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State of knowledge and management of Ibero-american coastal aquifers with different geo-hydrological settings

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Coastal aquifers have played a major role in modern human occupation and economic development in Iberoamerica. Most of Iberoamerica population inhabits coastal areas, and water needs are frequently fulfilled with groundwater. Possible climate changes and consequent sea level rise will deeply affect coastal aquifers, putting considerable pressure in those water bodies. For the prediction of how these aquifers will behave in face of such challenges, and also to establish preventive measures against undesired effects, adequate knowledge is essential. This paper presents the state of knowledge of a number of Latin American coastal aquifers reasonably representative of the overall situation through a literature review, with compilation and synthesis of data. A synthetic comparative analysis conducted on 33 coastal aquifers in Latin America and the Iberian Peninsula is showed, as well as detailed information about three out of those aquifers with relatively more abundant data and of particular interest: Mar del Plata, in Argentina; Recife, in Brazil; and Low Llobregat, in Spain. Some of the conclusions of the comparative analysis are: very frequently, intensive groundwater abstraction has produced marine intrusion; management actions with different technical complexity have been undertaken in some areas, although the most common situation is a lack of management at all. However, legal and regulatory frameworks to protect groundwater are slowly improving or uprising. Major challenges are unawareness on aquifer problems and underfunding for management and investigation.

Introduction

Coastal areas are transition spaces between the marine and continental domains where natural or anthropogenic processes of consumption, production and exchange of mass and energy occur at high intensity rates. Such processes exercise an intense pressure on natural resources. One of the main resources in coastal areas is groundwater, which plays a very important role as the main - and in many cases a unique - source of fresh water for human populations, and the industrial and agricultural sectors, as well as for local ecosystems. Consequently, sustainable use of groundwater resources is imperative in these locations. Creation of effective public policies towards sustainability is necessarily based on the knowledge of aquifers functioning and on the evaluation of their environmental role, hydrogeological characteristics and vulnerability and developability as a freshwater source, as well as the effective involvement of groundwater stakeholders in monitoring and management.

Sea level is expected to rise 0.6 to 1.2 m by the end of this century. This will increase seawater intrusion into coastal areas but with highly variable results depending on aquifer characteristics and coastal conditions, from almost imperceptible to large penetrations. This, jointly with possible recharge changes due to climatic and global factors, may induce increased risks in the areas here considered.

In order to establish preventive measures against undesired effects, adequate knowledge is essential. Thus, to predict how these changes will affect the future role of coastal aquifers and to prevent unwanted effects, when possible, it is necessary to gather and systematize available data.

This paper presents a literature review and the state of knowledge and management of a number of Iberoamerican coastal aquifers reasonably representative of the overall situation, and illustrates the work of compilation and synthesis with details of three aquifers seemingly better known: Mar del Plata, in Argentina; Recife, in Brazil; and Llobregat Delta, in Spain.

To achieve those goals, published and unpublished information on 33 coastal aquifers of the Iberian Peninsula and islands (Spain and Portugal), the Caribbean Sea (Cuba) and the Atlantic and Pacific

coasts of Latin America (in Argentina, Brazil, Colombia, Costa Rica, Chile, Mexico, Nicaragua, Peru and Uruguay) has been extracted, synthesized and analysed (Fig.1). It is not an objective of this work to propose a classification for aquifers, but in order to manage all the information obtained as to compare and get common statements, it was helpful to group the aquifers. Taking into account the most common situations in Iberoamerican coastal areas, aquifers were divided in five operative categories: carbonated aquifers, thick detrital aquifers, small aquifers of local interest, urban and peri-urban aquifers and aquifers in small islands.

In the majority of the cases, intensive groundwater abstraction to satisfy local populations' needs or tourist-focused developments has produced significant depression of piezometric levels and marine intrusion. Additional problems include salinization caused by upconing, irrigation return flows and groundwater contamination due to lack of sewage systems and urban waste leaching in disposal areas. In some cases, the decrease of groundwater flow to streams, lagoons and wetland areas is already noticeable. Therefore, a great variety of situations such as geological settings, people's educational and income conditions, exploitation and contamination pressures, and other factors, occur in the vast area here considered.

Mar del Plata, Recife and Llobregat Delta aquifers have in common the fact that they are intensively exploited, with salinization and other pollution problems, and of great social and economic value in their settings. They also have monitoring and management plans, with public policies protecting their use and development (Bocanegra et al., 2008; Niñerola et al., 2009; Montenegro et al., 2008), so they are analysed to provide deeper insights of the studied aquifers.

The purpose of the article is therefore to present the state of knowledge about those aquifers. This will help to anticipate future developments and to assess the possible impacts of future global and climate change scenarios. Thus, in the following pages an attempt is made to look for common grounds and systematize the multitude of scenarios to portray a picture of the state of knowledge and awareness on coastal aquifers in Iberoamerica.

Materials and Methods

Scientific work on the 33 studied aquifers responds for most of the references cited here. Data from a variety of sources were compiled, integrated and typified according to Bocanegra et al. (2010) for operative purposes.

The 33 aquifers were, on a broad perspective, classified in 5 different types according to some specific characteristics: (1) Coastal aquifers in small islands are very sensitive and vulnerable. Intensive groundwater exploitation, mostly for tourist supply, has recently developed or is currently under development; (2) Carbonated coastal aquifers are prone to increasing permeability due to enhanced calcite dissolution in the mixing zone. Although this is a slow process, it has to be considered when the fresh-saltwater position is disrupted by pumping; (3) Thick detrital coastal aquifers, which are usually highly heterogeneous and anisotropic; (4) Mixed coastal aquifers, which do not show specific conditions, but may experience problems of different aquifer types simultaneously; finally, (5) Small coastal aquifers of local interest that share many features with urban and peri-urban aquifers, but their dimensions provide some specific factors.

The aquifers subjected to the extend analysis were selected due to the following factors: relative abundance and quality of data;

management actions currently implemented or under planning; and being a major field work area of the authors. This lead to the choice of three aquifers: Mar del Plata, Recife and Llobregat Delta.

Review of Iberoamerican Coastal Aquifers: A Summary

Main features of the studied coastal aquifers and related problems

Coastal aquifers are bounded by the sea, a base level characterized by a local mean value that not always coincides with the topographic datum. In detail, local sea level is subject to tides, waves and wind effects, occasional rare events, marine currents and evaporation in half-closed sea water bodies. Seawater is denser than freshwater, 1.025 versus 1.000 g/L for typical salinities and temperatures. Provided hydrodynamic forces are not significant in the groundwater body, freshwater floats on saltwater. Freshwater flow towards the coast reduces saltwater penetration into the continent, which forms a wedge that thins out landwards. The transition from freshwater to saline water may be quite sharp, thus forming an interface, or may be a more or less thick mixing zone, depending on local circumstances, the relative intensity of freshwater flow, and the fluctuations of sea and groundwater levels. Mixed (brackish) water in the ground is towed towards the coast by freshwater movement, which means that there is a marine water counterflow to compensate the salinity balance. This entire means that hydrodynamics of the continental-marine boundary is complex and depends on local circumstances of permeability, depth and layout of (heterogeneous) materials, as well as on freshwater and seawater flow oscillations (Custodio and Bruggeman, 1987).

Trends in seawater level, in the past or foreseen as a consequence of global change, modify the freshwater-saltwater relationship. In large aquifer systems, it evolves slowly, with lags of centuries to millennia. The aquitards respond especially slowly to the changes, as well as aquifers separated from the sea by aquitards. This means that taking into account water salinity distribution, the number of different coastal aquifers types is very large, and in reality each coastal aquifer, or sector of it, is unique and needs specific studies to address sustainability and management.

However, the main features of problems, management actions and needs are rather common to any type of coastal aquifer, and relevant differences are mostly related to local climate, to the country development level and to the set of available freshwater sources to supply demand. The main common features in the 33 studied coastal aquifers are:

- *Groundwater salinization by different causes* (induced marine intrusion; saline water upconing; connate marine water mobilization; recharge under arid conditions; infiltration of irrigation excess water). When groundwater development takes place, aquifer hydrodynamics are changed and so, consequently, the freshwater-saltwater relationships. In the case of intensive development, groundwater flow pattern may be deeply modified. This depends not only on well abstraction and penetration, but also on vertical permeability and interlayered heterogeneities. Trying to define common scenarios the following situations have to be taken into account:
 - Water-table coastal aquifers, open directly to the sea. Thickness

along the coast is important (thin and thick aquifers), jointly with permeability (large, as in karstified formations, young volcanics and well-sorted alluvium; small in other materials) and groundwater flow per unit coastal length (large if groundwater does not overflow before attaining the coast; otherwise small).

- Confined and semi-confined coastal aquifers. They can be open to the sea at an offshore position (the greater marine water density may hinder freshwater discharge into the sea bottom if freshwater head is not high enough), or separated by an aquitard or by recent sea-bottom low permeability sediments (caprock).
 - More or less homogeneous formations along the shore, as in some sandy formations.
 - Conspicuous heterogeneities along the coast, affecting transmissivity and aquifer bottom depth. Such are filled up incised palaeovalleys, coastal terraces and alluvial fans, main fractured zones in hard rocks and volcanics, and preferential karstic developments.
- *Generalized pollution by urban, industrial and agricultural activities.* In urban and peri-urban areas, where large industrial areas usually settle, the lack of sewage systems, the deficient conservation of networks or their late construction may be the cause of point but widespread groundwater pollution. Particularly in developing countries, groundwater pollution is usually observed at a rather late time, and only when generalized, serious water quality problems appear. Intensive agricultural activities are a frequent cause of coastal groundwater impairment in many areas.

- *Lack of planning for groundwater management.* Among other undesirable consequences, strong spatial concentrations of abstraction wells is a common feature. This leads to localized, large drawdowns that disturb the former saline-fresh water equilibrium and induces brackish and saline water to progress landward and saline water upconing, among other undesirable effects.
- *Lack of monitoring networks.* The existence of adequate groundwater monitoring networks in coastal aquifers is more rare than common, even in developed countries.
- *Insufficient knowledge* about the aquifer functioning, the existing problems, the needs for conservation, and the extent of possible anthropic impacts. This is often compound with inadequate conceptual models and lack of awareness about the risks facing groundwater resources.

Typification of the studied aquifers

Typification usefulness is to find some common feature, in order to help in the specific studies. Some specific characteristics can be drawn for the aquifer types defined with basis on the present research. They are summarized in Table 1 according to this applied classification.

For example, *coastal aquifers in very small islands* make any possible problem to reach easily the aquifer boundaries. Also, in many small islands intensive groundwater exploitation, mostly for tourist supply, has developed very recently or is currently under development. In all the studied aquifers of this kind, this has always happened

Fig. 1. Location of the studied aquifers. Numbers correspond to those in the first column of Table 1.

Table 1. Typification of the reviewed aquifers and their main hydrogeological characteristics, existing problems and some references

<i>Country / Aquifer name</i>	<i>Hydrogeological characteristics</i>	<i>Main existing problems</i>	<i>Management actions</i>	<i>References</i>	<i>Type of Aquifer</i>
<i>Cuba</i> [1] Cayo Largo del Sur	3 km ² ; 10 to 13 m thick. Sands overlying a karstified limestone.	Overexploitation. Saline intrusion	Monitoring, desalination plant, construction of drains	López Infante (2000)	Aquifer in small islands
<i>Chile</i> [2] Isla de Pascua	166 km ² . Volcanites, dominantly basalts. Thin freshwater lens around the island.	No springs, no surface water. Salinization of coastal wells	Spreading abstraction, placing the wells far from the shore	Herrera et al. (2004), Herrera and Custodio (2008)	Aquifer in small islands
<i>Spain</i> [3] Amurga Massif; Gran Canaria island; Canary Islands	30 km ² , up to 300–500 m thick piling of phonolitic flows with ignimbrites	High salinity for human and agricultural uses, of climatic origin. Low recharge rate	Desalination plants, groundwater import, treated sewage water reuse	Custodio and Custodio (2001)	Aquifer in small islands
<i>Spain</i> [4] Betancuria Massif; Fuerteventura, Canary Islands	300 km ² ; 100 to 200 m thick. Old shield basalts and intrusive rock bodies, with some recent volcanic flows	Low recharge. Brackish groundwater recharge due to arid climate	Desalination plants. No ground-water management plans but for well distance to the coast	Herrera and Custodio (2000)	Aquifer in small islands
<i>Spain</i> [5] Telde aquifer; East of Gran Canaria, Canary Islands	Some 400 km ² . Volcanic aquifer, some interlayered conglomerates	Overexploitation. Salinization due to irrigation return flows. Marine intrusion	Water desalination. No clear perception of problems	Cabrera and Custodio (2004)	Aquifer in small islands
<i>Colombia</i> [6] Isla de San Andrés aquifer	25 km ² ; 100 to 150 m thick. Karstic aquifer with limestones and consolidated calcareous silts.	Marine intrusion over-exploitation, lack of planning, high water demand.	Environmental management policies; control actions	INGEOMINAS (1993)	Carbonated aquifer
<i>Costa Rica</i> [7] Cahuita aquifer, Limón, Caribbean coast.	Unknown geometry. Fluvio-marine sands, clayey materials, and coralline limestone.	Overexploitation, marine intrusion, groundwater contamination.	No specific actions	Rodríguez Estrada (2002)	Carbonated aquifer
<i>Cuba</i> [8] Costera Sur de La Habana; Artemisa-Quivicán aquifer	968 km ² ; 100 - 500 m thick. Upper aquifer: karstified limestones; lower aquifer: karstified clayey limestones.	Intense exploitation. Stable hydrodynamic situation	Shoreline protection wall 35 km long.	Rudovol (1974)	Carbonated aquifer
<i>México</i> [9] Yucatán Península aquifer	Karstic aquifer: very hard limestone. “Cenotes” semicircular belt 240 km long; submerged cavities 15–100 m long.	Seawater intrusion up to 40 km inland; lack of sewage system	Managed by the National Water Commission	Marín (1990)	Carbonated aquifer
<i>Portugal</i> [10] Aveiro-Baixo Vouga Basin	1,800 km ² . Thick Meso-Cenozoic sequence underlying Quaternary deposits. Dominant siliceous sandstones	Water level decline increases water salinization risk through confining layers.	Construction of new boreholes is forbidden.	Melo et al. (1998) Marques da Silva (1988)	Thick detrital aquifers
<i>Spain</i> [11] Campo de Dalías aquifer system (SE coast, Almería)	330 km ² . Triassic dolomites and Upper Pliocene calcarenites	Intensive irrigation; lateral and downward salinization.	Desalination. Enhanced recharge by creek dams. Water reuse.	Molina et al. (2000) Dominguez and Custodio (1992)	Carbonated and thick detrital (mixed) aquifers
<i>Spain</i> [12] Inca-Sa Pobla aquifer system, Mallorca island	140 km ² ; 100 to 200 m thick. Calcarenes, reef carbonates, bay clays and recent alluvium	Effects on rural areas and protected wetlands. Sea water intrusion.	Rules to limit abstraction	Manzano et al. (2001)	Carbonated and thick detrital (mixed) aquifers

Table 1. Continued

<i>Country / Aquifer name</i>	<i>Hydrogeological characteristics</i>	<i>Main existing problems</i>	<i>Management actions</i>	<i>References</i>	<i>Type of Aquifer</i>
Spain [13] Pla de Palma aquifer, Mallorca island.	60 km ² ; 120 to 150 m thick. Calcareenites, reef carbonates, clays and some recent alluvium	Overexploitation, marine intrusion, seasonal salinity changes.	Desalinization. Importation and management of other water sources.	Custodio et al. (1992) Barón and González (1995)	Carbonated and thick detrital (mixed) aquifers
Argentina [14] Coastal aquifer of Bahía Blanca industrial area, Prov. Buenos Aires	Upper aquifer: 15-30 m thick, lagoon and salt marsh coastal deposits. Lower aquifer: 100-200 m thick, loess and silt cemented with carbonate.	Subsidence, damage to buildings, industrial contamination.	Monitoring plan. Environmental education.	Bonorino and Albouy (2003)	Thick detrital aquifers
México [15] Costa de Hermosillo aquifer	3200 km ² ; 200 m thick. Crystalline bedrock. Graben- horst sequence filled by Tertiary sediments and alluvial deposits.	Marine intrusion; central mixing zone penetration rate 650 m/year; current position up to 32 km inland.	Abstraction reduction and well relocation.	Rangel Medina et al. (2004)	Thick detrital aquifers
Spain [16] Baix Camp – Tarragonés, Catalonia	300 km ² , 30 to 150 m thick. Mostly gravels and sand layers; clayish interlayering more frequent downwards, which may contain saline water.	Overexploitation, increased saline water, saline encroachment problems.	Water transfer from the Ebro river. Control of abstractions and drilling of new wells	Schneider (2003) Custodio et al. (1986a) Bayó et al. (1992)	Thick detrital aquifers
Spain [17] Plana de Castelló aquifer system	464 km ² . Detrital sand and gravel layers interbedded with silty and clayey layers. Porous, mostly confined.	Marine intrusion, over-exploitation for irrigation, industry and tourist resorts.	A water users' association has been recently created.	Andreu et al. (1986) ITGE (1989)	Thick detrital aquifers
Spain [18] Doñana aquifer system Huelva-Sevilla	2700 km ² ; a few to >150 m thick. Detrital aquifer; mostly sands and silts, locally gravels and clays.	Contamination by agriculture. Decreasing discharge to ecologically sensible areas. Salinization.	Restrictions on abstraction. Well closing. Administrative control.	Manzano et al. (2005) Custodio et al. (1994) Custodio et al. (1994)	Thick detrital aquifers
Argentina [19] La Plata coastal aquifer, Pcia. Buenos Aires	100 km ² . Upper aquifer: 25-45 m thick. Lower aquifer: 15-25 m thick. Sandy or clayey silts and carbonate layers.	Intensive exploitation, marine intrusion, anthropogenic pollution.	Environmental education.	Bonorino and Sala (1983)	Urban and peri-urban aquifers
Argentina [20] Mar del Plata coastal aquifer, Pcia. Buenos Aires	900 km ² ; 70 to 100 m thick. Bedrock forms a graben- horst sequence. Silty-sandy sediments of fine-grained sandy textures	Intensive exploitation, marine intrusion, anthropogenic pollution.	Water Plan. Municipal control of abstractions.	Bocanegra et al. (1993) Bocanegra et al. (2008)	Urban and peri-urban aquifers
Brazil [21] Recife coastal plain: Cabo, Beberibe and Boa Viagem aquifers, Recife Metropolitan Region, Pernambuco	Extent: 112 km ² . Cabo aquifer: semi-confined, 90 m thick: sandstones. Beberibe aquifer: semiconfined, 100 m thick sandstones. Boa Viagem aquifer: unconfined, 40 m thick, sand and silt.	Intensive exploitation, piezometric level drawdown, increasing salt content in several wells, pollution, influence from estuarine areas and mangroves.	Ownership, well drilling, use, artificial recharge and contaminant protection are regulated by State laws	Custodio et al. (1977) Montenegro et al. (2008)	Urban and peri-urban aquifers
Nicaragua [22] San Juan del Sur aquifer	400 km ² . Discontinuous and shallow aquifers formed by meteorization and faulting or fracturing of volcanic and sedimentary rocks, partially filled by alluvial deposits.	High demand for a growing population and tourism. Lack of sewage system.	The Municipality is working in a territorial management plan.	Ramakrishna (2004)	Urban and peri-urban aquifers

Table 1. Continued

<i>Country / Aquifer name</i>	<i>Hydrogeological characteristics</i>	<i>Main existing problems</i>	<i>Management actions</i>	<i>References</i>	<i>Type of Aquifer</i>
<i>Peru</i> [23] Máncora Coastal aquifer	Detritic alluvial aquifer with variable depth with confined sands and gravels.	High salinity rise, mostly climatic. Future over-exploitation by tourism activity.	None cited	Ardila (2001)	Urban and peri-urban aquifers
<i>Uruguay</i> [24] Raigón aquifer	1800 km ² ; 10-30 m thick. Fine sands to gravels with conglomeratic lenses and clay levels.	Overexploitation. No appropriate sewage system. Chemical plants.	Monitoring and territorial plan.	De los Santos (1998)	Urban and peri-urban aquifers
<i>Brazil</i> [25] Coastal aquifers, Eastern Rio de Janeiro State	Shallow sand dune and beach deposits interbedded with finer lagoon sediments	Overexploitation, fragile system equilibrium, lack of sewage system.	Environmental education; use of surface sources from other basins.	Silva Jr. and Pizani (2003)	Small aquifer of local interest.
<i>Colombia</i> [26] Eje Bananero of Urabá aquifer	288 km ² ; 25 to 200 m thick. Alluvial deposits underlain by a sedimentary sequence.	Intensive exploitation, seawater intrusion.	Abstraction concessions and well permits. Monitoring.	Cossio and Vargas (1995) Gutiérrez (2006)	Small aquifer of local interest.
<i>Colombia</i> [27] Morrosquillo aquifer	310 km ² ; 65-80 m thick. Fine quartz sands, gravels and granules with clay interbeddings.	Overexploitation, marine intrusion, septic wells, agrochemicals.	Municipal development plan to reorder land use.	Gutiérrez (2006)	Small aquifer of local interest.
<i>Colombia</i> [28] Santa Marta aquifer	48 km ² ; 32 m average depth; Unconfined alluvial terraces formed by gravels and sands.	Overexploitation, marine intrusion, sewage effluents	Pilot artificial recharge structure on the river; induced infiltration	Rodriguez et al. (1994)	Small aquifer of local interest.
<i>Costa Rica</i> [29] Tamarindo aquifer; Guanacaste	Unknown extent; thickness around 10 m. Alluvial and colluvial deposits.	Intensive tourism, unplanned development; seawater intrusion.	Pumping control.	Arellano and Vargas (2001)	Small aquifer of local interest.
<i>Portugal</i> [30] Campina do Faro aquifer system	86.4 km ² ; up to 400 m thick. Confined to semiconfined karstified sandy limestone aquifer and phreatic aquifer with coarse sands.	Salinization and nitrate contamination from agriculture.	Measures to reduce nitrogen load on groundwater, with poor results.	Stigter et al. (2005); Stigter et al. (1998)	Small aquifer of local interest
<i>Portugal</i> [31] Luz-Tavira aquifer system	28 km ² ; up to 700 m thick. Confined to semiconfined karstic limestone aquifer and phreatic karstified sandy limestone aquifer.	Salinization and nitrate contamination from agriculture.	Measures to reduce nitrogen load on groundwater.	Stigter et al. (2005); Stigter et al. (1998)	Small aquifer of local interest
<i>Spain</i> [32] Baix Llobregat aquifer system, Catalonia	80 km ² ; 30 to 100 m thick. Water-table aquifer that is in the delta centre becomes a two layer aquifer (unconfined / confined) separated by an aquitard.	Conspicuous sea water intrusion into the deep aquifer.	Joint groundwater and surface water use. Artificial recharge. Reclaimed water injection into wells. Users' association.	Custodio et al. (1986b; 1979); Niñerola et al. (2009)	Small aquifer of local interest
<i>Uruguay</i> [33] Paloma aquifer, Rocha	120 km ² ; 30 to 150 m thick. Silty-sandy loessic sediments with fine-grained sandy textures.	Marine intrusion, anthropogenic pollution. Iron in groundwater.	No pumping in winter. Aeration to reduce iron problems.	Roma (2007)	Small aquifer of local interest

without land and water planning. Decreasing groundwater pumping is advisable, but this must be at least accompanied by other measures, like sewage collection and reuse of treated waste water, as well as relocation of wells.

Carbonated coastal aquifers are prone to increasing permeability due to enhanced calcite dissolution in the mixing zone, leaving cavities. They may be disrupted by pumping and may provoke sinkholes by cave collapsing, which is a serious hazard in urban and peri-urban areas. Also, preferential groundwater flow through underground conduits may facilitate pollutants to unexpectedly reach particular water supply wells or springs, without being noticed by existing monitoring networks.

Thick detrital coastal aquifers are usually highly heterogeneous and anisotropic, which generates relevant spatial permeability variability. Some measures like pumping and new drilling control, or water transfer from foreign basins, have been launched. However, none groundwater and land management plan has been identified.

Mixed coastal aquifers do not show specific situations, but they may experience the problems of different aquifer types at the same time. The studied mixed aquifers share some of the circumstances of carbonated and thick detrital aquifers.

The main common feature for **urban and peri-urban coastal aquifers** is probably a stressing competence for land and water between urban, industrial and agricultural uses. Regardless of their lithology and dimensions, the local climate, and the existence or not of surface water sources, those aquifers are usually the cheapest water source, so they are heavily exploited and easily contaminated. Salinity, and especially antropic contamination may arise and provoke very serious health problems, most dramatically in some big coastal urban areas in developing countries.

Small coastal aquifers of local interest share many features with urban and peri-urban aquifers, but their dimensions provide some specific factors. Probably the most relevant one is that they act as a water reservoir that may be emptied during the dry season and refilled during the wet one. Thus, groundwater is usually very recent and show quality problems derived from recharge water already impacted by human activities. They show different degrees of knowledge and management, but almost all of them (except the Tamarindo aquifer, in Costa Rica) have been studied for hydrodynamics, groundwater quality and vulnerability.

The Mar del Plata, Recife and Llobregat Delta Case Studies

The state of knowledge and management of three selected Iberoamerican coastal aquifers with relatively abundant data, Mar del Plata (Argentina), Recife (Brazil), and Llobregat Delta (Spain) ([20], [21] and [32] in Table 1, respectively), are presented with some detail to highlight cases of successful groundwater development, monitoring and remedial measures, as examples of what can be proposed in the future for a sustainable management in other reviewed aquifers.

Mar del Plata

Mar del Plata, located in Argentine northern coast, is the main tourist centre of the country, with a stable population of 621,000 inhabitants and a seasonal population exceeding 1 million. Water needs

are almost exclusively supplied by groundwater sources. The geology consists of a quartzitic Palaeozoic bedrock overlain by a sedimentary cover of Upper Tertiary and Quaternary deposits. Miocene clayey-sandy sediments are found at 100 m depth, covered by Quaternary loess-like sediments. From a hydrogeological viewpoint, Quaternary sediments are the most important reservoir, forming a multilayered phreatic aquifer with thickness ranging from 70 to 100 m, hydraulic conductivity of 10-15 m/day, and transmissivity of about 600-800 m²/day in the urban area and between 1000 to 1400 m²/day in the rural area (Bocanegra et al., 2007). The storage coefficient obtained from pumping tests is 0.001, and porosity is approximately 0.15. The average rainfall in 1930-2009 was 910 mm/year in this city. Natural discharge is towards the sea. Artificial discharge due to pumping has historically lead to significant aquifer head decline.

The most commonly occurring environmental problems related to water resources are: high urban expansion, seawater intrusion, agricultural pollution of groundwater, inadequate waste management, and recurrent or rare flash floods in urban and surrounding areas. Although salinity problems occur, in this case nitrate and biological pollution are more relevant than chloride as pollution indicators.

Regarding management actions, the use of indicators of pressure, state and response to analyse groundwater conditions in Mar del Plata was considered by Bocanegra et al. (2007) as the most effective tool for groundwater management decision making. Despite the critical political and economic context, there have been satisfactory answers to the problems and demands originated around the groundwater resource. Evaluation of global and climate change effects on the role and conditions of Mar del Plata aquifer could be possible with the same indicators used by Bocanegra et al. (2007), that could eventually allow prospective of future behaviour facing those problems.

Recife

Recife, located in Brazilian northeastern coast, is one of the largest cities in Brazil, with approximately 3.7 million inhabitants in the Metropolitan Area. It is located on a flat lying plain (Recife Plain) ranging from 1 m to 10 m above sea level, with the Atlantic Ocean to the East. Geology comprises a basement of crystalline rocks, covered by sedimentary rocks of the Pernambuco-Paraíba basin and volcano-sedimentary rocks of the Cabo Basin. The crystalline basement crops out in the western portion of the Metropolitan Area. The Recife Plain aquifer system consists of two semi-confined deep aquifers, Cabo and Beberibe, overlain by a water table aquifer, Boa Viagem. The Cabo aquifer consists of sandstones, siltstones and mudstones, presenting an average thickness of 100 meters. The Beberibe aquifer, to the north of the dominant Pernambuco lineament, has an average thickness of 100 m and consists of sandstones with interbedded siltstones and mudstones. The Boa Viagem aquifer, with an average thickness of 40 meters, covers the Beberibe and Cabo aquifers, and is composed of sands, silts and clays. In this aquifer, groundwater is easily exploitable and plays a fundamental role in the recharge of the two underlying aquifers. The Beberibe Formation is the most exploited aquifer in this area (Montenegro et al., 2008). The semi-confined Cabo aquifer has the largest number of wells in exploitation, but with relatively low discharge rates, and is an important source of private water supply for Recife. Boa Viagem aquifer has a much higher specific capacity than the other aquifers. Transmissivity and storage are relatively low in all aquifers.

Presently, under intensive exploitation conditions, the aquifers

are vulnerable to degradation by different causes. Several wells in this region have been showing increasing salt content over the years, and in some cases they were disabled but in others simply abandoned, increasing the risk of aquifer contamination from several sources. The southern area of the Cabo aquifer is intensively exploited, which may explain the salinity increase by seawater intrusion. Salinization also can be caused by wells interconnecting different aquifers, with the upper aquifer contaminated by sewage disposal, presence of mangroves and connection with river estuaries. The vertical flow through the semipermeable layer that connects the two aquifers is another probable cause of the upcoming salinization of the Cabo aquifer. Either the way, the condition of intensive exploitation of the aquifer system has a decisive influence on the increasing levels of groundwater salinity in the Plains of Recife.

Llobregat Delta

The Llobregat River lower valley and delta are located at the southwest of the Barcelona's Metropolitan Area, to the Northeast coast of Spain. They consist of about 30 km² of alluvial valley up to 1 km wide, and a delta of roughly 100 km². The system contains very transmissive aquifers fed by rainfall infiltration, by small creeks draining the mountainous boundary, and by the Llobregat river water infiltration through the river bed and in the irrigated agricultural areas along the valley, which use river water. The aquifer system is a key groundwater source and reserve for a densely populated area (ca. 4 million), besides industrial settlements and remaining irrigated agriculture (Niñerola et al., 2009).

The delta is formed by a sedimentary package ranging from Pliocene to Quaternary in age, the current shape resulting of the delta's progradation during the last Holocene post-glacial marine high stand. In the low valley there is one unconfined aquifer, while in the delta there are one upper and unconfined aquifer and one deep and confined aquifer. These two aquifers partially merge at the delta boundaries. Both aquifers are separated by a wedged body of silt, clays and sandy clays, its thickness increasing towards the sea at the time that produces a more effective isolation of the two superimposed aquifers. The most important aquifer layer for human water supply is the one of the low valley and deep delta's aquifer, this last being also economically important for industries (Niñerola et al., 2009).

Intensive groundwater abstraction produced severe quantity and quality problems already detected more than 30 years ago, which prompted the Water Authority to develop studies during the last four decades. An important landmark for the aquifer management was the creation in 1975 of a Groundwater Users Community aiming to improve the situation and halt the disposal of contaminants in the territory, especially as filling materials of former gravel pits. But the main problem is marine intrusion in the most used deep, confined aquifer. The situation worsened along the years, and it urged to develop more detailed geological and hydrogeological studies ending with groundwater flow and transport modelling. It also prompted the design and implementation of a coastal injection barrier which uses highly treated waste water. Other severe pollution problems, like the appearance of dissolvents in supply wells have been afforded by the own users through the air stripping technique. After the 1985 Spanish Water Act, and especially after the enactment of the European Water Framework Directive of 2000 (WFD), the aquifer status is regularly monitored and deterioration trends are being identified in order to design reversing actions and thus complaint the WFD objective of

good chemical and quantitative status (Vázquez-Suñé et al., 2006).

Other management actions under rule are artificial recharge in ponds, induced recharge though river bed scarification, and the combined use of groundwater and surface water (river water and treated water) along the year.

Discussion and Concluding Remarks

The comparative study performed under the scope of UNESCO IGCP 519 international cooperation project of, regarding 33 coastal aquifers in Iberoamerica, has revealed some common features in terms of groundwater use, problems and groundwater management, such as:

- intensive exploitation;
- need for studies to support planning and management actions at the needed level;
- need for monitoring;
- need for arising awareness and involvement of users and society in management, planning and actions.

Besides, the analysis reinforces that control management actions, beyond economic considerations and specific works, depend upon:

- characteristics of the system;
- participation (society, stakeholders).

International integration could improve promotion of sustainable management in endangered coastal aquifers. An example of international cooperation regarding coastal aquifers in Europe is SALTRANS project (SALTRANS, 2004). The final document stresses that international cooperation and periodic meetings of specialists, such as SWIM meetings, have advanced the state-of-the-art on seawater intrusion.

In general, a strong correlation between economic and human development and aquifer problems awareness and management can be observed. This is clearly seen for the case of urban and peri-urban aquifers, which have the largest number of aquifer studies and of management actions.

The aquifers with fewer management activities are usually those in which there is a low level of knowledge regarding their geometry, flow dynamics and hydrogeology. Conversely, aquifers that are well known, regularly monitored and to which modern and more sophisticated techniques have been applied (such as hydrogeochemical and isotopic techniques, flow and transport modelling, evaluation of marine intrusion and contamination risk assessment) usually have diverse management strategies. Common activities include remediation by artificial recharge, decrease and relocation of extractions, and even procedures to modify the dynamics of saltwater-freshwater relationships by means of freshwater injection and saltwater abstraction.

In some cases, legal and regulatory activities to protect groundwater resources are scarce or nonexistent, whereas in other cases they constitute the support of an effective management plan. It was noticed that, in general, the creation of effective institutions that reunite and successfully represent the users and the civil society is a necessary step for monitoring and to propose and implement adequate management strategies.

Nonetheless, this approach also requires important efforts to build technical knowledge and credibility.

The greatest challenge in coastal areas is the lack of awareness of most decision makers and users regarding the negative impact of aquifer overexploitation and contamination. Another important deficiency is the lack of financial resources for scientific and applied research, which are most necessary in order to generate and implement alternatives of sustainable management of coastal aquifers.

International co-operation could help improve the current situation of coastal areas in the Iberoamerican region and thus to promote sustainable management of endangered coastal ecosystems. Efficient water-management policies would help to dramatically reduce the vulnerability of groundwater systems to marine intrusion and impairment, and consequently the present degradation risk for biodiversity, human population and economic development in coastal areas of at least thirty three different systems.

Typification of coastal aquifers based on common scenarios, as presented here for Iberoamerica, could be used in other regions of the world, with the eventual inclusion of other aquifer types that do not exist in the region. A simple and representative characterization of the world's coastal aquifers could be achieved, presenting their state of knowledge, main problems and management actions. On the other hand, comparing the situation of particular aquifers within the same group is very useful to detect the nature of lacks in every area.

The aquifers of Mar del Plata (Argentine), Recife (Brasil) and Llobregat Delta (Spain) are detrital, large size and urban and peri-urban. The three of them supply large populated areas and also industries and agriculture. All of them have different degree salinization problems, as well as other pollution problems. In the Llobregat Delta, the early awareness of the users impelled the Water Administration to support studies and management actions since late in the 1970 up to nowadays, when a sophisticated set of actions like artificial and induced recharge, injection of treated fresh water in the coast, and planned use of the aquifer as a reservoir, are ruling regularly. In Mar del Plata, detailed studies of the aquifer functioning, including groundwater flow modelling, are under way, and they are used to support the design of the public exploitation network. Also, the use of pressure, state and response indicators to analyse groundwater conditions is supporting management action from the public institutions. In the Recife Plain, salinization and other pollution problems have been detected, but the concrete sources and mechanisms are yet to be identified. A Legal Act from 2000 established criteria for analyzing groundwater requests in intensively exploited regions, but management actions to control groundwater use are still fragile.

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