Intensive exploitation and groundwater salinity in Recife coastal plain (Brazil): monitoring and management perspectives

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Abstract— Recife, capital city of Pernambuco State, is located in the Northeast coast of Brazil. Even though the surface water is the main source for supply in the region, several constraints have been imposed to the supply system due to the increasing demand, limited resources in terms of quantity and quality, and frequent droughts. Groundwater use in the area has been growing for the past 30 years, with an increasing number of deep and shallow wells, supplying hotels, industries and residential buildings. Recife coastal plain has an area of 112 Km^2 and a population around 1.5 million inhabitants, being highly urbanized. Recife Metropolitan Region, comprised of fourteen towns, has also difficulties in balancing water demand and availability and also relies on groundwater for supply, regardless difficulties in natural recharge to adequately compensate the withdrawn. The over-exploitation of groundwater and difficulties in recharging the aquifers has severely depleted the potentiometric levels. In addition, the coastal aquifers in the area increase their vulnerability to sea water intrusion as a consequence of the over-exploitation. Many wells have been abandoned due to the high salt content in groundwater, or the excessive drawdown in some areas. One of the most critical areas identified is in Boa Viagem beach, a residential and tourist area with high population density, concentrating a large number of private wells. In part of Boa Viagem Beach, denominated "A Zone", drawdown in piezometric levels of more than 40m has been observed in some wells. A monitoring program has been pursued to assess groundwater salinity in Recife coastal plain, including the so-called "A Zone". This paper presents the results of the monitoring program and analyses the causes for the high salinity levels in some points. Electrical conductivity and selected ions were analyzed and ionic ratios were calculated in order to investigate time and spatial changes. Selected cases are presented. Results reveal areas where the salinity is high, although a unique pattern for salinity variation in time has not been identified. Analyzing also rainfall data, the results reveal the effect of natural recharge on groundwater salinity in some places. Present practices and perspectives of management of groundwater quantity and quality are also discussed. This study has joined the International Geoscience Programme (IGCP) Project No. 519 "Integrated Management of Coastal Aquifers in Iberian America", supported by UNESCO (2005-2009). The project aims developing joint methodologies on marine intrusion process analysis in coastal aquifers and management strategies.

***Index Terms*— over exploitation, groundwater management.**

I. INTRODUCTION

In the Northeast coast of Brazil, two aquifers compose the Plain system of Recife, Cabo and Beberibe, of semi-confined characteristics, underlying an unconfined aquifer, the Boa Viagem. As for the Pernambuco state, occurrence of groundwater is quite limited, this system represents a high quality source that would have to be treated as a strategical reserve. Water supply has always been mainly based on surface resources.

However, the supply deficit in the Recife Metropolitan Region (RMR), with increasing population in a high rate, has led in the last years to a search for more reliable water sources and producing, as a consequence, an intensive exploitation of the coastal aquifers in the most densely occupied area in the state. This extreme exploitation associated with the difficulties in the process of natural recharge, due to impermeabilization associated with the urbanization has posed the system under threat of degradation, both in terms of quantity and quality, associated to the risk of salt water intrusion.

Recife was built on the estuarine area of Capibaribe river and other small rivers that share the same estuary. Recife has been developed through the last five centuries, alongside several rivers. that run through the town. These rivers provide beautiful landscapes but also contribute to salt propagation from the sea into the aquifers.

Investigations in the area [1], [2], [3] have shown an unbalance between extraction and replenishment in the aquifers and a point of concern is the salinization process that occurs in several points of Recife plain. The main causes that have been pointed out for the increasing salinity in this intensively exploited coastal aquifer system are seawater intrusion, and connection with mangroves and estuarine areas. Several studies have been undertaken estimating water balance in the system, evolution of potenciometric levels [2], [4] and trying to identify the causes of the salinization process, mainly in the central area of Recife [5], and along the coast in one of the most densely occupied area in Recife, Boa Viagem beach and surroundings [6], [7], [8]. Reference [5] presented results that indicates that the groundwater

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salinization process in the Central Region of Recife is due to brackish water in Capibaribe River at high tide. Another critical area is in Boa Viagem beach, a residential and tourist area with high population density, concentrating a large number of private wells in residential buildings and hotels. Many wells have been deactivated, since the 1970´s in this area, others areas in Recife and in others neighbor towns, such as Olinda and Jaboatão dos Guararapes, comprising the RMR, due to high depletion in potenciometric levels and increasing salt content in groundwater. Subsidence related to overexploitation of groundwater has also been pointed as a potential problem in the area.A research program has been established in May 1999 to investigate the temporal and spatial variation in groundwater quantity and quality, especially salinity and infer the salt intrusion risk, though modeling. This work presents some results of the monitoring program related to salinity of groundwater in the aquifer system in the south coast of Recife, around Boa Viagem Beach.

II. AREA OF STUDY AND GEOLOGY

Recife Metropolitan Region (RMR) includes the city of Recife, and 13 neighboring municipalities. Recife is located in the northeastern coastal region of Brazil (8º04'03"S, 34º55'00" W) (Figure 1). The total area of RMR is 2,768 Km² and population is 3,339,616 according to census in year 2000. Population concentrates at localities near Recife city center, at beaches neighborhood especially at Boa Viagem beach. Population has been increasing in a relatively high rate. Recife is build on a plain, with average level of 2,0 m above the sea level, and is surrounded by low hills. The Recife plain occupies an area of about 112 km2 and corresponds to a region of fluvial- marine geologic formation, located in the geographic limits of occurrence of the sedimentary basins of Cabo and Pernambuco-Paraíba.

Figure. 1 – Map of Brazil, Pernambuco State and Recife.

The geology in RMR is divided in two main tectonic units: a) The basement rocks and b) the phanerozoic covers. The basement rocks includes granitic, migmatic and gneissic rocks of the Pernambuco-Alagoas Massif, whereas the phanerozoic cover includes cretaceous sediments of the Pernambuco and Paraíba Groups. Tertiary sediments of the Barreiras Formation and Quaternary sediments of the Recife coastal plains ([9]).

Reference [4] stressed that the aquifers in the RMR are classified, according to the geomorphologic domain (Figure 3) in: 1) Basement rocks plain (fractured aquifer; 2) Northern Sedimentary and Recife Coastal plains (porous aquifers).

Table 1 shows characteristics of the main aquifers at Recife plain. "Beberibe" is the semi-confined aquifer on the North of Recife, "Cabo" is the semi-confined aquifer on the South. Both underline the Boa Viagem aquifer (Figure 2). Table 2 presents average well characteristics and hydrological properties of the aquifer.

TABLE 1- HYDROGEOLOGICAL CHARACTERISTICS OF RECIFE AQUIFERS [4].

Aquifer	Average thickness (m)	Geology	Transmissivity	Storage coeficient
B.Viagem	40	Sand, silt and clay	Low to medium	Low to medium
Beberibe	100	Sandstone,with intercalations of mudstone	Medium	Medium
Cabo	90	Sandstone, siltstone and mudstone	Medium	Medium

TABLE 2 – AVERAGE WELL CHARACTERISTICS AND HYDROGEOLOGICAL PROPERTIES OF RECIFE AQUIFERS [4].

Parameters	B.Viagem	Beberibe	Cabo
Depth of the well (m)	27	126	126
Static water depth (m)	8.85	26 35	31 24
Dynamic water depth (m)	17.41	40 96	53 17
Pumping rate (m^3/h)	17.00	18.48	7.82
Hydraulic conductivity(m/s)	1.7×10^{-4}	2.2×10^{-5}	1.0×10^{-5}
Storage coefficient	-	2.0×10^{-4}	1.0×10^{-4}
Effective porosity	1.0×10^{-1}	1.0×10^{-1}	7.0×10^{-2}

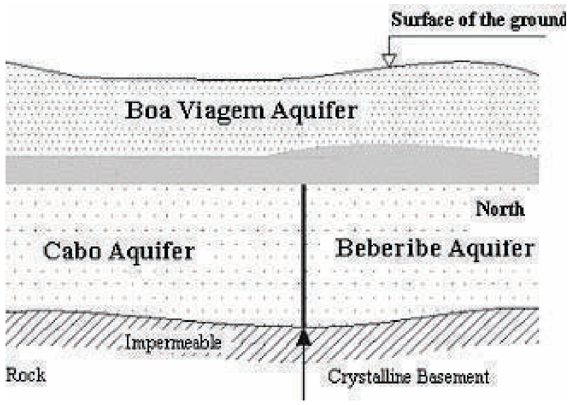

Figure 2- Schematic diagram of Beberibe, Cabo and Boa Viagem aquifers (Cross-section).

Boa Viagem aquifer is the most vulnerable due to its proximity to ground surface. It is heterogeneous, and has good water quality in some places, but there are other locations with poor water quality, with problems caused by sewage and by salinization from mangroves and river estuaries. Beberibe aquifer is the most important, with the highest quantity of stored water. Its water presents very good quality, but there are already a few wells with increased level of salinity. Cabo aquifer has been overexploited for several years.

Rainfall is highly irregular both in time and space in Northeast Brazil, with much higher rainfall values around the coast than in the inland areas. Figure 3 depicts annual rainfall values for recent years and the historical mean value. The rainy season in the area is between May and August.

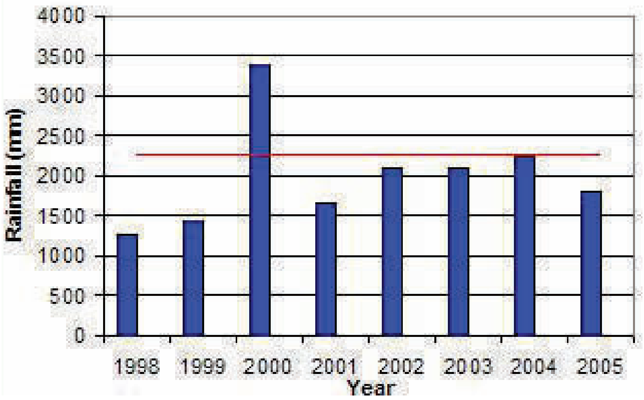

Figure 3. Rainfall in Recife (line represents historic long term mean value).

III. GROUNDWATER USE AND PROBLEMS

In year 2000, there was in Brazil almost 80% of population in urban areas, and water supply has been a problem in many large cities in Brazil, especially in the Northeast. Pernambuco is the state in Brazil with less water availability per capita. Groundwater has been historically used in the area as a complementary source in the Recife Metropolitan Region, in the Northeast Coast of Brazil. However, recent shortage on water supply, due to droughts, besides problems related to losses in the water supply system, has led part of the population to look for guaranty on water supply, drilling private wells. COMPESA, the Public Water Company, is in charge for the operation of the water supply system, while the Pernambuco State Secretary for Science, Technology and Environment- SECTMA is on duty for the management, associated to CPRH- Water resources and environment Agency of Pernambuco State.

The water demand of the RMR, with 14 cities, is about 15,309 m^3/s. For the water supply of the RMR, the COMPESA operates several surface water systems and deep wells, located in the North area of the region, but insufficient production capacity (10,69 m^3/s) and high water loss in the supply system has led to a deficit. The water losses are accounted as higher than 50%. In Recife, the actual supply from COMPESA is of 5,02 m^3/s from surface water systems and 0,389 m^3/s from wells. The water demand is of 6,142 m^3/s for a population of 1.484.009 inhabitants. Private wells have been installed, mainly in Recife, to supply condominiums, hospitals, hotels, and commercial establishments. These are mainly deep wells, which installation can only be afforded for part of the population. Drilling companies are in charge for installation of the wells, with the service contract at risk to the customer, in case of failure of effectively using the well due to not adequate quality or pumping conditions. The cost to drill and install deep wells (more or less 150 meters) is around US$10,000.00. Shallow wells usually with low quality water have also been drilled by poor people (cost less than US$300.00). Residential buildings many times have shallow wells for gardening and car washing. In year 2000, there were more than 10,000 shallow wells (depth less than 20.00 meters). According to [2], there are 13,000 wells only in Recife (about 110 wells/Km^2), with around 33% in the deep aquifers. Facing difficulties due to population growth and increasing water consumption, COMPESA has also increased the number of public operating wells.One of the critical areas in Recife in terms of number of drilled wells is Boa Viagem Beach, with high population concentration (around 6529.43 inhabitants / square kilometer) with good economical living standards. Almost all residential buildings have its own deep well to complement public supply. The Cabo aquifer has the highest number of operating wells and is an important source of supplying for the city of Recife.

Such over- exploitation has changed potentiometric gradients between the upper and the lower aquifers, and between the sea and the lower aquifer. Studies have shown [3] that now, in some places, head gradients produce flow from the sea to land, with high risk of seawater intrusion and in some places from upper to lower aquifer. At some points there is evidence of high drawdown in potenciometric levels, up to 70 m in 20 years. Table 3 and Figure 4 present groundwater level variations in time in one of the most critical areas, denominated A Zone, in Boa Viagem. In general, precipitation does not produce major variation in groundwater depths. It should be highlighted that the recharge rate in the upper aquifer is estimated as 936,000 m^3/year, whereas the extraction rate is estimated as 11,000,000 m^3/year [1].

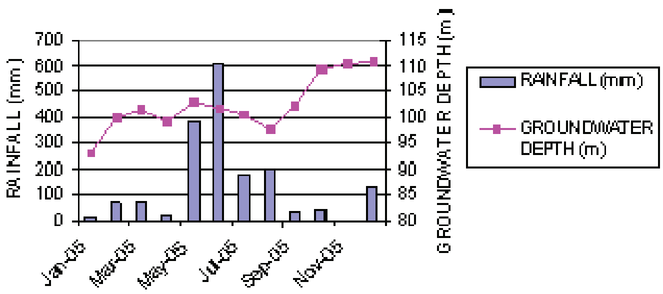

Figure 4- Rainfall and groundwater potentiometric depth in 2005 in Boa Viagem Beach.

TABLE 3- TIME SERIES OF POTENTIOMETRIC GROUNDWATER DEPTH IN BOA VIAGEM BEACH.

PERIOD	GW DEPTH (M)	PERIOD	GW DEPTH (M)
Jan-92	51	May-05	102,87
Nov-03	84,86	Jun-05	101,59
Dec-03	89,13	Jul-05	100,50
May-04	86,2	Aug-05	97,47
Jan-05	92,95	Sep-05	102,17
Feb-05	99,99	Oct-05	109,43
Mar-05	101,22	Nov-05	110,44
Apr-05	99,08	Dec-05	110,61

IV. WATER RESOURCES MANAGEMENT IN PERNAMBUCO STATE

Water resources in Brazil are regulated by a Federal Law (9.433), from January 1997, establishing the Water Resources Management National Policy. The National Policy includes both surface water and groundwater. Each state in the Federal Republic of Brazil has its particular water resources policy. For some few states, there are separate laws for groundwater management policy.

In Pernambuco, water resources is regulated by a state law from January 1997 which establishes the Water Resources Management Policy. Although it does also include groundwater in its aims, there is in the state a specific law from January 1997, which adresses groundwater conservation and protection. The groundwater law and its associated legal acts and resolutions regulate ownership, well drilling and groundwater use, artificial recharge, and protection from contamination and wastage based on defined criteria. The Pernambuco State Secretary for Science, Technology and Environment- SECTMA, created in 1988, along with CPRH- Water resources and environment Agency of Pernambuco State, created in 1976 are responsible for the implementation of the groundwater management policy, with its control instruments and for inspection. As control instruments, the two state institutions promote allocation and licensing based on a zoning, or management plan, for groundwater exploitation. Drilling license must be first demanded by the user, considering all different uses. If drilling is authorized, afterwards the user must demand an operation license. All wells less than 20 m deep or with pumping rate less than 5 m^3/day are exempted from licensing.

A legal act established in year 2000 defines criteria for analyzing groundwater use request in overexploited regions. The criteria is based on a zoning produced as a result of a study financed by the Canadian International Development Research Center (IDRC) [4]. The study focused on evaluating the time changes produced in both quantity and quality in the aquifers in the RMR and its actual conditions and use. The main contribution of the reported study was the proposal of a groundwater management plan for the Cabo aquifer. According to this plan, all the new-drilled wells should encompass devices to allow evaluation of groundwater level and discharge rate. The management plan established control zones, each one with a maximum extraction rate per single well. In one of these zones, the so- called A ZONE, located in Boa Viagem, drilling would no longer be permitted and the existing wells should reduce in 50% the pumping rates. The study has been recently updated and the exploitation zones and groundwater use criteria were redefined [2]. Figure 5 depicts the defined zones for groundwater use in the Cabo aquifer in the cities of Recife, Olinda, Camaragibe and Jaboatão dos Guararapes, in the RMR. The conditions were established based on:

- Current potenciometric levels
- Current exploitation conditions (estimated number of operating wells and pumping rates).

The conditions of use are specified for zones A, B, C. D, E and F. The A zone is the most critical one. The main restrictions are for groundwater use in Recife. For A zone, operation licenses for all wells must be renewed once a year. The conditions of use are presented in [2].

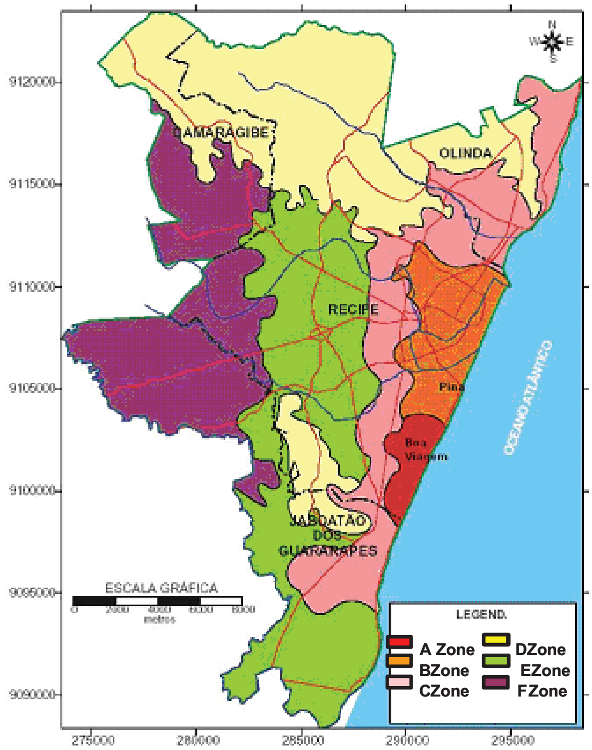

Figure 5. Groundwater exploitation zones in Recife Metropolitan Region [2].

At the time it was proposed, the management plan could not have been implemented from the Government due to a severe water supply shortage caused by a drought occurred in the Northeast Brazil in 1998 and 1999 (Figure 3). For these years, the annual rainfall volume has been less than 65% of the average annual volume. As a consequence, an excessive and disorganized exploitation of the coastal aquifers has occurred, aiming to overcome surface water supply shortage problems. During these years, a high number of wells were drilled without any control.

The rainy season in the year 2000 has changed this scenario. The annual rainfall volume has been around 50% more than the average annual volume (Figure 3). Since then, the water authorities have been trying to implement the established conditions of the management plan. But, yet restrictions are not completely followed because the licensing is not fully controlled. In the A Zone, wells are still drilled. The technical team of the institutions is reduced and inspection is not able to detect all irregularities. Thus, the management plan aimed for groundwater protection and conservation has not been effective and the coastal aquifers under conditions of overexploitation are threatened of deterioration.

As a support tool for control groundwater use conditions and the impacts on the aquifers, monitoring should be performed both for groundwater depths and salinity levels. A telemetric monitoring network has been implemented by CPRH to control groundwater exploitation in Recife. Initially there were selected 10 wells located in strategic places, taking into consideration aspects related to water quality and the evolution of the potentiometric surface. The information obtained from the wells (conductivity and the water level measurement) is sent by telephonic line, in real time and saved in computers, in CPRH.

V. GROUNDWATER SALINITY MONITORING PROGRAM

A monitoring program funded by the Brazilian Federal Government through research projects has been established for investigating groundwater salinity levels in the Cabo aquifer in the most exploited areas. A set of wells has been monitored since May 1999, with individualized frequency. The main focus of the monitoring program has been a sample of wells located alongside the coast in a region approximately 10 km long and 300m wide with more than 500 deep wells operating and where salinity levels had caused some wells to be abandoned. Most of the monitored wells extract water from the Cabo aquifer but some shallow wells extracting water from the upper formation (the Boa Viagem aquifer) have also been included. The groundwater in the upper formation is generally of poor quality, due to the presence of saline mangroves and sewage. The purpose of including some shallow wells in the monitoring program was to try to infer an evidence of the differences in salinity pattern between the two formations. The monitored wells are located in the neighborhoods of Pina, Boa Viagem and Piedade. Table 4 presents the details of the monitored wells. Since the beginning of the monitoring program, many wells were deactivated. During all the surveys, samples were analysed for electrical conductivity, and some for Na^+, K^+, Cl^-, Mg^{+2} and HCO_3^- contents. The selected wells had been monitored with individual frequency, established in function of observed variation in electrical conductivity. The wells were monitored from May, 1999 to September, 2006. Figure 6 presents the frequency distribution of the depths of the monitored wells.

TABLE 4- STATUS OF MONITORING WELLS IN RECIFE PLAIN.

Number of wells	Number of wells with depth information	Number of deactivated Wells	Number of surveys	Number of analyzed samples (EC)
100	90	20	27	881

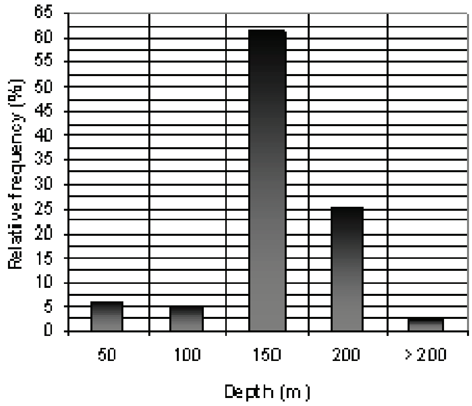

Figure 6- Relative frequency of well depths in Recife Plain.

VI. RESULTS AND DISCUSSION

For the sample analyzed, electrical conductivity ranged from 0,04 to 36,5 dS/m. In some wells, the electrical conductivity exhibits very low variation in time, while in others, the observed variation along the observation period is high. In some cases, the groundwater salinity increases with time and decreases afterwards. After the rainy period in 2000, with rainfall higher than the historical average values (Figure 3), some wells decreased salinity levels (Figure 7). Also, it was observed cases were salinity increases when the well starts operating after drilling and afterwards it decreases. It may be due to local effect of old salinized water in the formations that dissipates with pumping. It has also been observed, in some cases, following a new well being drilled, water is of relative good quality and then increases salinity.

As in previous analyses, the results indicate zones where salinity is high for several wells. But also, in some cases wells with relatively good quality water are closely located to others with high salinity (Figure 8). The salinization patterns are also different among closely located wells. The heterogeneities in the formation may be related to this behavior. Figure 9 presents the variation in electrical conductivity in two wells closely located that were deactivated due to high salinity. Figure 10 shows the variation of the electrical conductivity at the same building. The values up to year 2002 are for a well which has been deactivated, while the data after 2005 are for a new drilled well.

Field data acquisition is not a straightforward process, as users feel they may be fined if they are not in a regular situation. Thus, in some cases the figures that are obtained by the chemical analyses do not completely clarify the real situation. What really causes this is not clear

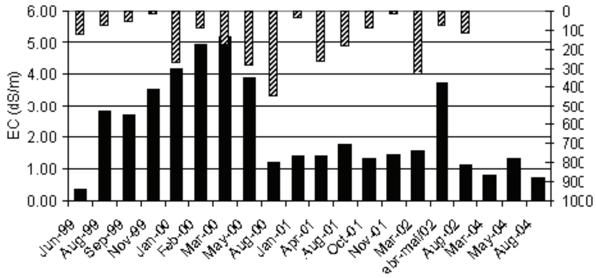

Figure 7. Electrical conductivity of groundwater influenced by rainfall.

The increase of salinity may be associated to a temporary effect in the formation, that changes with groundwater movement. But, the sudden improvement in quality may be due to a new well drilled irregularly, since no operation license is detected for the well.

Figure 11 presents a well where salinity already relatively high increases suddenly and then sharply decreases.

Table 5 presents the ionic ratios, chloride content and the cation exchange code $(Na^{+}+K^{+}+Mg^{2+})$corrected, compared to $(1/2Cl^{-})^{0.5}$ for the well which electrical conductivity was depicted in Figure 11.

The results reveal that in December 2004, the observed values may be indicative of the presence saline water in the aquifer. The cation exchange code for the case showed deficit of marine cations, indicating cation exchange caused by salinization [10].

Figure 8- Electrical conductivity mean values in Boa Viagem coastal zone.

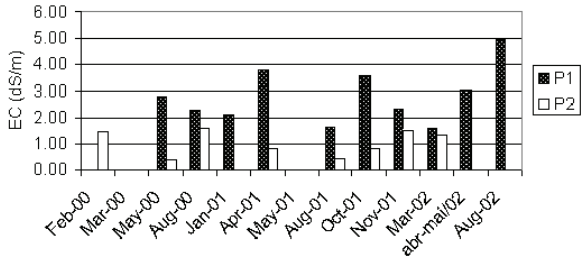

Figure 9- Groundwater electrical conductivity in two monitored wells, closely located.

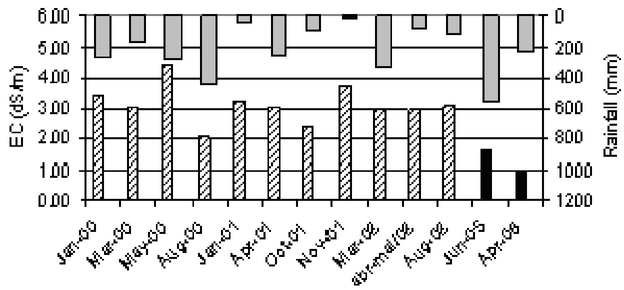

Figure 10- Electrical conductivity levels in two nearby wells, in the same building.

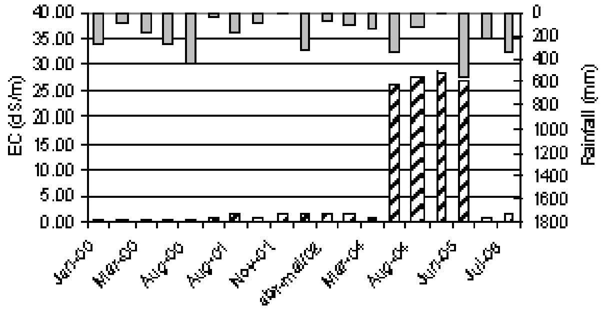

Figure 11- Sudden electrical condutctivity reduction in a well .

TABLE 5- IONIC COMPOSITION OF GROUNDWATER FOR WELL IN FIGURE11.

	Oct-00	Nov-01	Mar-02	Dec-04	Apr-06
EC (dS/m)	0.63	1.48	1.49	28.40	0.80
Cl	147 50	244.90	387.80	8431.40	100.00
rCl / rHCO3	3.70	7.84	13.16	73.68	0.40
rMg / rCa	1 15	1.25	1.15	2.77	0.36
(Na+K+Mg) corrected	0.67	0.71	1.75	33.24	1.98
$(1/2Cl)^{0.5}$	1.44	1.86	2.34	10.90	1.19

Previous analyses in this monitoring program were performed for stable isotope [11]. The data helped to understand the behavior of groundwater recharge and mixing, but it is still not conclusive regarding the origin of salinization of the aquifer system in Recife. From the isotopic signature it can be said that the groundwater in the aquifer system has a three-fold component: fresh groundwater recharge component, old evaporated groundwater and saline water. Therefore, detailed studies including $\delta^{18}O$ and $\delta^{2}D$ ratios in surface, estuarine and sea-water are required in order to better explain the recharge and mixing mechanism of groundwater in the RMR aquifer system.

VII. FINAL CONSIDERATIONS AND MANAGEMENT PERSPECTIVES

This paper has showed that although there is a management policy in Pernambuco state for controlling groundwater user, it has not been effective and the aquifer coastal system under overexploitation conditions is threatened of degradation, including risk of sea water intrusion.

As a future perspective for the control of the groundwater salinization in the Recife Metropolitan Region, inserted in the context of groundwater management in the coastal area, it should be highlighted: - the necessity of research aiming to evaluate the economical viability and environmental sustainability of artificial recharge strategies, using different water sources, among them rainwater. Preliminary studies in this direction have been carried out [12], [13], [14]; the urgency of systematic groundwater monitoring both in terms of water level and salinity, in regions of intense exploitation. Actions in this direction has begun in 2004 by the water resources authority by implementing automatic stations, as reported by [15]. Field data acquisition through non-automatic measurements must be carried out including inquires to population, in order to investigate effectiveness of controlling and inspection mechanisms. Efforts must be made to improve the groundwater management policy.

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