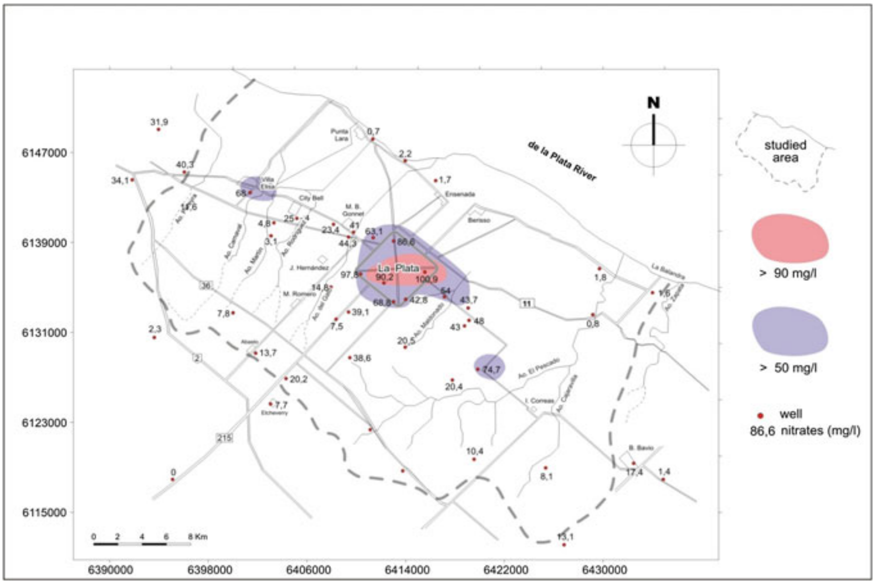


Fig. 56 Puelche Aquifer nitrates

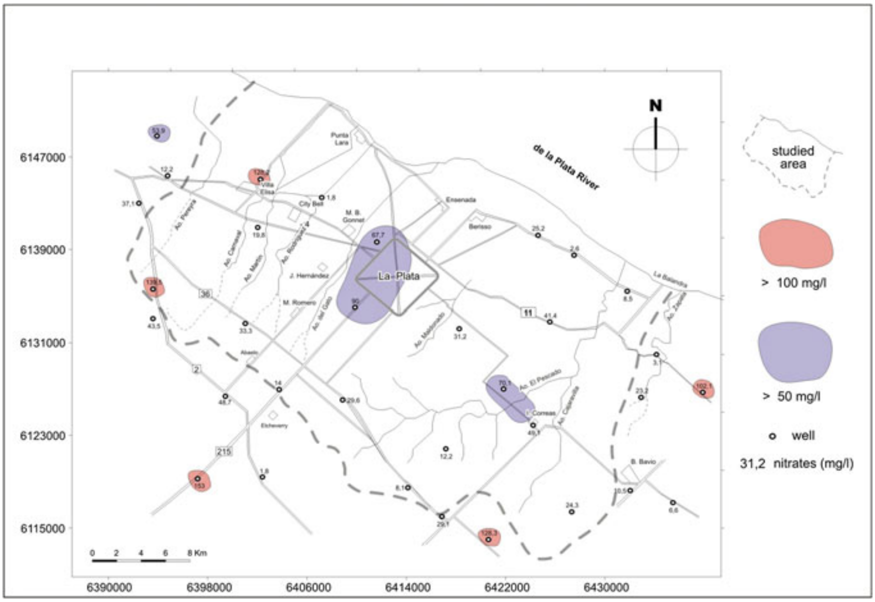


Fig. 57 Pampeano Aquifer nitrates

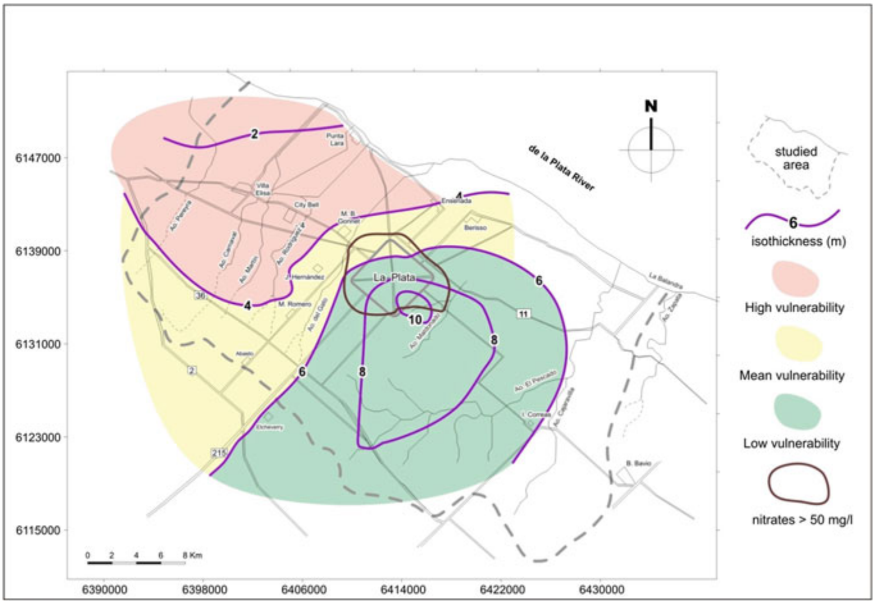


Fig. 58 Puelche Aquifer vulnerability aquitard thickness

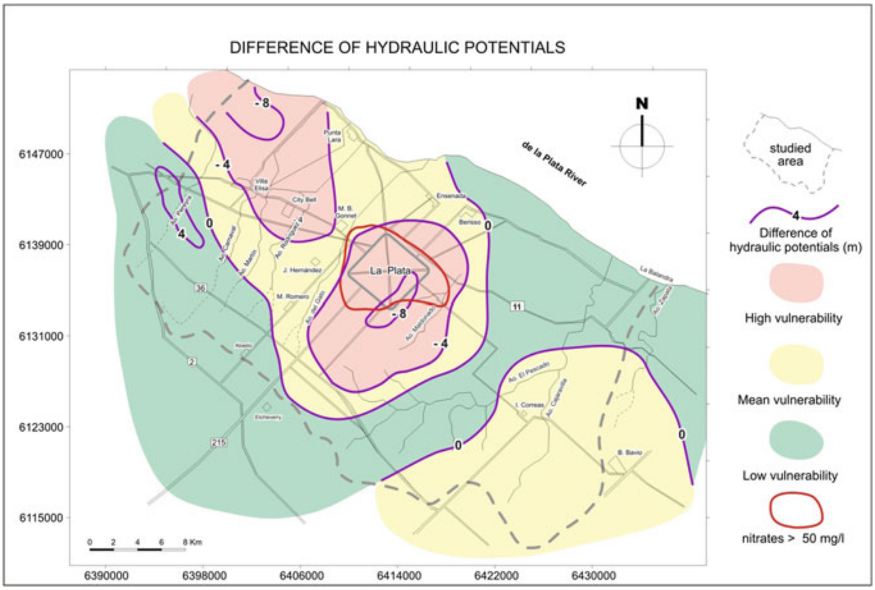


Fig. 59 Puelche Aquifer vulnerability

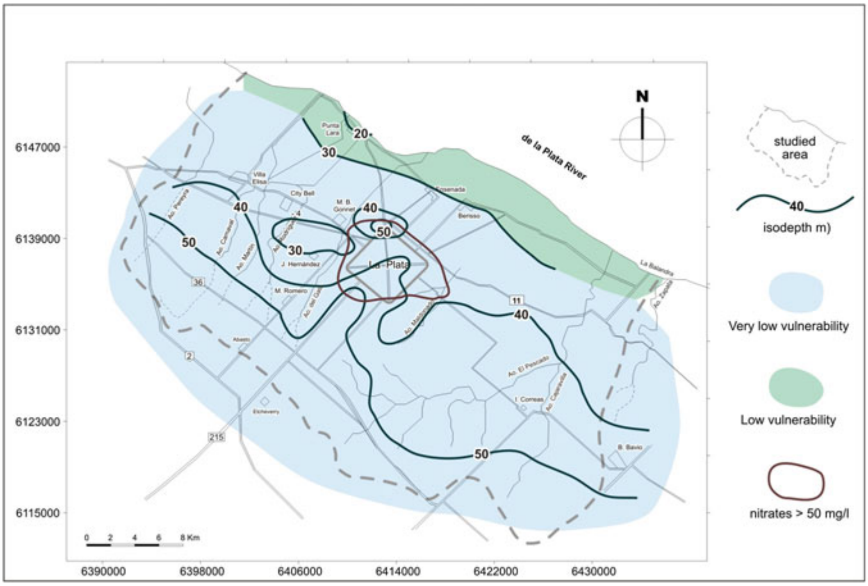


Fig. 60 Puelche Aquifer vulnerability depth to top

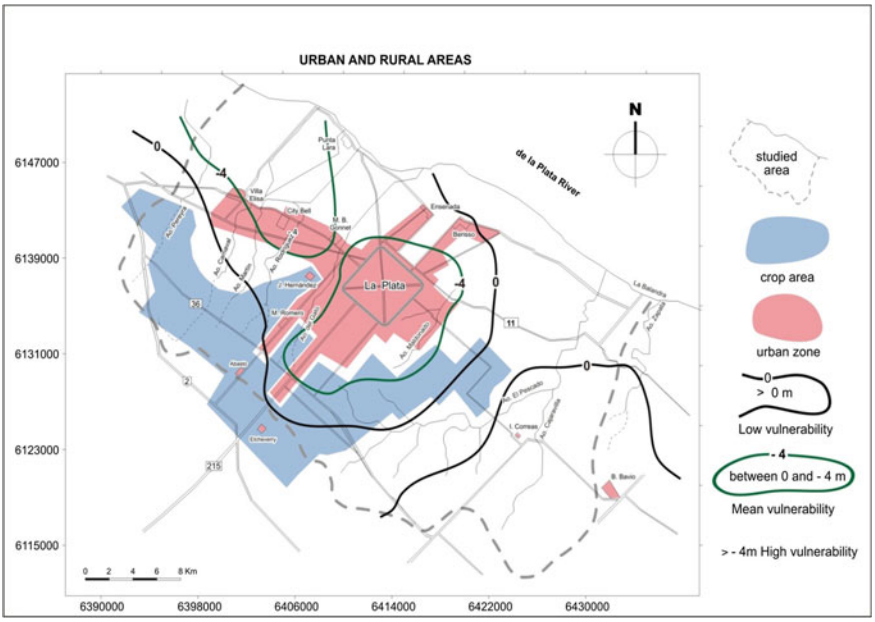


Fig. 61 Puelche Aquifer vulnerability—hydraulic potential difference pollution load

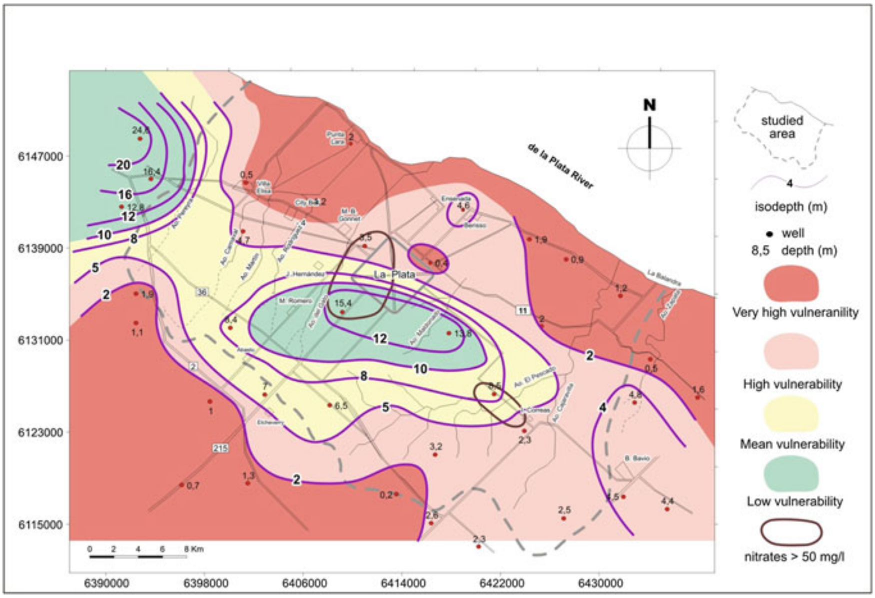


Fig. 62 Pampeano Aquifer vulnerability water table depth

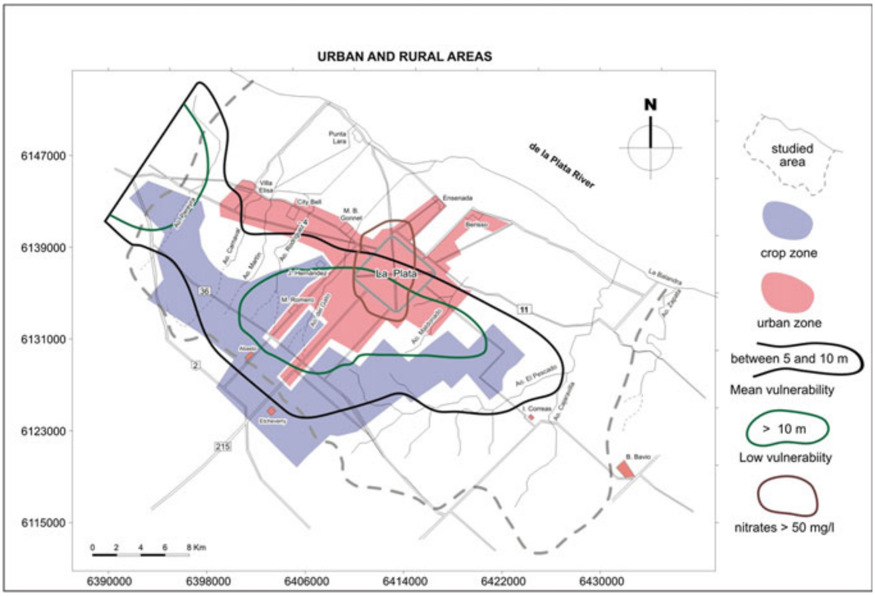


Fig. 63 Pampeano Aquifer vulnerability pollution load

because it is one of the localities where the aquifer is more intensively exploited, both for drinking water and for irrigation.

In Fig. 53, the stratigraphic and hydrogeological relationships of the most interesting section for water capture, since it is yielding fresh groundwater, are reproduced. In this section, whose location is indicated in Fig. 54, the disposition of the Puelche Aquifer is presented, separated from the Pampeano Aquifer, which behaves as a free aquifer, with a silty-clayey aquitard between 2 and 10 metres and a mean thickness of 6 meters. The aquitard allows the descending vertical passage (the Puelche recharge) and the ascending one (Puelche discharge) from and towards the Pampeano Aquifer, respectively. The contact between freshwater and salty water takes place in a topographically depressed environment known as the Maldonado Swamp, a swamp which was repeatedly occupied by several marine transgressions during the Holocene, located between National Route 11 and the coast of the de la Plata River estuary (Fig. 54). In this environment, both the Pampeano and the Puelche aquifers have salty water (Fig. 53).

Stratigraphically underneath the Puelche Aquifer, from a depth of 70 m to the hydrogeological basement, composed of Precambrian granitic and migmatite rocks at 485 m deep, ground water has very high salinity (Auge 1997).

In Fig. 54, the influence of the pumping of 127 freshwater wells to supply the city of La Plata and surrounding towns, over the flow of the Puelche Aquifer, is clearly appreciated. The rate is in the order of 74 hm^3/year (cubic hectometres) or 2346 l/sec, which represents 60 % of the total fresh water supply. The remaining 40 % is conveniently treated water pumped out of the de la Plata River.

The depression cone is out-bounded by the equipotential curve of 0 m, which has a WNW-ESE elongated shape, with its longer axis of 13 km and the shorter one between 3 and 6 km (Auge et al. 2004). This curve extends over a distance of around 35 km and it was the one which was used to estimate the underground flow that enters the cone. Using Darcy's law, the following is calculated:

$$\mathrm{Q} = \mathrm{T} \cdot \mathrm{i} \cdot \mathrm{L} = 500\,\mathrm{m}^2/\mathrm{day} \cdot\ 8 \times 10^{-3} \cdot 35{,}000\,\mathrm{m}\ =\ 140{,}000\,\mathrm{m}^3/\mathrm{day}$$

where

Q yield
T transmissivity
i hydraulic gradient
L length

The amount of 140,000 m^3/day is equivalent to 51 hm^3/year and, since the pumping reaches 74 hm^3/year the actual deficit is as high as 23 hm^3/year. The piezometric stability observed in the last years indicates that the incoming yield must be similar to the outgoing one and therefore, the aforementioned deficit must be covered by natural and man-made supply, both of them coming from the Pampeano Aquifer. The first one, by vertical leakage through the aquitard, the other one, of artificial origin, is a product of the existing losses in the freshwater network for human consumption, estimated in 15 % of the water in the network. Since the water circulation in the network is of 124 hm^3/year (74 hm^3/year of groundwater and 50 hm^3/year of surface water), the artificial recharge of the Pampeano Aquifer ascends to around 19 hm^3/year. Adding the flow (51 hm^3/year) to this last value, a rather acceptable equilibrium between outflowing (74 hm^3/year) and inflowing (70 hm^3/year) flows is achieved.

In Fig. 55, the flow net of the Pampeano Aquifer is reproduced, noting two well defined divides. One of them SW of the city of La Plata, which generally follows National Route 2 and which separates the flow towards the city from that oriented towards the South. The other one, more extended, has an E—W strike.

Figures 56 and 57 are maps of the NO_3^- content in both aquifers, observing that the more affected portion is the urban area, particularly of the La Plata city and surroundings.

The coloured area with more than 50 mg/l NO_3^- in the Puelche Aquifer includes 4700 hectares of the urban and peri-urban quarters of the city of La Plata, and within it, another smaller area has contents of 90 mg/l and over (Fig. 56). This contamination has a diffuse character, affects an important volume of ground water and comes from the Pampeano Aquifer, by descending vertical leakage, through the aquitard. The Pampeano Aquifer receives also the polluting load of septic wells and losses of the local sewage system.

The whole of the urban area has a network for the evacuation of sewage effluents, but most of the suburban area has not. Moreover, in some sectors of the urban area the replacement of the septic wells by the sewage network has less than 20 years.

To make it possible that the network freshwater fits with the drinkability regulations with respect to NO_3^-, that request a content lower than 50 mg/l, the groundwater is mixed up with that coming from the de la Plata River estuary, which normally does not exceeds 10 mg/l.

In the rural zone, only 2 wells of the total of 54 which have been sampled has more than 50 mg/l of nitrates.

With respect to the Pampeano Aquifer, the pollution spot occurs also in the city of Plata and surroundings, but another one with more than 50 mg/litre appears as well in the El Pescado Creek, and in 5 wells with more than 100 mg/l in the rural area (Fig. 57), but in this case contamination is here highly localized and thus affecting only a small volume of groundwater.

The maps represented in Figs. 58, 59, 60, 61, 62 and 63 have been prepared to verify the correlation between those variables used to establish the specific vulnerability and the degree of NO_3^- contamination in both aquifers.

In the map of Fig. 58, the thickness of the aquitard is used as a comparable variable, observing that the sector of the Puelche Aquifer with a larger content in NO_3^- is coincident with the thicker portion of the aquitard (from 6 to 10 m), which is the sector with lesser vulnerability. Contrarily, that of smaller thickness (less than 4 m) (high vulnerability) correlates with lower values of NO_3^-, with the exception of the Villa Elisa well. This lack of correlation is a product of the behaviour of the polluting substance (very soluble, mobile and persistent), a reason why it is not absorbed in its vertical descending passage through the aquitard.

The map of Fig. 59 reproduces the difference of hydraulic potential between both aquifers. In this case, a very good correlation is observed between the larger hydraulic potential differences in favour of the Pampeano Aquifer (high vulnerability) and the sector of further deterioration in the quality of the Puelche Aquifer. This is another evidence of the aquitard incapacity to retain the nitrates, originated by urban pollution, initiated in the phreatic water.

Figure 60 illustrates the depth of the Puelche Aquifer top and no correlation is detected with the area of higher NO_3^- contamination. For this reason, neither the thickness superimposed to the Puelche Aquifer, composed of the Pampeano Aquifer, plus the sub-saturated zone, has incidence upon the vertical NO_3^- passage.

The map of Fig. 61 is an attempt to assign relative vulnerabilities according to the land use and the differences of hydraulic potential between the semi-confined Puelche Aquifer and the free Pampeano Aquifer. The values between 0 and −4 m ($H1 > H2$; see Table 5) are assumed as of middle vulnerability and those greater than −4 m, always in favour of the free aquifer, as of high vulnerability. In this case, as in Fig. 60, a good correlation between the chosen variable and the amount of pollution is observed and also the control of the urban sector upon it.

The lowering of hydraulic potential with depth typifies the recharge environments and the descending vertical flow.

In Fig. 62 the depth of the phreatic surface and its correlation with the NO_3^- content of the Pampeano Aquifer are represented. However, discrepancy occurs because a sector with more than 50 mg/litre of NO_3^- is located where depth is larger than 10 m (low vulnerability). Notwithstanding, other sectors with more than 50 mg/litre of nitrates are found with depths of the water table between 2 and 5 m (high vulnerability; see Tables 2, 3 and 4).

Figure 63 indicates the vulnerability of the Pampeano Aquifer, relative to the thickness of the sub-saturated zone (phreatic depth or water table depth) and the land use. As it happens with the Puelche Aquifer, the places more impacted by pollution are the urban ones, although parts of them lie within the iso-depth curve of 10 m (low vulnerability).

As a conclusion regarding the attempt of correlation, it appears that:

- One of the most used variables for the qualification of the specific vulnerability, as it is the depth of the phreatic surface or the top of the semi-confined aquifer, does not present a good correlation concerning nitrate pollution in the free Pampeano Aquifer nor in the semi-confined Puelche Aquifer.
- Contrarily, the correlation between the hydraulic potential difference of the free aquifer with that of the semi-confined aquifer and the nitrate pollution of the Puelche Aquifer is very good, particularly in the urban environment.

6.6 Final Vulnerability Remarks

- The definition and reach of the concept of aquifer vulnerability to contamination are still under discussion, even though more than 30 years have passed since the introduction of these terms. In this sense, most authors consider vulnerability as a qualitative property of the aquifer, which indicates the degree of its natural protection with respect to pollution. In general, the vulnerability is named as **low, intermediate or high**, sometimes with the additional categories of **very high** and **very low**.
- The aforementioned definition refers to what is also known as **intrinsic vulnerability**, that is, the vulnerability derived from the specific properties of the aquifer and its environment, leaving aside the activity of the contaminant substances themselves. When, in addition to the physical and hydrological characteristics of the aquifer and the surroundings, the incidence of polluting substances is taken into account, **specific vulnerability** is the term applied.
- The more commonly used variables for the qualification of vulnerability or intrinsic vulnerability are the depth of the phreatic surface, the lithological and hydraulic characteristics of the sub-saturated zone, the thickness and type of soil, the magnitude of the recharge, and the lithology and type of aquifer. However, the solubility, mobility and persistence of certain polluting substances as nitrates make that some of these variables are less consistence regarding vulnerability, as it happens in the city of La Plata, if the depth of phreatic surface or the top of the semi-confined aquifer are taken into consideration. Moreover, since some of these components are of a dynamic nature (position of the phreatic surface, recharge, renovation), the vulnerability of a certain site may temporarily change.
- There are numerous methodologies to qualify the vulnerability and allow its mapping at different scales. Most of these techniques have been developed for free aquifers. The selection of one or other method depends upon various factors among which, the following should be highlighted: diffusion, reach and scope of the methodology, available information, range and spread of the evaluation, and the validation of results.
- Regarding the karst aquifers, the mostly used methodology in Europe is **EPIK**. For the aquifers showing partial confinement (semi-confined), the methodological development is still incipient, and for this reason, the main objective of the Project “Vulnerability of the Puelche Aquifer to Nitrate Pollution in the city of La Plata, Argentina”, jointly developed by the universities of Buenos Aires (Argentina), Autónoma de Madrid (Spain) and São Paulo (Brazil), has been precisely to develop a methodology for the study of the vulnerability of semi-confined aquifers, taking as a base the investigation of the Puelche Aquifer. Thus project has been conducted within the framework of the “Aquifer Vulnerability Network”, with the sponsoring of CEAL (Latin-America Studies Centre).

- The advances in the development of numerical models and the advantages exposed by systems such as GIS, allow the storage of a large quantity of information, which may be rapidly processed, to obtain geographically and temporally up-dated products which foresee a progressive tendency to the definition of quantitative methodologies in the future.

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