American Journal of Environmental Sciences 8 (3): 220-235, 2012
ISSN 1553-345X


# Groundwater Flow Systems and Their Response to Climate Change: A Need for a Water-System View Approach

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**Abstract: Problem statement:** The interest in early hydrogeological studies was the aquifer unit, as it is the physical media that stores and permits groundwater transfers from the recharge zone to the discharge zone, making groundwater available to boreholes for water extraction. **Approach:** Recently, the aquifer concept has been complemented by the groundwater flow system theory, where groundwater may be defined by local, intermediate and regional flow systems. This implies that groundwater may travel from one aquifer unit to another aquifer unit (or more) located above or below the former. Water in a local flow system takes months or several years to travel from the recharge to the discharge zone. These flows usually transfer the best natural quality water, so a reduction in precipitation would lessen recharge and diminish stored water, making them more vulnerable to contamination and variability in climatic conditions. Thus, there is a need to define local flows and to enhance actions to protect them from contamination and inefficient extraction. **Results:** In contrast to local flows, intermediate and regional flows travel from a region, or country, into another, with their recharge processes usually taking place in a zone located far away from the discharge zone (natural or by boreholes). There is a need of groundwater flow systems evaluation by means of an integrated wide system-view analysis of partial evidence represented by surface (soil and vegetation covers) as well as hydraulic, isotopic and chemical groundwater characterization in the related geological media where the depth of actual basement rock is paramount as well as discharge areas. The flow system definition may assist in extraction management strategies to control related issues as subsidence, obtained the water quality change, desiccation of springs and water bodies, soil erosion, flooding response, contamination processes in recharge areas, among others; many of which could be efficiently managed leaning on groundwater functioning. There is increasing evidence that climate becoming more variable and key driver of ecosystem health. Even with climate stability, most developing countries will confront serious water problems by the mid-21st century due to an insufficient knowledge of the functioning of their groundwater sources representing ≈ 99% of available water. **Conclusion:** Many such problems may be adequately controlled when local flows are defined, since changes in climatic condition are more prone to affect local flows rather than intermediate and regional flows. The value of the flow systems arises from the fact that a wide system view analysis allows adequate crossed examination among relevant data from where water management proposals might more adequately represent field conditions. Examples of successful application of the groundwater flow systems in Mexico and Argentina will be presented including: induced fluoride control, subsidence response, desiccation of springs, flooding water origin definition, basement position in flow-system control, inter-basin flow.

**Key words:** Groundwater flow, regional flow, discharge zone, local flow, recharge zone, aquifer unit, diminishes stored water, climatic conditions, regional flow systems

## INTRODUCTION

About 97% of the continental water on earth is groundwater (Freeze and Cherry, 1979). The rest includes surface water, water in the atmosphere and water in living organisms. Further knowledge is required on groundwater functioning to cope with different climate conditions that would have visible and invisible effects. The visible ones will be the diminishing of the rate in rainfall and its corresponding runoff. The invisible effects will be represented by less recharge rates and by minimizing volumes of discharge water and store. To

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diminish impacts to humans and the usage of water by the environment, water sources must be understood and utilize in the most efficient way possible.

There is increasing evidence that climatic behavior is becoming more variable. However, there are still uncertainties as to whether this may be attributable to climate change (i.e., caused by human intervention) or how the climate of the Planet Earth is responding as part of the universal system (climate variability). Increasing climate unpredictability may lead to a concern on intensification of the hydrological cycle components. Both, precipitation and evapotranspiration (actual) are perceived as key elements to diagnose climate change; their spatial and temporal analyses allow an understanding of hydrological responses to develop sustainable basin management strategies. The increases in magnitude and frequency of extreme events have already being observed in many regions for centuries. In addition, there is a possibility that future extremes are projected to be even more severe than those experienced to date. Climate variability and change will enhance the components of the hydrological cycle from place to place, so there is a need to investigate them using local climate scenarios (observed and predicted) based on long-ranged rigorously collected and managed climatic data that need to be analyzed in 3-D over long time span scenarios. However, such data is difficult to obtain at a world scale, for instance about 70% of the Earth surface is covered with water where related rainfall and temperature measurements lack a desirable coverage. Also, solid data are required at tropical as well as Southern, Arctic and Antarctic latitudes.

Foresighted groundwater management practices will be needed in helping to cope with and adapt to any changes. Climate variability and change have been identified as key drivers of ecosystem health and the growth and spreading of water-related diseases; however, even without climate change, most developing countries in arid regions will be confronted with serious water problems by the middle of the 21st century.

It has been recognized that adaptation to climate change requires different actions, among others: (i) science-based knowledge, (ii) resilient development policies, (iii) appropriate institutions and regulatory mechanisms, (iv) adequate economic resources and instruments, (v) international collective action. In regard to the first action, groundwater flow systems definition is paramount to develop a sustainable strategy for management of groundwater extraction, such definition should be integral part of any water administration framework aimed to minimize and control, related negative environmental impacts. Such impacts have been predicted for future climatic conditions suggesting an annual average precipitation decrease in most of the Mediterranean, northern Africa, northern Sahara, among others. This condition is coupled with an increase in temperature trend; however, an opposite behavior has been traced in extensive regions in South America. The continuous expected increase in population and productive activities in the arid (and semi-arid) regions exercises an additional pressure on existing groundwater flow systems. When the environment and ecosystems in these regions are altered by groundwater extraction this could show changes in: soil erosion, subsidence, obtained water quality, human-induced land use, biodiversity and landscape. Therefore, the definition of groundwater flow system (Toth, 1999) becomes a significant issue.

A definition of flow systems may be reached through an integrated approach using direct and indirect evidence that includes isotopic, chemical, geological, vegetation, soil and hydraulic groundwater characterizations. Such flow system depiction is a valuable tool to define groundwater vulnerability to climate change at local or global scale. This knowledge may assist in defining an appropriate strategy to sustain and protect local flows and to take advantage of regional and intermediate flows which have the lowest response to climate change, but are subjected to trans-boundary groundwater issues.

Present groundwater studies related to its management regarding climate change issues or those related to trans-boundary groundwater require an updating of existing models. An original focus of interest in early groundwater studies has been the aquifer unit as it is the physical media that stores and permits groundwater transfer from the recharge to the discharge zone, making it accessible to boreholes for its extraction. The aquifer unit concept has been studied mainly through groundwater hydraulics modeling and by applying the water-balance method as in Eq. 1:

$$P = Evpt + Ro + Q + R + Chs \quad (1)$$

Where:

P = Precipitation
Evpt = Evapotranspiration (actual)
Ro = Runoff
Q = Groundwater extraction
R = Recharge
ChS = Change is groundwater storage

However, this technique has had several constraints due to the nature of the variables included, which often are not measured to a good degree of certainty (such as precipitation) others are not directly measured such actual evapotranspiration, runoff, groundwater extraction. The change in groundwater storage may be established with an acceptable degree of uncertainty; however, Recharge (R) is usually obtained by working out the difference with other variables in Eq. 1. An additional limitation is that it is usually applied as a lumped model which produces severe restrictions such as to know the processes involved as for example a precipitation of 30 mm/month in real terms (as opposed to modeled) would have not the same effect on the other variables of the balance equation (as evapotranspiration or runoff) if it fell on the ground at a rate of 1 mm/day or the 30 mm fell on a few days, as it is often the case in arid and semi-arid regions. A yearly application of Eq. 1 may produce more significant uncertainty. Further, the geological framework as well as the water quality and isotopic characteristics need to be integrated in due estimates as cross-checking procedure. An additional technique, the groundwater flow systems, also includes such characteristics as well as information on vegetation and soil to complement the water balance equation from a system-view perspective which could give the required support in understanding groundwater behavior.

**Groundwater flow systems:**

**Recharge, transit and discharge zones:** Usually rainfall that enters the surface of the earth initially does so in a recharge zone (Fig. 1) from where it constantly moves downwards to reach the water-table; then groundwater moves laterally in the transit zone and eventually it will move vertically upwards in the discharge zone (i.e., lake, wetland, river, salty soil, spring). These traveling characteristics of groundwater provide with a series of distinctive physical and chemical properties that reveal its particular path and functioning. The depth to the water-table is deep in a recharge zone and shallow in a discharge zone. Distinct characteristic are cold water temperature in a recharge zone, warmer in the discharge zone. Chemical conditions are contrasting with high Dissolved Oxygen (DO) and Eh and low pH and salinity in a recharge zone; in a discharge zone a low DO and Eh as well as high pH and salinity will prevail. Once water has entered below the ground it collects data in its molecules. Stable isotopes in rainfall are an initial tracer suggesting storm elevation as well as evaporation effects. Trace, minor and major elements describe its traveling path and processes involved from the recharge to its discharge zone. This implies that groundwater discharge conditions will provide with data about the natural flow system in which water has traveled along and will help to understand water functioning including recharge processes.

**Flow system hierarchy:** Ocean currents follow specific and separate paths even they are found to have a jointly displacement this is often carried out in contrasting direction (i.e., North-Equatorial and South-Equatorial currents). Similarly, groundwater flow systems have a different and often jointly circulation path (Fig. 1); it is in not unusual to find that these flows travel through different geological (aquifer) units.

Groundwater movement is directly controlled by geomorphology which incorporates both topography (responsible for kinetic energy and gravitational force) and hydraulic properties of aquifer material related to water storage and motion. Thus gravitational water movement is responsible of the presence of local, intermediate and regional groundwater flow systems (Fig. 1). This implies that groundwater may travel from one aquifer unit to another aquifer unit located above or below the former. The behavior of groundwater (its recharge zone and path followed) traced by its isotopic and geochemical characteristics as well as referred to its geomorphologic environment is also manifested in a specific soil and vegetation cover which allows not only to identify prevailing hierarchy of present flow systems, but to proposes existing natural, or induced, water connection among aquifer units, as well as the relation between surface water and groundwater, from where inter-basin groundwater flow may be postulated (Toth, 1995).

As a general reference according to the comparative (not absolute) path and depth groundwater follows, a flow systems may be referred to as local, intermediate or regional. In a local groundwater flow system water takes months or years to travel between the recharge to its discharge zone, this flow has a short travel distance, recharging and discharging in the same valley. This flow usually transfers low salinity quality water. A reduction in precipitation would lessen recharge and rapidly will diminish stored water, making local flow systems more negatively vulnerable to such alteration in climatic condition. Thus, the need to define the position and functioning of local flows is required to enhance actions to protect them from contamination and from the danger of inefficient extraction that could be environmentally and an uneconomically hazardous.

In contrast to local flows, intermediate and regional flow systems might travel for longer and deeper distances, their recharge processes are usually taking place in a zone located far away from the discharge zone (natural or by means of a borehole). Consequently, a flow of this nature might initiate its traveling path in a surface drainage basin and discharge in a neighboring basin containing (above) at least one local flow (Fig. 1).

A definition of flow systems may be reached through an integrated approach using direct and indirect field evidence that includes classic groundwater hydraulic characterization (hydraulic conductivity, porosity and storage coefficient) as well as studies on groundwater characterization from the physical (isotopic, temperature, pH) and chemical (major, minor and trace elements) perspectives, which need to be interpreted within the geomorphological, as well as soil and natural vegetation covers perspectives.

The characterization of the flow systems is a valuable tool to define groundwater vulnerability to climate change at local or regional scales. This knowledge may assist in defining an appropriate strategy to sustain and protect local flows and to define future policies to manage regional and intermediate flows which have a lowest response to climate variability (and change).

Understanding the hierarchical position of each flow system in a study area can assist to plan and control groundwater extraction by defining which is more vulnerable to local groundwater extraction and those that related to withdrawal beyond the surface basin under consideration. Analogously, the definition of zones where recharge processes occur could assist in enhancing recharge under new possible scenarios of the expected rainfall intensity to runoff production. Only through a better understanding of the biophysical relationship among groundwater with all of the components of the environment can informed decisions be made.

**Flow systems application:**

**Fluoride control:** Importance of fluoride management: Groundwater is the major source of potable water supply in semi-arid and arid areas. However, its availability may be threatened not only by the introduction of contaminants through human activities but also by induced natural processes. Recently, the impact of trace elements in the water supply sources of México has started to be given consideration in groundwater management. The contribution of trace elements (i.e., fluoride, iron, arsenic, lead, cadmium) that change groundwater quality with extraction time is a substantial health hazard in many groundwater regions world-wide (Appleton *et al*., 1996). Fluoride is a common natural element that threatens groundwater supply in both industrialized and developing countries.

Dental fluorosis in the habitants of the city of San Luis Potosi (SLP) has been recognized as the result of high exposure to naturally occurring fluoride in drinking water supply (Grimaldo *et al*., 1995), this is causing some degree of dental fluorosis (Medellin-Milan *et al*., 1993) in 84% of inhabitants between 6-30 years of age; 34% of children 11-13 years old showed severe fluorosis. Only children show severe dental fluorosis, as opposed to senior citizens who lack significant effects (Sarabia, 1989) suggesting the quality of the water supply has evolved. As fluoride shares a common source with arsenic, lead and cadmium, the presence of the former is of additional concern as the latter may also be introduced into the water supply (Medellin-Milan *et al*., 1993).

**Hydrogeological framework:** The SLP-Basin is located in central Mexico, within the sierra madre occidental groundwater region (Back *et al*., 1988), which is about 1,500 km long and 220 km wide. This mountain range contains acid silica rich (rhyolitic) rock units of similar nature to those of the SLP-Basin. The porous nature of the volcano-tectonic grabens and related normal fault system permit groundwater within this basin to travel along neighboring (surface) drainage basins. Fractured rock zones related to fault systems have higher hydraulic conductivity than the rest of the region through which groundwater finds long flow paths to follow (Carrillo-Rivera, 1992). The definition of the thickness of rocks sequence by geothermometry assisted in understanding the depth to which groundwater flow is taking place as well as the expected water quality. The maximum thickness of the Quaternary (basin fill) is in the range of 450 m at the centre of the drainage basin. The geological basement is represented by an undifferentiated Cretaceous calcareous mudstone and a post-Cretaceous quartz-monzonite intrusive rock (Carrillo-Rivera, 1992). No geothermal activity has been identified within 300 km of this drainage basin which implies that observed extracted groundwater temperature (>40°C) is due to natural geothermal gradient.

**Geochemical behavior:** A saturation indices study suggests that fluoride concentration in regional flow water is controlled by fluorite solubility irrespective of groundwater temperature extraction. Calculation with geothermometry proposed that this water attains a temperature of about 75°C at depth (about 1,000-1,700 m) and that is in equilibrium with respect to fluorite (and calcite) (Carrillo-Rivera *et al*., 2002). Extracted water (at discharge temperature) is under-saturated with respect to fluorite. Such results are interpreted as a fluoride loss occurring in the ascent of regional flow water to borehole discharge.

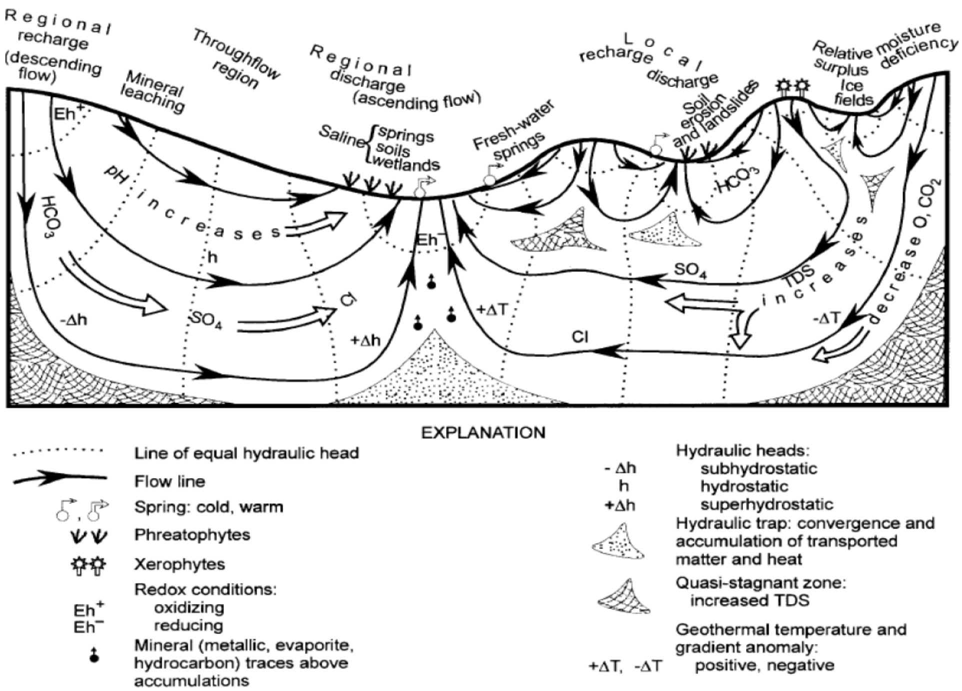


Fig. 1: Gravitational groundwater flow systems, depicting controls of recharge-transit-discharge zones as well as local, intermediate and regional flows. Adapted (Toth, 1999)

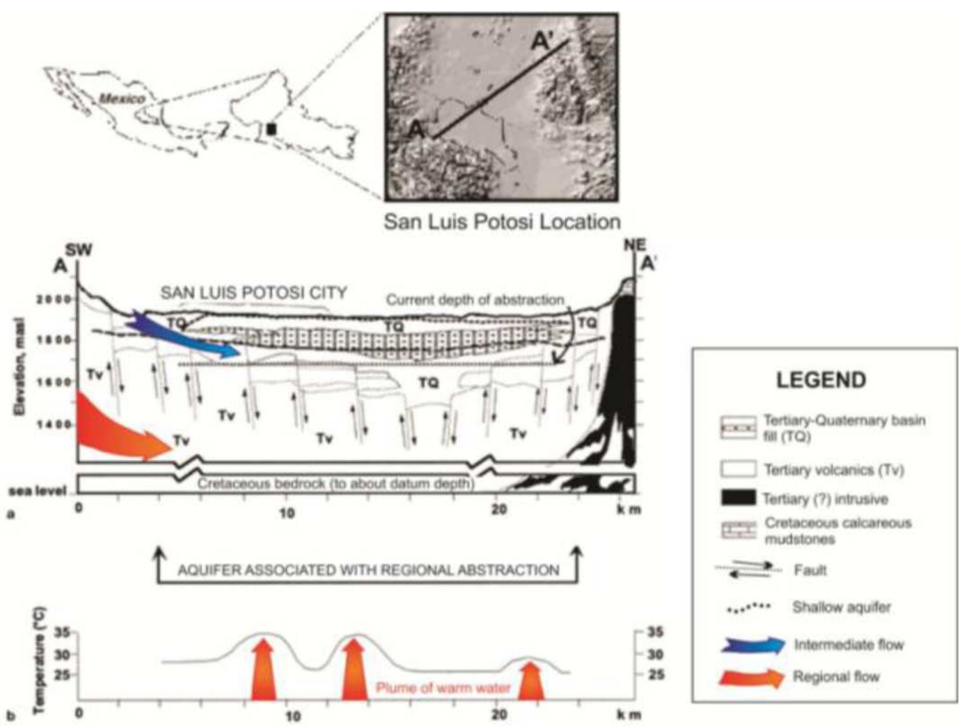


Fig. 2: Intermediate and regional flows beneath San Luis Potosi surface drainage basin. Adapted from (Carrillo-Rivera, 1992)

A natural fluoride concentration control may be postulated by lowering water temperature and increasing calcium and which is feasible as thermal water is calcite under-saturated (or near equilibrium). Calculations indicate that this mechanism is feasible. As fluorite over-saturation is not anticipated, an application of this solubility control was recommended for natural fluoride reduction for future groundwater extraction schemes. Specific borehole design under specific geological conditions may be used to induce extraction of regional flow to circulate through the granular material which is calcium-rich to trap dissolved fluoride (Carrillo-Rivera *et al*., 2002). Suitable mixing in a borehole between intermediate and regional flows keeps fluoride within acceptable drinking water limits. Regular pumping or step-drawdown tests should be devised including a definition of the particular temperature-fluoride relationship.

Any efforts to diminish fluoride concentrations in extracted groundwater in the SLP basin taking advantage of the hydrogeological and geochemical controls of fluoride could prove to be beneficial. In México, at least 15% of the total population estimated to be in excess of 110 M, are supplied with regional fluoride rich-water only in the semi-arid eastern portion of the Sierra Madre Occidental. The proposed model and fluoride control could have wider applicability in similar hydrogeological framework in other parts of Mexico and of the world where groundwater is obtained by boreholes tapping various flow systems. The application of proposed controls of fluoride attenuation by the hydrogeological environment may be optimal to conventional treatment plants, which represent a higher cost due to the initial purchase value of such plants and their current inefficiency performance due to the expected change in water quality with extraction time. There is an additional environmental concern in terms of the sludge that will require additional management. Consequently, there are several advantages in using flow systems functioning to gain natural fluoride control. The flow systems (Carrillo-Rivera *et al*., 2002) have been defined as:

- Regional flow (40.4°C) is related to a thermal system, as suggested by B+ (0.17 mg $L^{-1}$), F- (3.1 mg $L^{-1}$), Na+ (53.2 mg $L^{-1}$), Li+ (0.19 mg $L^{-1}$) concentrations that imply large residence time and interaction with rhyolitic rocks
- Intermediate flow (25.5±1°C) implies a cold system with low content of B+ (0.03 mg $L^{-1}$), F- (0.4 mg $L^{-1}$), Na+ (14.6 mg $L^{-1}$), Li+ (0.01 mg $L^{-1}$) which suggests short residence time and granular material interaction

**Extraction effect with time:** historical chemical analyses of water belonging to the identified regional flow show remarkable similarity with time for major ion composition (Carrillo-Rivera *et al*., 2009). Field groundwater temperature measurements have a linear relationship to fluoride concentrations which permits an estimate to be made of fluoride content in extracted groundwater. Current groundwater extraction increased from ≈ 0.6 $m^3$ $sec^{-1}$ in the 1960" s ≈ 2.6 $m^3$ $sec^{-1}$ in 1987, this induced vertical fluoride-rich flow into extraction boreholes located to the centre of the SLP basin, such increase in extraction enhanced the surface area affected by fluoride (>2 mg $L^{-1}$) inflow from 73 $km^2$ in 1987-135 $km^2$ in 2007. At present there is an estimated withdrawal is ≈4.1 $m^3$ $sec^{-1}$, additional boreholes are mainly tapping the regional system at the foot of the felsic volcanic highland to the west of the Basin.

Fluoride concentration of up to 18.5 mg $L^{-1}$ is found (Hurtado and Gardea-Torresdey, 2004) in groundwater obtained in western central Mexico. Tapped groundwater in 1987 for the SLP surface basin (Fig. 2) located in central Mexico, induced various proportions of a shallow intermediate flow (that travels in granular undifferentiated material, water tempera ture is between 23-28°C and low-fluoride and TDS) as well as a deep regional flow (that travels in volcanic felsic rocks, water temperature between 30-38°C and fluoride-rich) (Carrillo-Rivera *et al*., 2002). The mixing of these flows takes place depending on extraction regime, local contrast in hydraulic characteristics and borehole construction, depth, design and operation. Maximum fluoride concentrations found in 1987 (3.7 mg $L^{-1}$) were argued to become higher still, in time and space, should the input of regional fluoride-rich flow to the extraction boreholes was to be enhanced. The same information suggested that by the control of the extraction borehole-head water temperature at 28-30°C, an extracted water mixture with fluoride content close to the maximum drinking water standard of 1.5 mg $L^{-1}$ could be obtained. Additional fluoride control by extraction boreholes could take advantage of fluoride solubility controls to reduce its concentration in obtained groundwater by incorporating lithology (with $CaCO_3$ debris) and borehole construction design to regulate the different groundwater flows induced into an extraction borehole. The worst scenario would be the result of obtaining regional flow groundwater directly, which is fluoride rich.

Proposed natural fluoride controls appear to be managing the presence of fluoride in extracted groundwater in the SLP basin. Data for 1987 and 2007 further suggests that the devised controls of fluoride (Carrillo-Rivera *et al*., 2002) before water is extracted are applicable and that it is advisable to fully acknowledge them when new boreholes are constructed as well as in the management of existing ones as the costs of related paraphernalia to reduce fluoride once is at the surface is costly and environmentally unfriendly.

The flow system technique provides with a definition of the various flow systems that are present in the study area and its understanding regarding the natural controls that are enforced in the groundwater extraction process.

**Subsidence control, desiccation of springs:**

**Land subsidence:** scientific and technical studies on subsidence of the ground-level of Mexico City as related to groundwater extraction have been made since the beginning of the 20th century (Marsal and Masari, 1959). However, the increasing environmental impacts identified in the basin since the first springs dried-out in Xochimilco at the turn of the first half of the 20th century (whose disappearance coincided with a construction boom in construction of extraction boreholes in Xochimilco and elsewhere in the basin) include not only soil consolidation, but a damage to related ecosystems as well as to the health of the population due to an increasing deterioration of extracted groundwater quality. This suggests that the approach of carried out related studies has not been adequate.

There are two main causes of soil subsidence: (i) by natural conditions (influence of plate tectonics, seismic response and water-rock relation, among others) and (ii) by anthropic influence (extraction of: oil, groundwater, or minerals). Groundwater extraction can cause or trigger various environmental impacts such as: activation of geological faults, cracking and/or consolidation of soil.

Soil consolidation is the compaction of a unit of geological material caused by a change of stress. In this case the response to a change in pore-stress (Ppore) that at any point of the saturated zone is usually a response on the drop in hydraulic pressure (Phydraulic) because the total pressure (Ptotal) must be maintained constant, according to the following relation:

$$P_{total} = P_{pore} + P_{hydraulic} \quad (2)$$

Equation 2 suggest that total pressure should remain constant; so, a reduction on hydraulic pressure is complemented by an increase in pore-stress, which is evident as reduction in the volume of the aquifer material and this is manifested as subsidence or sinking of the ground-level.

There are four physical phenomena (Bouwer, 1978) linked to consolidation that contributes to an increase in pore-stress, these effects are often underestimated and their relevance in the functioning of the hydrogeological media is therefore unclear:

- Replacement of cold groundwater by warm water (Phydraulic is a function of water temperature)
- Transfer of water from one geologic strata to another
- Change of flow direction from upward (discharge) to downward flow (recharge) conditions
- Construction of heavy civil engineering infrastructure

The first two phenomena are linked to local management of groundwater; due to its inefficient extraction which locally induce ascending low density thermal water from deep geological units resulting in a reduction of hydraulic head (warm water has a low specific weight) which consequently increase pore-stress. The second, is an indirect response related to the flow of water from an aquitard towards an underlying aquifer material, which occurs when there is hydraulic communication between these two (semi-confined conditions); such flow occurs as a response to extracting water in a borehole obtaining water through an aquifer material that is induced from an aquitard. The low hydraulic conductivity of an aquitard implies the water loss from this unit is not naturally replaced; subsidence is the manifestation of volume loss. The third results from a change in groundwater flow direction that is produced as the regional water-table drops due to the summation of various effects such as change in land-use (effect on recharge conditions), as well as groundwater extraction of regional flow systems (whose recharge is generated outside the surface basin). This phenomenon is linked to a drawdown in the water-table below the roots of existing vegetation; drawdown that is also responsible of the disappearance of springs. The fourth is due to the construction of infrastructure on the ground level causing the compaction of the material.

**Brief hydrogeological description of Mexico basin:** this basin originally included a system of lakes: Texcoco, Chalco-Xochimilco, Tenochtitlan, Zumpango and Xaltocan (Fig. 3), the city has been constructed on the surface corresponding to that of the first three lakes. The Texcoco Lake contained brackish water while Xochimilco and Tenochtitlan were exceptionally low in salinity (Durazo and Farvolden, 1989). This water conditions prevailed until the end of the 18th century when the lakes of Tenochtitlan and

Texcoco were artificially drained by a tunnel and a drain built across the north limit of the basin.

This basin lies at the center of the Transmexican Volcanic Belt which crosses the Centre of Mexico E-W with a length and width of 950 and 110 km, respectively. The belt is the result of volcanic activity of Tertiary andesitic-basaltic type with sporadic spills of rhyolitic rocks during the Middle Tertiary and even Late Pliocene. Most of the volcanic activity is along regional faults with an E-W orientation, which incorporates other systems as a NW-SE in the western part and an NE-SW on the east side. A series of tectonic episodes produced several horsts and grabens which formed a succession of closed basins, such as the one of Mexico, whose filling material presents a variable sequence of sediments reaching more than 500 m of thickness. These volcanic materials are represented by a thickness of about 2,000-3,000 m rest on Cretaceous limestone rock with an estimated thickness of more than 1,500 m. The basement rock has not been defined (Edmunds *et al*., 2002). The sediments in the basin fill material have been of special interest as the aquitard (up to 300 m thick) outcropping on top of the lacustrine material has low hydraulic conductivity (horizontal, ~5 $* 10^{-6}$-2 $* 10^{-4}$ msec$^{-1}$; vertical ~$10^{-9}$ ms$^{-1}$) (Vazquez-Sanchez, 1995) and is related to groundwater dynamics and subsidence); this unit has a water content in the order of 60% or more (NRC, 1995).

Runoff result of rain (average 600 mm year$^{-1}$) descends from mountains representing a theoretical continuous yield of about 180 m$^3$ sec$^{-1}$, which usage is limited to transport wastewater generated in the city. The drainage density of the highland associated to the PNA-X (area of interest) is low due to the presence of highly porous basalt lava flows that control the surface runoff.

Evidence that the PNA-X area is located in a groundwater discharge zone is associated to vegetation and previously existing springs. Water quality of springs may be inferred by the quality of the water from boreholes that were constructed on a spring site ($Cl^-$ less than 10 mg L$^{-1}$ and temperature 17-24°C), quality that is associated with the presence of riparian vegetation. The low salinity reported for Lake Xochimilco suggests a contribution of flows of local and intermediate types (Durazo and Farvolden, 1989). In contrast, a contribution of regional flow implies a larger traveling distance and depth than the previous ones, so generated springs are thermal (38-42°C) and with high salinity as reported in Lake of Texcoco and Peñon de los Baños spring (Cl-650 mg L$^{-1}$) (Edmunds *et al*., 2002), conditions associated with Halophyte vegetation and alkaline and saline soils.

**Disappearance of springs:** that fed the PNA-X channels was the earliest evidence of alteration of the natural discharge conditions. The water-table and water level decline in channels by early 1950s were attributed to the construction of borehole fields that captured groundwater flow that used to feed channels and springs. This 7 intensive groundwater extraction was used so the growth of Mexico City could be imposed (Fig. 3).

Field observations in the PNA-X indicate that the effects of consolidation resulted in soil subsidence that has spread to not urbanized areas where the chinampas (artificial agricultural land built on a shallow lake) were formerly located; however, channels were closed to be dried-up during the early impacts of intensive extraction in the 1950´s. Recently, some 2 m$^3$ sec$^{-1}$ import of secondary treated sewage water have been used to improve water extraction deficit on channels. The water-table is now more than 70 m depth, just some meters below the base of the aquitard, so confined conditions have changed to unconfined (there is an unsaturated zone below the base of the aquitard causing low hydraulic conductivity conditions) Intensive and deep soil cracking has been commonly reported since the 1970s.

Results of detailed leveling carried out by the Local Water Works and Services office of the Government of Mexico City indicate a decline in the rate of consolidation since the decade of the 1980's, where the sinking of the ground was in the order of-0.49-0.25 m year. For the decade of 1990’s the sinking speed was minor,-0.28-0.22 m year$^{-1}$. This trend continues and for the year 2000, the reported values are from-0.18 m year$^{-1}$ and with a reported positive value of 0.02 m year$^{-1}$.

An application of the understanding of groundwater flow systems may imply that groundwater functioning from where the movement of water might be traced and the processes defined, as to deduce a possibility of natural control as for instance the rate of subsidence has been reduced by the disconnection of the hydraulic movement of water from the aquitard to the aquifer unit beneath (Huizar-Alvarez *et al*., 2004).

**Definition of the origin of flooding water:**

**The nature of flooding:** the northwest territory of the Buenos Aires province (Argentina) called “Pampa Arenosa” (sandy plain) (6`000,000 ha), is partially composed of two basic regions: Salado (salty)-Vallimanca (9`900,000 ha) and Lagunas Encadenadas (linked lagoons) of the west (1’100,000 ha); they are located in the Salado River basin comprising a surface of 17” 000,000 ha of the Buenos Aires province.

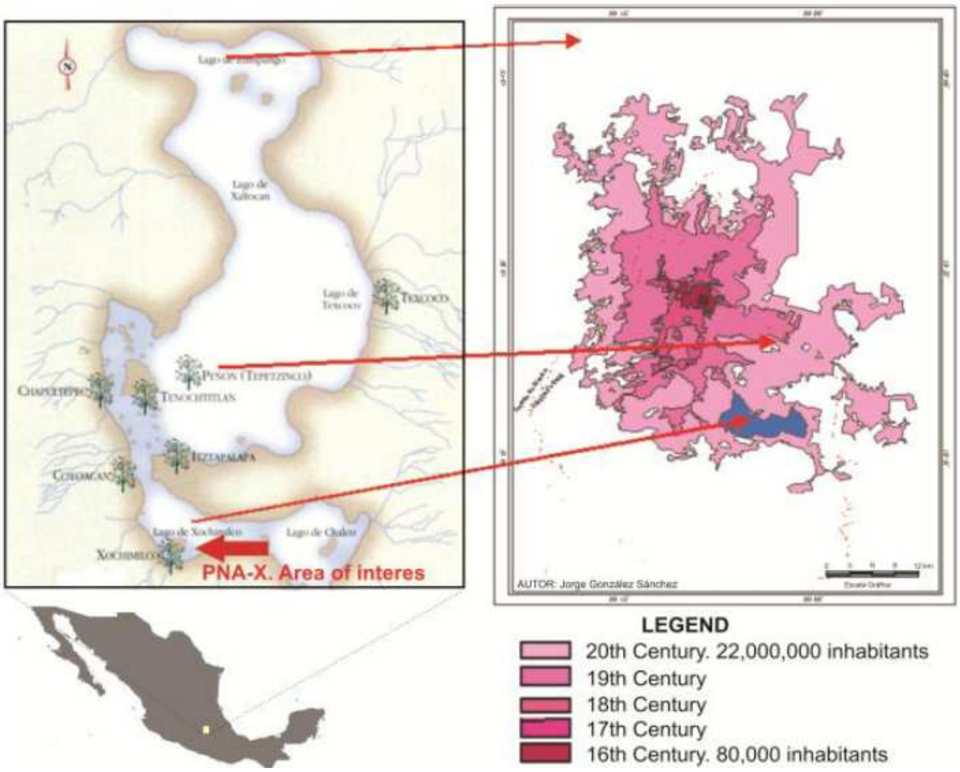


Fig. 3: Positions of Mexico City growth and area of interest

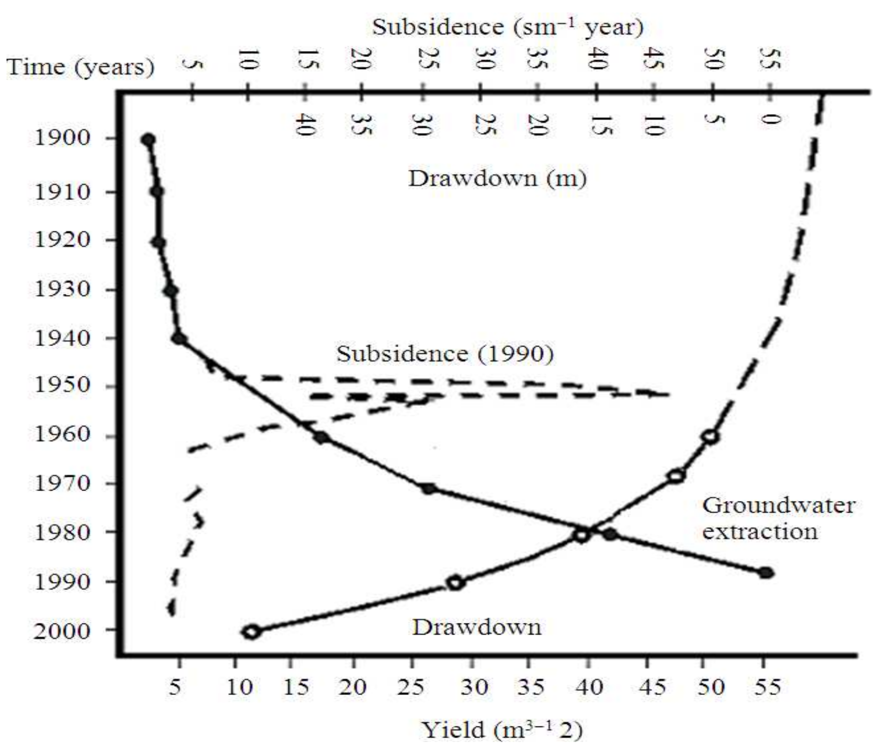


Fig. 3: Relation among groundwater extraction, subsidence rate end extraction, adapted (Marsal and Masari, 1959)

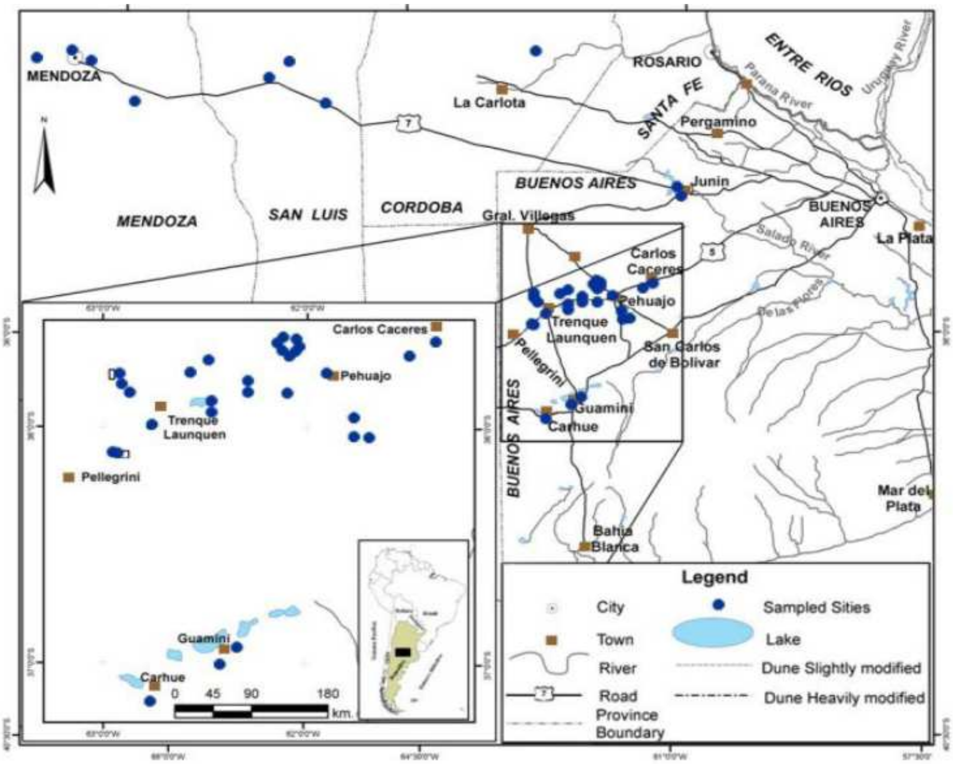


Fig. 4: Location of Buenos Aires study area showing water sampling sites. Adapted from (Alconada-Magliano *et al*., 2011)

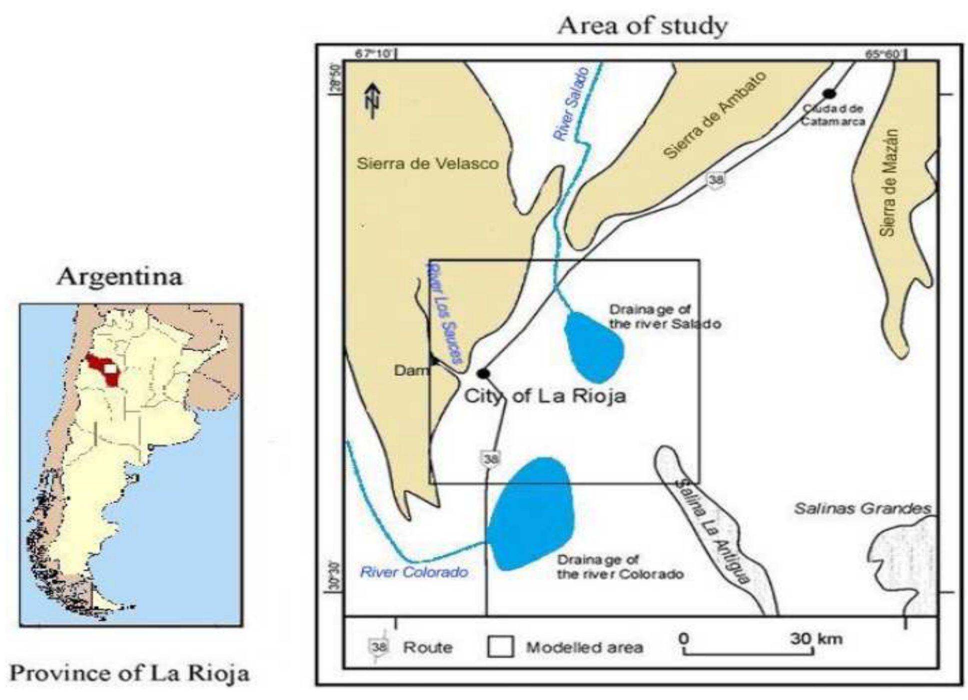


Fig. 5: Location of La Rioja study area, adapted (Martinez and Carrillo-Rivera, 2006)

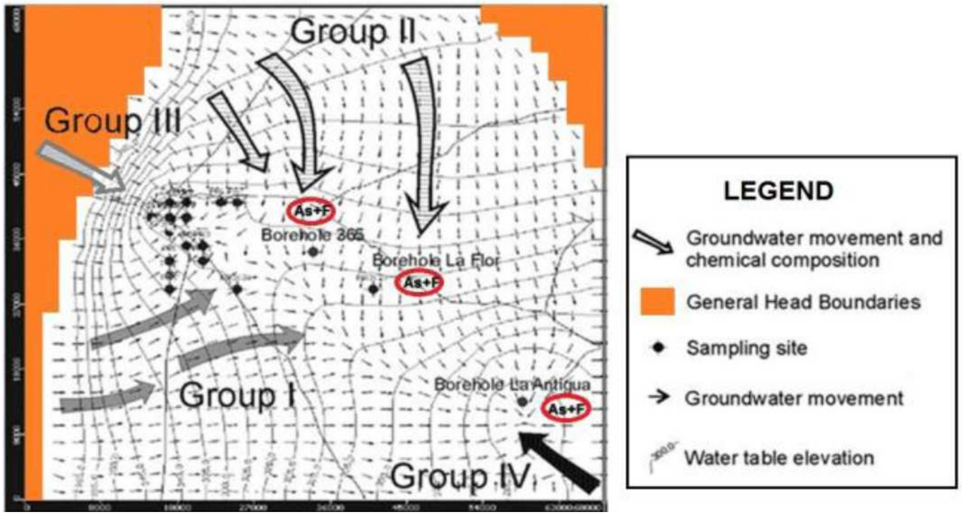


Fig. 5: Hydrochemical groups and groundwater movement distribution in the horizontal plane for La Rioja, adapted from (Martinez and Carrillo-Rivera, 2006)

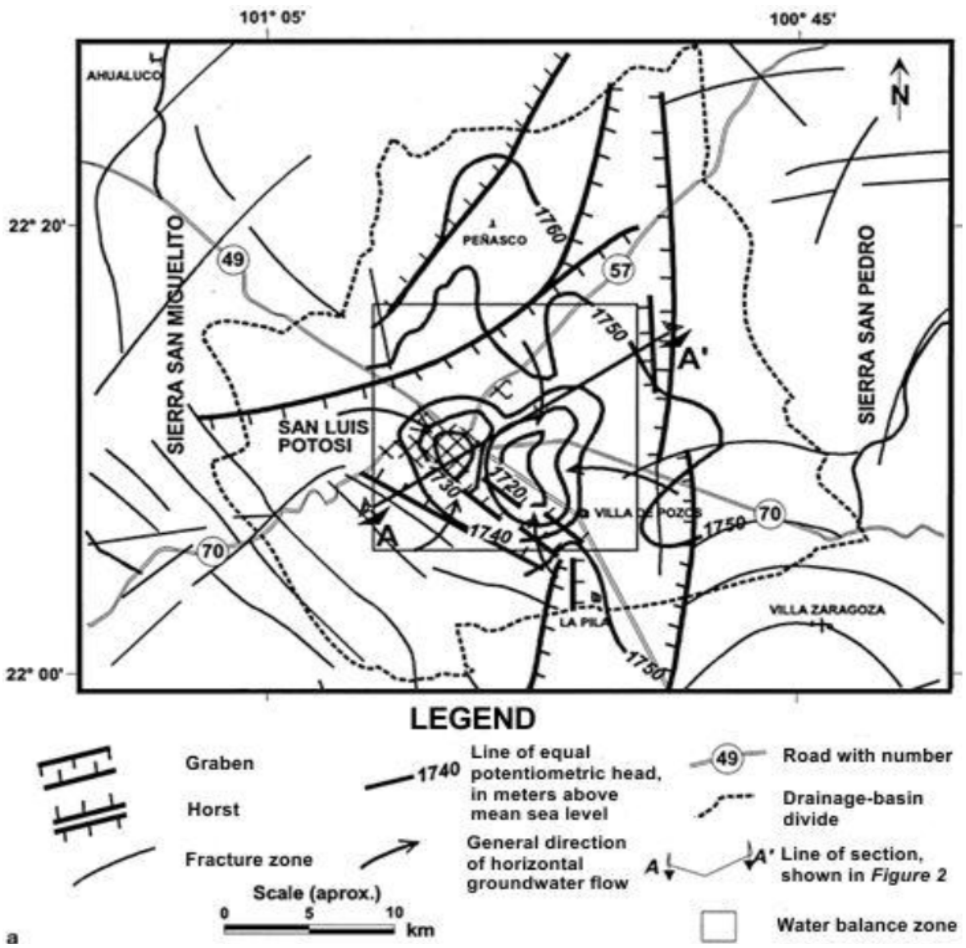


Fig. 6: General hydrogeological features and location of the groundwater balance zone for the San Luis Potosi study area, adapted from (Carrillo-Rivera, 2000)

These regions were recently connected to the Salado River by a canal (Jauretche-Mercante-República de Italia) which starts in the Hinojo-Tunas lakes complex and continues to the Bragado lagoon where it reaches the Salado River. The later starts in the mar chiquita and Gomez lagoons (Fig. 4). Economic activities are mainly agricultural. The climatic conditions of the territory are represented by periods of alternating drought/flooding as registered since 1576 (Alconada-Magliano *et al*., 2011; Alconada-Magliano, 2008), affecting the sustainability of the regions. The alternating behavior of floods has been blamed on natural and antropic causes; however, related processes had had little recognition. Local rainfall increase has been considered a direct and major natural factor in observed flooding enhancement, nevertheless average rainfall has been proved to have little influence on flooding as there has been flooding years without significant rainfall (Alconada-Magliano, 2008). Groundwater response using Modflow (McDonald and Harbaugh, 1988) modeling suggests that observed flooding water-levels might only be reproduced when head boundaries (inflow of groundwater originated outside the study area) were included in the analyzed system. A recharge of up to 50% of observed precipitation produced negligible water-level rise. Flooding has also been blamed on water transfer by rivers, canals and lagoons. A drought in the 1960`s produced the lowering of the water level in Encadenadas lagoons; the last humid cycle started in the 1970`s when a change in the annual mean rainfall started to increase from 700 a 1,000 mm (Alconada-Magliano *et al*., 2011; Alconada-Magliano, 2008). From 1985 the canal and related secondary constructed waterways increased flooding impacts due to water transfers and as barriers to flow, resulting in economic looses in the order of $516 USD millions in agriculture, $35 millions USD in cattle and $60 millions USD in rural infrastructure (Alconada-Magliano, 2008).

**Hydro-geochemical survey:** in order to find the nature of flooding water (and its possible control) a definition of present groundwater flow systems was carried out based on the geographical location of the study area that implies the possibility of hydrological influence of regional groundwater flows that recharge in the Andes Cordillera in the vicinity of Mendoza (1,400 m amsl) and probably San Luis (1,100 m amsl); it would be expected that these flows discharge in the extensive plain of the study area known as the Llanura Pampeana with topographic levels below 100 m amsl. This plain is located on sediments of Cretaceous to Pleistocene age in variable thickness (1,000-6,000 m), depending on the site; they fill up an irregular structure formed by a Pre-Cambrian-Paleozoic undifferentiated basement.

Based on the expected flow systems to be present a chemical interpretation of samples of surface and groundwater collected along a cross-section from Mendoza to Buenos Aires provinces was carried out by means of chemical trends, mass balance and water mixing models. The interpretation included major and minor elements as well as deuterium and 18-O. Groundwater influence of flows of local and intermediate nature were defined and the importance of recharge, transit and discharge zones was highlighted. Lagoon flood-water, as well as groundwater from observation and production boreholes showed evidence of flows with intermediate nature.

Surface water (dams, rivers) and groundwater from Mendoza and San Luis provinces are related to regional recharge zones. These waters show little chemical influence in the flooding water of the Buenos Aires area, as well as in observation wells and boreholes, all of them have lower levels of lithium that the 60.0μg $^{-1}$ traced in the recharge zones (Alconada-Magliano *et al*., 2011). The condition of intermediate (and local) flow discharge is postulated by the low value of lithium in lagoon water (35.2 $\mu g^{-1}$) as compared to Mendoza water. Similarly, a final prevalence in sodium as related to calcium and magnesium content is coherent with such lengthy path. Regional recharge water was identified in Mendoza and San Luis provinces and their discharge zone was inferred to be located in the Atlantic Ocean beyond the Buenos Aires province.

The composition of sampled groundwater in Buenos Aires belongs to intermediate and local flows; there is a lack of chemical and physical (i.e., presence of thermal springs) evidence of regional discharge zones forming lagoons or wetlands in the study area or neighboring sites (Alconada-Magliano *et al*., 2011). This is considered additional evidence on the flooding process that occurs, mainly, by the discharge of intermediate flow systems characterized by a temperature of about 35.5°C and STD of 8,286 mg $L^{-1}$ (sample BA2, Alconada-Magliano *et al*., 2011) of the Buenos Aires. For flow mixing modeling the intermediate and local flow (sample 17) with 19.0°C and 1,805 mg $L^{-1}$ TDS were used as end-members (Alconada-Magliano *et al*., 2011). Results were further assistance on the definition of the chemical characteristics of flooding areas.

The changes in observed composition along the flow path for the studied water, start with sulphate-bicarbonate and bicarbonate-sulphate type water in the recharge zone in Mendoza and change into bicarbonate-chloride type, following a chloride-bicarbonate type.

The final evolution represented by chloride and chloride-sulphate water suggests a large flow path proposing that flooding water is not related directly to an increase in precipitation.

Flow systems characterization allowed defining the nature of flooding water and related processes, which in turn permitted to suggest friendly environmental and economical measures to control flooding water according to its nature by bio-drainage alternatives (Alconada-Magliano *et al*., 2009).

**Basement position in flow-system control:**

**The nature of the questions:** the city of La Rioja, Argentina (Fig. 5) is in an arid region where groundwater is the potential source for development. Economic development of this Province in 1979 started when surface water sources were fully distributed to satisfy the needs of inhabitants (0.19 $m^3 s^{-1}$) and irrigation (0.21 $m^3$ $s^{-1}$) of inner city allotments (Alconada-Magliano *et al*., 2009). Additional water needs after 1980 have been covered with groundwater.

Increasing groundwater extraction for existing growth management created social unrest resulting from studies reporting negative hydrological balances. Hydro-myths started to circulate from early 1980s: „„boreholes are getting dry" "and„ boreholes are getting salty" . The public in general feared that prevailing development was endangering the groundwater sources; further, proposals for water imports would force La Rioja to rely on water with an origin beyond its administrative limits. Therefore a study (Martinez and Carrillo-Rivera, 2006) was carry out to define the groundwater flow systems and their functioning as related to the city of La Rioja from where a reliable reference for development could be established and to propose feasible economic activities in harmony with accessible water sources.

**The stratigraphic column:** Outcrops partially in the highlands of the study area, major outcrops represent Pre-Cambric to Lower Paleozoic rocks of intrusive (granite) and metamorphic nature, which are considered the hydrogeological basement. However, the Pre-Cambric and Paleozoic rocks show regional intensive faulting as well as related fractures and weathering features that could suggest positive water-bearing properties for these rocks. Tertiary sedimentary rocks (mainly cemented sandstones and conglomerates) are observed in restricted places on the eastern side of eastern bounding mountain range (Sierra de Velasco). Sandy strata combined with layers of gypsum and silica and calcareous concretions widely outcrop in the northeast of Sierra de Velasco. The topography that prevailed at the end of the Tertiary on the eastern side of the Sierra de Velasco was filled up with Quaternary deposits. These are widely exposed and cover old units with up to 700-900 m of mainly, alluvial sediments transported by Los Sauces and Salado rivers, forming the plain of the study area (Fig. 5). These materials vary in size from boulder in and close to the highlands to fine sand and silt in the plain resulting also from fluvial as well as eolian processes.

**The groundwater flow system:** Was found to be composed of three main flows: A regional, an intermediate and several local. The intermediate system provides water for extraction boreholes and discharges naturally in Salinas La Antigua. A chemical perspective suggests that the intermediate system has three groundwater groups. Group I (Fig. 5) defined to the north of the City of La Rioja with the highest temperature (26.8-33.0°C) and with high fluoride concentration (1.98-3.10 mg $L^{-1}$), the lowest lithium content (0.029-0.059 mg $L^{-1}$) and moderate arsenic (>0.038 mg $L^{-1}$). Group II has the moderate arsenic content (>0.038 mg $L^{-1}$) detected to the south of the City and high lithium (0.024 0.085 mg $L^{-1}$). Group III has the lowest TDS (456-931 mg $L^{-1}$) and arsenic (0.007-0.012 mg $L^{-1}$) and the highest lithium (0.067-0.141 mg $L^{-1}$). A regional flow is represented by Group IV with one order of magnitude higher strontium (4.870 mg $^{-1}$), lead (0.021 mg $L^{-1}$) and uranium (0.362 mg $L^{-1}$) content than the other groups. Results provide evidence to eliminate well-established hydro-myths about „„the boreholes are getting dry" and „„boreholes are getting saline water.

**Modeling basement position:** The general stratigraphy of the study area and the hydraulic properties (hydraulic conductivity, storage coefficient and porosity) of related units as well as the water-table elevation where documented (Martinez, 2001). The application of Modflow (McDonald and Harbaugh, 1988) modeling requires the position and nature of (hydraulic) boundary conditions, among which basement topography is required to be acknowledge as the lowest limit of groundwater flow. Such data was unavailable and several positions where claimed. Basement position was inferred from Na-K-Mg geothemometer (Martinez and Carrillo-Rivera, 2006; Martinez, 2001) obtaining the depth of groundwater circulation. The minimum obtained equilibrium temperature was ~50°C (ambient temperature of 20°C and a geothermal gradient of 3°C 100 m depth) implied that groundwater flow reached to a depth of 700-900 m. This result was in agreement with expected aquifer units thickness and flow modeling results which included three scenarios that incorporate an increase in extraction from 1980 with 0.076 $m^3$ $sec^{-1}$ 0.473 $m^3$ $sec^{-1}$ in 1998. The drawdown for that period of time was about 0.5 m. In scenario A, basement to a depth of 0.75 km with a graben structure produced an additional drawdown of 20 m. Scenario B, a basement to 3.0 km depth (without graben) resulted in water levels ~10 m above observed values. Scenario C, basement depth of 1.5 km (without graben) resulted in water levels some 2 m above observed values. Scenario D, with a flat basement to a depth of 0.75 km resulted in water-table elevations within observed values (±0.20 m) and in agreement with geothermometer calculations as well as with defined aquifer thickness of Tertiary and Quaternary material whose sequence extents beyond the study area.

These results assisted in defining a discharge of about 0.6 $m^3$ $sec^{-1}$ flowing evaporating through La Antigua Salty Plain; this groundwater could be used to additional development of the area in SPA (eco-tourism) activities, fish farming and in cultivation of protected species.

**Inter-basin flow:** Since the second half of XX Century the water balance has been the common method used to evaluate water sources; until recently, the surface basin of San Luis Potosi has not been the exception. So, the standard groundwater-balance equation (change in storage = recharge - extraction + inflow-outflow) was applied to this basin to get its functioning (Carrillo-Rivera, 1992; 2000). Groundwater hydraulic characteristics coincide with the conceptual hydrogeological model; the computed value for storativity (0.001) for the confined part of the deep aquifer unit was derived numerically from aquifer-test analyses (Carrillo-Rivera, 1992). A calculation of the total annual extraction from the deep aquifer was 85×106 $m^3$ (error ±20%). Groundwater inflow traveling to the centre of the confined extraction zone was calculated at 4.7×106 $m^3$ $year^{-1}$ (as for October 1986 to September 1987) using transmissivity (of production layer) values of 1.9×10-4-1.9 10-3 $m^2$ $sec^{-1}$ and 8.1×10-4-4.0×$10^{-3}$ $m^2$ $sec^{-1}$ for the fractured media and granular material, respectively. As all water flows towards the balance-zone, outflow is negligible. These values represent the yearly average horizontal groundwater flow (4.7×$10^6$ $m^3$) moving towards the extraction zone. Due to observed confined conditions, recharge is infeasible (rainfall entering the balance region indicated in (Fig. 6) as “aquifer associated with regional abstraction”); hence, any inflow would be based on purely 2-D horizontal flow. An important aspect is that the assumption of horizontal flow in the groundwater-balance equation fails to explain the remarkable temperature rise as extraction time has increased. The computed values of storativity do not reflect the reported small drawdown difference of 0.9 $m^{-1}$ year for 0.8 $m^{3-1}$ s extraction in 1972 and 1.35 $m^{-1}$year for 2.7 $m^{3-1}$ s extraction in 1987. When storativity value of 0.001 is applied, the water-table (or hydraulic head) would have been more than 200 m deep if there were not a water source coming from outside the surface drainage basin. Therefore, groundwater from regional sources becomes paramount in the hydrological understanding of the functioning of the SLP-Basin, from where adequate general water policies and particularly drought relief schemes may be devised or effects as climate change could be minimized.

**Groundwater flow systems functioning:** Therefore if the functioning of the regional flow system is overlooked, errors derived from the conceptual model to cope with drought or climate change conditions may produce severe environmental impacts such as those already observed in the SLP-Basin where: (i) the ignored vertical components of flow are responsible for changes in induced water quality that involve natural elements as fluoride (and sodium) as presented on Fluoride Control where its concentration increases with extraction time causing serious health problems among children and elderly; and (ii) similar behavior of extracted water response has been observed in geologically analogous drainage basins in Mexico as well as other parts of the world where thick aquifer layers are present and only the first hundred meters are tapped.

## CONCLUSION

The availability of PCs as well as related groundwater paraphernalia such as its modeling through the flow system theory has created a powerful advantage to study its functioning. This also poses an additional challenge to logically incorporate a water-system view approach. The vertical component of flow in recent studies is acquiring more interest as it suggests the presence and response of regional flow systems. A water-system view approach acknowledges the importance of: “not to seek to know all the answers, but to understand the question”. This old saying implies both thinking and acting, based on correct observations of the problem, thus allowing formulation of the correct question before recommending the correct solution. Examples of successful application of the groundwater flow systems in contrasting geological media suggest an agreeable groundwater functioning for each case was achieved. Proposed functioning permitted to recommend solutions that are more economical and environmentally friendly to control fluoride, diminishing of subsidence, or to manage flooding water, although they may have lesser technical and financial appealing (Carrillo-Rivera, 2003). Flow system identification provides with sound data to plan basin development and to acquire managing in postulated climatic evolution scenarios.

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