PRELIMINARY EVALUATION OF AQUIFER STORAGE AND RECOVERY IN THE RECIFE METROPOLITAN REGION, PERNAMBUCO, BRAZIL

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Abstract - The water shortage problem in northeastern Brazil has challenged local water suppliers over the years. Groundwater development in areas with adequate hydrogeology has been intensively used to supplement water demands. As a result, underground resources are subject to adverse environmental impacts associated with overdraft conditions. The city of Recife is a good example of an area the extensive decline in groundwater levels has brought up the concerns for potential impacts such as salt water intrusion and subsidence. This paper provides a preliminary evaluation of the applicability of Aquifer Storage and Recovery (ASR) in the Recife Metropolitan Region (RMR). ASR is an environmentally-friendly water supply alternative that helps meet water demand needs and plays an important role in resolving several water resource and environmental issues. This preliminary investigation points out ASR benefits for the area, identifies issues affecting operations, and recommends steps to be taken to demonstrate the feasibility of ASR for the RMR. Based on the extent of the available data, an ASR program appears feasible in the RMR as a tool to mitigate water shortage conditions, declined water levels, salt water intrusion and potential subsidence within the coastal aquifers.

Keywords – Aquifer Storage and Recovery, ASR

1.0 INTRODUCTION

The water shortage problem in northeastern Brazil has challenged local water suppliers over the years. To date, supply alternatives have relied primarily on surface water reservoirs and retention basins, which are exposed to high evaporation rates

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throughout the year. In areas where the local hydrogeology allows for groundwater development, many wells have been drilled to supplement water demands.

In utilizing groundwater resources, water managers need to carefully evaluate the potential impacts resulting from trying to meet critical water demands in a given area.

The city of Recife is a good example of increasing groundwater exploitation as means to supplement the insufficient surface water supply. Sitting on top of two sedimentary basins which feature moderately to highly porous aquifers, the city has undergone a groundwater usage "boom" over the last 5 years, with over 2,000 water production wells being drilled in the coastal area of Boa Viagem. As a result, local aquifer systems are prone to negative impacts such as reduction in groundwater levels, salt water intrusion and subsidence.

As an emerging technology in the United States and around the world, ASR has been an environmentally-friendly water supply alternative that helps meet water demand needs, and brings operational advantages and cost savings to the water management plan. In addition, ASR plays an important role in resolving several water resource and environmental issues, by helping mitigate some of the associated impacts of groundwater exploitation.

This paper provides a preliminary evaluation of the applicability of ASR in the Recife Metropolitan Region, both as a potential tool for managing the city's critical water condition, and to address arising problems such as salt water intrusion and subsidence in the Beberibe and Cabo coastal aquifers. This paper will describe relevant aspects of the study area, the concepts and steps in implementing an ASR project, and the feasibility of ASR in Recife.

2.0 THE RECIFE METROPOLITAN REGION (RMR)

2. 1 GENERAL DESCRIPTION OF STUDY AREA

The Recife Metropolitan Region (RMR) is located in the state of Pernambuco in northeastern Brazil and comprises a total area of about 2,777 km^2. It extends for approximately 125 km along the Atlantic coast and 20 to 35 km inland. The RMR is currently ranked Brazil's third most populated metropolitan region, with nearly 3.1 million inhabitants (Costa et al, 1998).

The climate within the RMR is warm and humid, with low and high temperature averages of 23.9 C and 26.6 C. Rainfall in the area is abundant , but irregularly distributed throughout the year. During the rainy season (March to August), rainfall totals 1909 mm, as opposed to 549 in the dry season (September to February).

There are three distinct topographic features within the RMR: the Lower Coastal Plateau, the Coastal Tablelands and the Fluvial-Marine Coastal Plain. The Lower Coastal Plateau, known as “Chãs”, consists of high, ridged areas of sculptured crystalline bedrock, with elevations ranging from 60 to 150 m within the RMR. The Coastal Tablelands are characterized by sub-horizontal, strongly eroded, seaward dipping strata, and comprise both flat and hilly areas which rise between 80 and 150 meters. The Fluvial-Marine Coastal Plain are formed by recent sediments of coastal and fluvial origin. It encompasses the entire surroundings of the state capital of Recife, where it is denominated the Recife Plain.

2.2 SUMMARY OF GEOLOGY AND HYDROGEOLOGY

The geologic region addressed in this paper is a subset of the RMR and comprises the portions of the Tablelands and Recife Plain which overlie the sedimentary strata. Table 1 provides a summary of the geological strata within the study area:

Table 1 – Sedimentary Series within the RMR

<table>
<tr><th>Age</th><th>Pernambuco-Paraiba (PE-PB) Sedimentary Series</th><th>Cabo Volcanic Sedimentary Series</th></tr>
<tr><td>Quaternary</td><td colspan="2">Recent and undifferentiated sediments: poorly-sorted deposits of gravel, sand, silts and clay, of fluvial and marine origin

Barreiras Formation: clay sediments and clayey sandstones of continental origin</td></tr>
<tr><td>Tertiary</td><td>Marinha Farinha Formation: clastic limestone, low primary porosity, limited fissures and fractures.</td><td></td></tr>
<tr><td>Upper Cretaceous</td><td>Gramame Formation: calcareous sandstones gradually substituted by clastic limestones, clay-sized sediments and dolomite on top layers, forming fossiliferous beds of dolomitic limestones and marls.

Beberibe Formation: lower member - quartz sandstones of multiple grain sizes, intercalated by beds of siltstones and shales. upper member - hard and compacted sandstones of coastal origin, highly cemented by calcite</td><td rowspan="2">Estivas Formation: calcareous arkoses (bottom) to fossiliferous dolomitic limestones intercalated by beds of marl (top).

Ipojuca Formation: basalts, andesites, trachytes and rhyolites

Cabo Formation: feldspar-rich conglomerates, siltstones, arkoses, claystones and sandstones</td></tr>
<tr><td>Lower Cretaceous</td><td></td></tr>
</table>

The following aquifers are found in the RMR:

- Beberibe – This is the most important groundwater resource of the RMR. The two members of this aquifer, the Upper and Lower Beberibe, are very well distinguished in the northern RMR, with reported depths of 100 m and 200 m, respectively. In the Recife Plain, the Upper Beberibe is limited to 30 m on average, while the lower member is 100 m thick on average.

- Marinha Farinha – Gramame - This is a carbonate aquifer with low primary porosity, but it yields small amounts of water through fractures and fissures originated from the dissolution of calcite (secondary porosity). This groundwater resource is not used for supply purposes within the RMR due to its low water yield and hardness associated with the high carbonate content of the native water.

- Cabo aquifer - Together with the Beberibe aquifer, the Cabo aquifer is currently the major water supplier for the Recife Plain, where it reaches and average thickness of 90 meters.

- Barreiras – This is a clayey sandstone aquifer 40 meters thick on average. The largest water yield is obtained from remote areas located in the northwest portion of the RMR. This aquifer is not used as a supply source for the populated Recife Plain.

- Boa Viagem - Identified by Costa et al in 1994, the Boa Viagem aquifer is an unconfined, shallow system, which is heterogeneous and porous. This aquifer is 40 meters thick in the Recife Plain and 20 meters thick in the Tablelands. It is part of two hydrogeologic systems along the Recife Plain, referred to as Boa Viagem/Beberibe and Boa Viagem/Cabo aquifers.

3.0 THE RMR PROBLEM STATEMENT

3.1 WATER SUPPLY VS DEMAND

With a water demand of 12m^3/s (Costa el al, 1998), the entire RMR has been dealing with a serious water supply deficit for several years.

The water supply, treatment and distribution systems are operated by COMPESA, which collects 8.6 m3/s of surface water obtained from nearby watersheds. Costa et al, 1998 and CONTECNICA, 1998 reported that the contribution of groundwater to COMPESA's distribution system adds up to only 1.6 m^3/s , which are pumped from the Lower Beberibe in the nothern RMR. Even though a total volume of 10.19 m^3/s is treated and further distributed, about 37% is lost along the distribution system, which exacerbates the water deficit.

To overcome water supply shortages, a large number of private wells were drilled in the Recife Plain, throughout the Beberibe, Cabo and Boa Viagem formations. In 1998, Costa et al assessed an inventory of 1,800 wells, withdrawing a total of approximately 2 m^3/s.

With an actual water deficit of 3.66 m^3/s, the city started to implement the development of two new watersheds. The system under implementation will provide the area with an additional 6.6 m^3/s of treated drinking water. According to the studies for expansion of the surface water supply system, six other rivers are available for supplying the RMR, with a potential contribution of 14.8 m^3/s to the existing system. Should these resources be utilized, the total amount conveyed to COMPESA's system would be sufficient to meet water demands in the RMR until year 2,020 (Costa et al, 1998).

3.2 THE ROLE OF SURFACE WATER

Table 2 – RMR Integrated Water Systems

System	Total Water Supply (m3/s)**	WTP	WTP max. capacity (m3/s)***	System's Contribution (m3/s)***
Tapacurá/Duas Unas	3.65	M. Castelo Branco	4.0	3.65
Botafogo	1.8	Botafogo	1.8	1.8
Monjope	1.0	Alto do Ceu Botafogo	* 1.8	0.8 0.2 (as needed)
Gurjau	0.96	Gurjau	1.0	0.96
Beberibe	0.44	Alto do Ceu Caixa d'Agua	* 0.23	0.23 0.21
Suape	0.40	*	-	-
Dois Irmaos	0.13	*	0.16	0.13
Jaboatao/Jangadinha	0.11	*	*	0.11
Zumbi	0.10	*	*	*

* not available in literature; ** source: Costa et al. 1998 ***source: CONTECNICA, 1998

The major source of water supply for the RMR is surface water obtained from rivers, reservoirs and ponds along the coastal watersheds. The surface water collected within the RMR watersheds is conveyed to integrated and remote water utility systems comprised of catchment structures, lift stations, treatment facilities and water works operated by COMPESA.

COMPESA's integrated water supply systems are listed in Table 2. Some of these utilities have their source water conveyed to the same water treatment plant (WTP) prior to distribution, in order to meet target demands, transfer available excess water, and capitalize on the system's available capacity.

Several hydrologic assessments have been performed to determine the potential for expanding the existing surface water supply system. Ongoing projects include the construction of the Pirapama Dam (5.6 m^3/s) and the Varzea do Una/Capibaribe collection and treatment works (1.0 m^3/s).

Other surface water streams were also targeted as potential candidates for future development: Sirinhaem (7 m3/s), Ipojuca (3 m3/s), Carau (1.5 m^3/s /s), Arataca and Itapirema (1.3 m^3/s), Gurjau (1.1 m^3/s) and Jaboatao (0.9 m^3/s).

3.3 THE ROLE OF GROUNDWATER

3.3.1 Groundwater Usage

COMPESA pumps water from the Lower Beberibe in the northern RMR, through wells located in Olinda, Paulista, Abreu e Lima, Igarassu, Itamaraca and northern Recife. CONTECNICA (1998) indicated that 110 operating wells contribute with about 1.5 m^3/s to the public supply system. The wells are 100 to 400 meters deep, with 6 to 10-inch steel casing and 6-inch screen along the target water bearing interval. Water yields from these wells reach up to 74 m^3/s on average.

Over 1,800 wells have been drilled in the Recife Plain (Costa et al, 1998). Wells completed in the Beberibe and Cabo formations range from 4 to 6-inch PVC casing holes and can reach depths of up to 200 meters. These wells wells were drilled by private subcontractors and serve residences, hotels, public institutions, etc. Average water yields from wells located in the Beberibe and Cabo aquifers are 18.5 m^3/s and 8 m^3/s, respectively.

Wells installed in the Boa Viagem aquifer do not exceed 50 meters and vary from 2 to 4-inch auger-bored holes, 1-inch driven well points, and 1 to 2-meter cisterns. Individual wells yields are 17 m^3/s on average.

Well construction and installation differed significantly between the wells serving the public water system and those drilled on a private basis throughout Recife. Results from initial pumping tests conducted at the time of construction of 1,353 private wells revealed that the total volume of water yielded could have reached up to $170x10^6$ m^3/year, had well installation and pumping intervals been designed to optimize well efficiency.

Groundwater exploitation in the State of Pernambuco is regulated under Law No 11,427, which was promulgated to prohibit the installation of additional wells in areas under risk of salt water intrusion, contamination, extensive lowering of groundwater elevations, as well as to control existing withdrawals. However, the local water resource authority must implement the law enforcement measures, to ensure that withdrawal and drilling requirements are being met by the large number of well owners in the RMR.

3.3.2 GROUNDWATER IMPACTS

Extensive groundwater development within the RMR has adversely impacted the Boa Viagem/Beberibe and Boa Viagem/Cabo aquifers. Impacts include decline in groundwater levels, and increased potential for salt water intrusion and subsidence. In addition to it, poorly-installed wells in the Recife Plain have increased aquifer vulnerability for contamination, through infiltration of undesired runoff, as well as migration of high TDS water from upper formations.

The water levels within Beberibe and Cabo aquifers have been closely monitored since 1954. Costa et al (1998) provided contour maps of the evolution of the potentiometric surface within these two aquifers, indicating a severe drop in groundwater elevations over the last two decades. The analysis of the monitoring data revealed an increase in groundwater exploitation since 1971, with current depths to water of up to 55 meters below ground surface at the Boa Viagem aquifer.

Costa et al (1998) also revealed that the original easterly groundwater flow has been gradually disturbed in some locations, with converging flow zones resulting from the overlapping of cones of depression. The converging flow and the accentuated drawdown in the coastal areas may increase the risk for salt water intrusion in the Boa Viagem/Beberibe and Boa Viagem/Cabo aquifers.

The existence of saline zones within the Beberibe and Cabo aquifers is known but not yet well documented. Although researches indicated that the origin of the saline water is infiltration through the upper Boa Viagem aquifer rather than seawater intrusion, this issue is still debated among the technical community. The Boa Viagem aquifer is very prone for runoff infiltration due to its high permeability as well as large number of poorly-sealed wells throughout its domain.

Another environmental side is the potential for land subsidence. Although there has been no reported occurrences within the study area, migration of saline water from upper layers and/or seawater intrusion may not avoid ground subsidence of the area adjacent to the ocean, and the Recife Plain may be subject to the same type of subsidence effects as those occurring in Long Beach, CA.

4.0 AQUIFER STORAGE AND RECOVERY (ASR)

4.1 BACKGROUND

As an arising technology being implemented in the United States, Canada, and some countries of Asia and Europe, Aquifer Storage and Recovery (ASR) is a fairly new tool that brings new options in the field of groundwater management. A common application consists of using dual-purpose wells to inject excess treated drinking water into a suitable aquifer and recover the stored water volume at a later date to meet peak demands in the system, without further treatment other than disinfection upon recovery.

As opposed to single-purpose injection wells, ASR wells undergo recharge/recovery cycles which help maintain desired well efficiencies, reducing the potential for plugging. Another significant advantage of ASR is lower capital costs for equivalent peak capacity. Typical capital costs for peak capacity are approximately $450,000 per million gallons/day of capacity, with a range of ±$200,000. Costs depend primarily on storage zone depth and well yield. Other considerations are design lift, well completion, and disinfection requirements.

The use of ASR wells in combination with existing water treatment facilities brings several benefits to the water utility system. Treatment facilities are usually designed to meet maximum day demands, which may typically exceed average operating rates by factors of 1.2 to 2.5. Therefore, idle treatment capacities during periods of low demand can be used to treat additional source water for delivery to the ASR wells. The water stored can be recovered during periods of high demand, supplementing the original water supply system. ASR projects may defer the immediate expansion of treatment facilities, typically requiring less than half the cost of building treatment capacity.

4.2 ASR OBJECTIVES

ASR could play a key role in groundwater resource management. To date, ASR has been extensively used for seasonal and long-term storage of potable drinking water, which combined with other sources of water supply, helps utilities meet peak demands at reduced capital and operating costs. Furthermore, the ASR concept accounts for a wide variety of environmental, groundwater and utility needs. ASR applications may include seasonal and long-term storage for municipal water supply, restoration of groundwater levels, prevention of salt water intrusion, reducing subsidence, emergency storage, optimize water utility capacities, defer expansion of water treatment facilities, and maintain adequate distribution system pressure.

4.3 ASR REQUIREMENTS

The success and cost-effectiveness of an ASR program are directly related to the degree of investigation spent in the early stages of the project. A series of technical and non-technical issues dictate the feasibility of the ASR technology at a specific site. A phased approach to an ASR study is proposed by Pyne (1995). Although this baseline approach is site-oriented, three phases can be identified within an ASR program, as follows:

- Phase I: Preliminary Investigation and Conceptual Design - provides the basis for the remainder steps of an ASR program. It comprises a review and evaluation of all factors that lead to successful facility design and operation, as well as an analysis of the ASR concept within the larger water management picture.
- Phase II: Field Test Program - involves developing a prototype ASR facility and extended performance tests to assess baseline aquifer characteristics. It may require groundwater modeling to help determine the layout of the expanded system. Cycle testing is also accomplished at this stage to evaluate recovery efficiency, plugging rate, and optimum backflushing frequency.
- Phase III: Well Field Expansion - design of the ASR wellfield, expanding the prototype ASR facility to meet projected needs.

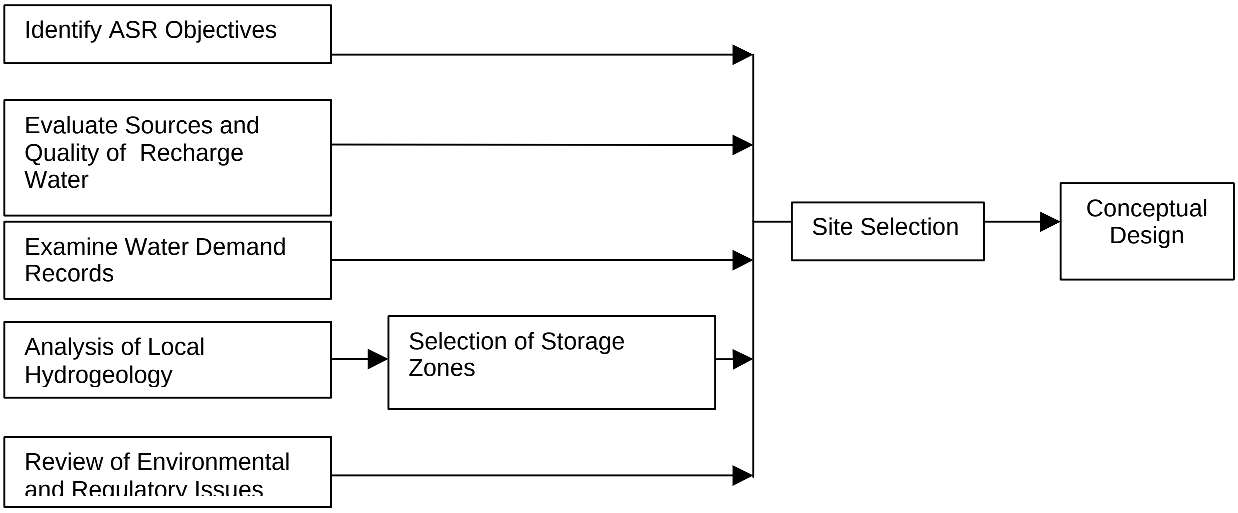
4.4 ASR PHASE I APPROACH

Phase I encompasses the technical and non-technical issues involved in ASR development. A typical Phase I approach is shown in Figure 1.

It is important to define the primary and secondary objectives of the ASR program for a given situation. The role of ASR should be evaluated against the overall water resource scenario to become an effective water management tool.

ASR source water may be in the form of surface water, rainwater, or other available resource. Water quality analysis is often necessary to confirm suitability for ASR use. In addition, a thorough geochemical analysis is conducted to examine source water and native groundwater compatibility. When sufficient documented data are not available at the Phase I stage, geochemical compatibility analysis is accomplished following completion of the preliminary study.

Figure 1 – Typical Phase I Approach



For most applications where ASR facilities are designed to supplement peak system demands, the examination of water demand records is an essential step in the planning process. Trends in water demand will determine periods where recharge and recovery will take place. Along with the evaluation of the existing system's capacity, such as available treatment facilities, results of current and future water demand studies will lead to assessment of the volume needed to be stored through ASR wells. This step helps identify idle utility capacities that can be used to treat excess water for ASR.

The hydrogeologic comprises a review of data such as stratigraphy and lithology, aquifer thickness, hydraulic characteristics, water quality and potential for contamination, as well as groundwater usage in the vicinity area. Additional field data collection might be needed to supplement existing literature data, and can be recommended as a next task to be implemented upon completion of the preliminary investigation.

Technically-limited groundwater resources, such as brackish and deep aquifers, may otherwise be favorable for ASR. The primary benefit of using brackish and deep aquifers is that these storage zones typically have less competition from surrounding groundwater users and less potential for contamination.

Non-technical issues such as environmental aspects, regulatory requirements and procedures, water rights and institutional constraints are also addressed during Phase I.

Once the site is selected based on the extensive literature review and supplementary field data collection, a preliminary conceptual design is developed to account for ultimate layout of required ASR facilities.

5.0 ASR APPLIED TO THE RMR

5.1 OBJECTIVES OF THE ASR PROGRAM

The main advantages that an ASR program could bring to the RMR scenario include supplemental water supply, prevent salt water intrusion, restoration of declining groundwater levels, and prevent land subsidence in the Recife Plain.

5.2 Source Water Alternatives

Within the RMR, source (recharge) water could be obtained from existing and future surface water reservoirs, groundwater from underutilized aquifers, rainfall catchment structures and runoff.

Surface Water

Surface water is a potential alternative for the RMR case study due to the extensive availability of streams and their current exploitation for supplying purposes. As previously mentioned, 84 percent of the water supplied by COMPESA come from regional watersheds that drain to the Atlantic Ocean. In addition, several projects involving the expansion of existing collection systems and development of new ones are either under construction or in planning stages.

In order to determine the feasibility of surface water for ASR, two basic analysis should be performed. First, trends in flow need to be evaluated to assess seasonal and monthly availability, as well as average and peak discharges relationships. This helps identify periods when excess water can be used for storage. Secondly, a thorough water quality analysis should be conducted to ensure the treated water is appropriate for injection. At this time, only average diverted flows are available for the streams that supply water for the RMR and those yet to be exploited. Therefore, a detailed hydrologic analysis will be required to quantitatively evaluate the resources.

Water diverted from rivers and reservoirs undergoes treatment in accordance with the final use. Since ASR water is often treated to drinking standards prior to injection, treated effluents from existing WTPs should meet this requirement. Treatment processes should achieve minimal suspended solids in the effluent to avoid well plugging. The review of the RMR's water utility system indicated that some water treatment facilities have idle capacities which can be used to treat water for storage in ASR wells.

According to Costa et at (1998) and CONTECNICA (1998), the city plans to expand existing systems and add new collection/treatment works to the RMR's surface water supply scheme. Some of this water may also be available for storage in ASR wells.

Groundwater

Groundwater from unexploited aquifers may also be used for ASR. Once aquifers with reasonable well yields are identified, a water quality analysis will dictate the degree of treatment required to permit injection.

Based on the review of local groundwater resources, this alternative may be limited for the RMR. Amongst the aquifers, only the Barreiras aquifer would qualify as a potential source. The remaining aquifers are currently undergoing severe overdrafts.

Water quality in the Barreiras aquifer is good, with average TDS concentrations of 165 mg/l TDS. Reported data indicate an average water yield of 16 m^3/h in the northern portion of the RMR.

Rainwater

Rainwater may also be considered as an alternative for ASR source water. Catchment structures such as building roofs could be used to capture enough rain in some areas of the Recife Plain.

Total rainfall in the RMR averages 2,254 mm/year, with about 78 percent of this precipitation occurring between March and August. This abundant rainfall recharges the shallow aquifer, providing perennial flows in the streams. Within the Recife Plain, however, a great portion becomes runoff, draining through gutters and other stormwater collection works.

From a quantity standpoint, precipitation is feasible for ASR purposes. On the other hand, this alternative would require limited treatment to remove high contents of suspended solids, as well as any other substance washed out from roofs. Previous ASR studies involving comparisons of different source water alternatives have reported a significant increase in cost associated with the design, operation, and treatment required for direct utilization of rainwater sources.

Runoff

This alternative would comprise the diversion and treatment of the runoff originated from excess rainfall. Although abundant, runoff may become economically unfeasible compared to other alternatives due to the high degree of treatment required to bring water quality to minimum acceptable standards. Runoff water may contain oil residues washed out from streets and parking lots, high concentrations of suspend solids, as well as other undesirable contaminants.

5.3 WATER DEMAND RECORDS

The analysis of current and projected water demands is essential for the proper planning of an ASR program. Records showing daily, monthly and annual variations in demands are very useful in determining the duration of peaks within the system, as well as maximum day to annual demand and maximum week to annual demand ratios. These data help define potential ASR operating parameters such as periods when recovery from ASR wells would be highly beneficial, and the annual volume of water required during recovery to meet systems demands.

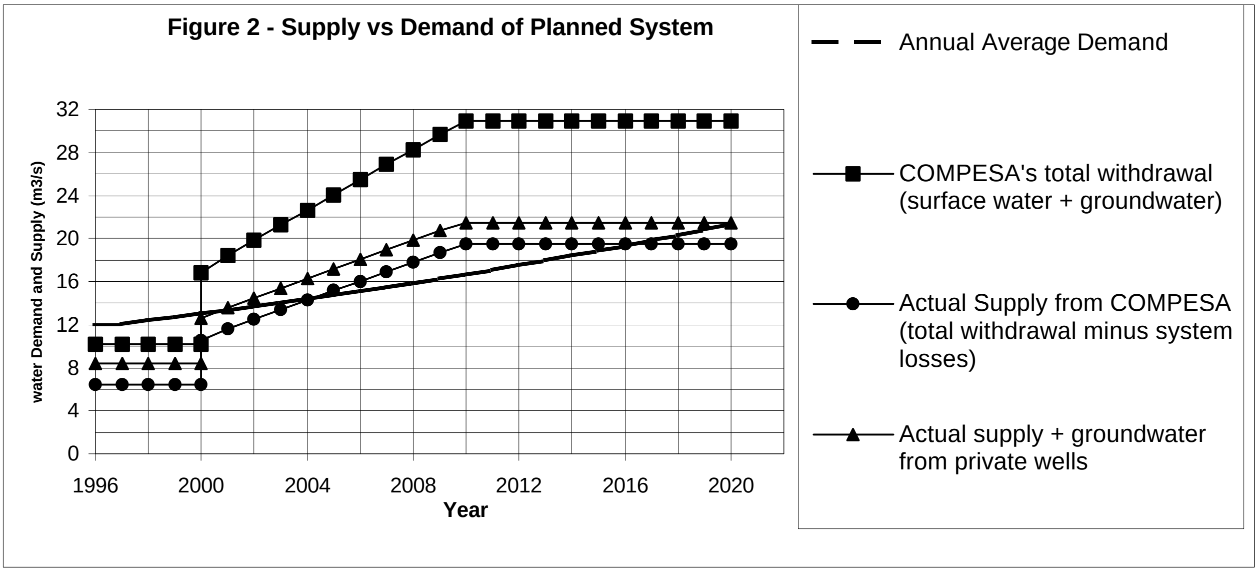


Figure 2 - Supply vs Demand of Planned System

At this time, detailed water demand data for the RMR are limited. The literature reviewed for this case study lacks information on daily, monthly and annual trends in water demands. Therefore, seasonal and peak variations in the system could not be assessed. Given the relevance of this type of information, a more detailed evaluation of demand records will be necessary before implementation of the next phase of ASR feasibility.

Based on the extent of data available in the literature, a preliminary projection of the annual average demand within the RMR was calculated, as depicted in Figure 2. Projected values were computed from the 1996 annual average demand of 12 m^3/s (Costa et al, 1998) and a population growth rate of 3 percent per year was considered from 1996 to 2020. Trends in the supply system were also plotted to provide a general comparison between future water supply and demand.

The water supply plots assumed that 6.6 m3/s of surface water withdrawals were added to the existing COMPESA system by year 2000. This provides a total of 16.79 m^3/s available for public supply. However, the projections also accounted for system losses of up to 38 percent, which significantly reduces the actual supply. As a consequence, the contribution of private wells to the overall system is still part of the future scenario.

The literature suggests that the system be further expanded to convey about 14.8 m^3/s from available surface water resources, providing sufficient water to supply the RMR until year 2020. This expansion is also illustrated in Figure 1. For the purpose of this analysis, it was assumed that the system would be expanded at a rate of 1.41 m^3/s per year from 2000 to 2010. This assumption should not be considered for design purposes, since both the timeframe and sequencing of new contributions are uncertain at this time. The resulting plots indicate that 5.64 m^3/s need to be added by 2004 in order to supply the RMR with COMPESA's allotment alone. Once the total of 30.89 m^3/s is reached, the actual supply can meet the system's demand until 2016.

Although additional analysis is required, an ASR program could improve the future water supply situation for the RMR. Once ratios between peak and average demands are determined, as well as monthly variations in supply and demand, a thorough evaluation of how and when ASR wells should be used in the RMR could be completed.

5.4 STORAGE ZONES

The geology and hydrogeology descriptions provided in the early sections of this paper suggest that three formations within the RMR may be suitable ASR storage zones. These aquifers are the Beberibe, Cabo and Boa Viagem aquifers.

The evaluation of suitable storage zones consists of analyzing each water bearing zone according to the available hydraulic, water quality, and groundwater usage data. Table 3 presents average parameters for the RMR aquifers, as reported by Costa et al (1998). Hydraulic parameters were determined from pumping tests performed on a limited number of wells. Due to considerable variability along the geologic formations, these parameters may vary significantly from one location to another. Furthermore, poorly-installed wells may have influenced results of pumping tests, providing misinterpretations of the actual aquifer hydraulics.

Table 3 – Average characteristics of selected RMR aquifers

	U. Beberibe	L. Beberibe	Cabo	Boa Viagem
Description	Calcareous sandstone	Sandstone with interbeds of shale and silt	Clayey sandstone	Undifferentiated sediments
Avg. thickness (m)	30	100	90	40
Avg. T (m^2/s)	2.38×10^{-3}	2.24×10^{-3}	8.62×10^{-4}	7×10^{-3}
Storativity	-	2×10^{-4}	1×10^{-4}	-
Water yield (m^3/h)		Tablelands : 58.3 R. Plain: 18.5	8.0	17.0
Avg. specific yield ($m^3/h/m$)		Tablelands : 3.13 R. Plain: 2.76	0.51	4.53
Static Water Level (m)		Tablelands : 34.81 R. Plain: 26.35	31.24	8.85
TDS (mg/l)		180	290	465
Potential for contamination	moderate	moderate	moderate	high
# existing wells		>880	>800	>600

Adequate transmissivity is a key element in ASR feasibility since an ASR well must be able to accept and yield sufficient amounts of water to meet project-specific needs (CH2M HILL, 1988). Previous results of ASR test programs suggest that suitable storage zones usually transmit water at rates greater than 8.0×10^{-4} m^2/s. Based on this criterion, the selected aquifers qualify are suitable candidates for storage zones.

The Upper Beberibe aquifer has a potential for ASR development in the northern portions of the RMR, where the calcareous sandstone is up to 100 meters thick. Areas where this aquifer is overlain by the low permeable layers of the Marinha Farinha and Grammame formations, as well as clayey sediments of the Barreiras Formation appear to be potential candidate storage zones. Although the reviewed literature did not report well yield data for this aquifer, the potential for secondary permeability due to the dissolution of calcite may provide sufficient water production rates. Secondary permeability is particularly attractive for ASR storage. Competition from existing users is considered low since the hardness content of the native water which limits aquifer exploitation for supply purposes. A detailed geochemical analysis should be performed to include the Upper Beberibe native water and the ASR source water. The purpose of this assessment would be to identify water quality compatibility issues associated with this storage zone.

The confined and semi-confined sandstones of the Lower Beberibe aquifer are also promising for ASR development. Saturated thicknesses of up to 200 m have been reported in the northern RMR, where individual wells yield in average 58.3 m^3/h. The water utility company currently withdraws about 1.5 m^3/s from a total of 110 wells installed in the Lower Beberibe. The aquifer is less prone to surface contamination within the northern portions of the study area where thick beds of low permeability strata overlie the aquifer. Conversely, the potential for surface contamination within the Recife Plain domain is much greater. An increase in TDS concentrations has been observed, which appears to have migrated from overlying layers. An important aspect influencing the suitability of this aquifer along the Recife Plain is the uncontrolled pumpage by private well owners. Competition from existing users would have to be addressed and minimized in order to make the ASR program feasible.

Despite the low overall permeability, there could be areas within the Cabo Formation where well yields would be adequate for ASR. The high clay content of the Cabo aquifer sandstones may increase the resistance to flow during recharge and cause head buildup near the well if clays are unstable. Therefore, recharge of fine-grained portions of this aquifer may require increased backflush frequency to maintain acceptable recharge rates. The potential for surface contamination is moderate, due to the same conditions which exist in the Beberibe aquifer. Competition from existing private users is also an issue that must be addressed in selection of ASR sites.

The undifferentiated sediments of the Boa Viagem aquifer provide a great potential for ASR. However, shallow depths to water in portions of this unconfined aquifer could limit recharge rates and, ultimately, the volume of storage available. In addition, ASR development should be focused on areas of coarser sediments to avoid well plugging. The potential for surface contamination may be a limiting factor for this storage zone. The high permeability of the alluvial sediments increase the potential for infiltration of undesired surface water. Researches believe this has contributed to increasing TDS concentrations in the Cabo groundwater modern times. Last, groundwater competition is also a relevant issue affecting the feasibility of the Cabo aquifer as a storage zone. Over 800 private wells currently pump water from this aquifer in the Recife Plain.

5.5 ENVIRONMENTAL AND REGULATORY ISSUES

ASR development in suitable portions of the Beberibe and Cabo aquifers may mitigate/avoid environmental-concerns such as saltwater intrusion and subsidence in the

Recife Plain. Furthermore, long-term storage could restore groundwater to historical levels.

Brackish water zones within the Lower Beberibe, Cabo, and Boa Viagem aquifers can be particularly attractive for ASR development. Although recovery efficiencies would likely be lower until a buffer zone of stored water could be established, competition for groundwater would be less than in freshwater portions of these aquifers. This benefit commonly outweighs the reduced recovery efficiency during early storage cycles.

The implementation of an ASR program in the RMR must be supported by regulatory measures to control groundwater exploitation in the area. This is of primary importance should ASR feasibility be confirmed within underground zones of the Recife Plain. Compliance with the requirements of the existing Law No 11,427, and perhaps more stringent amendments, will be essential for the success of ASR projects.

5.6 SITE SELECTION

The selection of a suitable site(s) for the ASR wells is likely determined by the occurrence of a suitable storage zone and the availability of a source water collection and transmission works. it is also recommended that the test ASR facility be situated in the vicinity of existing water treatment plants (WTP), which would ultimately treat ASR source water to drinking standards. This leads to cost savings associated with recharge/recovery transmission infrastructure. Once available treatment capacities are identified at regional WTPs, adjacent areas can be investigated for ASR suitability.

Table 2 lists the maximum capacity of several WTPs located within the study area. Some values were not found in the available literature and should be assessed to supplement this analysis. The data indicate that the M. Castelo Branco plant operates with an average idle capacity of 0.35 m^3/s. Furthermore, underutilized treatment capacities of 0.04 m^3/s, 0.03 m^3/s and 0.02 m^3/s are observed at the Gurjau, Dois Irmaos, and Caixa d'Agua facilities, respectively. It should also be noted that the Mojope system was designed to divert 0.2 m^3/s to the Botafogo WTP, as needed. Therefore, it is possible that the Alto do Ceu plant operates with an idle capacity in excess of 0.2 m^3/s during certain times of the year.

Based on the spatial distribution of these facilities, suitable thicknesses of the Upper Beberibe can be found in the vicinity of the Alto do Ceu and Caixa d'Agua facilities. Sites adjacent to the M. Castelo Branco can be further investigated to identify attractive ASR storage zones within the Lower Beberibe and Boa Viagem domains. The Gurjau treatment plant is located in the southern RMR. Surrounding sites may be conducive to ASR operation in the Cabo aquifer.

The reviewed literature lacks information about treatment capacities of the RMR's remote systems. Additional sites in the vicinity of these systems may also be attractive for ASR and should be accounted considered in subsequent ASR investigations.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 PRELIMINARY EVALUATION

Based on the results of this preliminary investigation, an ASR program appears feasible in the RMR. The region's critical water supply shortage, combined with potential adverse impacts caused by extensive groundwater overdrafts, support implementation of the ASR concept. Major advantages identified for the RMR were supplemental water supply, prevention of salt water intrusion, restoration of groundwater levels and prevention of subsidence in the Recife Plain.

Source water alternatives, water demand records, storage zones, environmental and regulatory issues, and site selection criterion were considered for the RMR, according to the extent of available data. A brief source water assessment suggested that surface water, currently and yet to be produced from nearby watersheds, and groundwater from the Barreiras aquifer are potential alternatives for recharge. Detailed hydrologic and water quality analyses are required to confirm resource availability and geochemical compatibility.

The examination of average demand data along with projected trends in demand and supply indicated that an ASR program could optimize water availability for the RMR. The actual contribution from ASR could not be assessed at this time since seasonal and peak variations in the system were not available. Information required for a thorough analysis also include daily, monthly and annual trends in water demands.

The Upper and Lower Beberibe, Cabo and Boa Viagem aquifers were considered as potential storage zones. Acceptable transmissivities have been reported for all candidate zones. Both members of the Beberibe aquifer have significant potential for ASR development in the northern RMR, especially in areas less prone to surface contamination. Competition from existing users is less in the upper layers due to the elevated levels of groundwater hardness. The saturated thicknesses of the Lower Beberibe and Cabo aquifers and the coarse sediments of the Boa Viagem aquifer in the Recife Plain are also attractive to ASR. However, the large number of existing users limit potential for ASR development. ASR implementation must be supported by regulations which control groundwater use in the area.

Adverse environmental impacts associated with overdraft conditions, such as saltwater intrusion and subsidence in the Recife Plain, could be mitigated through ASR development in the Beberibe and Cabo aquifers. Furthermore, long-term storage could restore groundwater levels depressed by extensive overdrafts.

A brief review of the existing system's capacities revealed average idle capacities in some of the water treatment plants. These can be used to treat water in excess of demand requirements for diversion to ASR purposes. The location of these facilities suggests that suitable thicknesses of the Upper Beberibe can be found in the vicinity of the Alto do Ceu and Caixa d'Agua facilities. Also, sites adjacent to the M. Castelo Branco may prove within the Lower Beberibe and Boa Viagem domains. The Gurjau treatment plant vicinity may be conducive for ASR wells in the Cabo aquifer.

6.2 ASR DEVELOPMENT

The following steps are recommended for a successful ASR program in the RMR:

- Detailed hydrologic and water quality analyses to confirm suitability of source water
- More thorough analysis of water demand records, including daily, monthly and annual trends in water demands (current and projected), to define periods of recovery and recharge
- Field investigation to provide a more accurate estimate of storage zone hydraulic parameters, as well as site-specific data for geochemical analysis
- Groundwater modeling to determine the extent of influence from existing users and ensure proper location of ASR wells
- Implementation and enforcement of groundwater regulations to control extensive overdrafts and provide a support for the ASR program
- Supplemental data gathering to identify additional idle treatment capacities within the RMR integrated and remote supply systems

Once the above steps are implemented, a conceptual design would be prepared to account for design injection and recovery rates, target seasonal storage volumes, and the number of the ASR facilities required to meet future demands. The cost of implementing selected ASR applications would be developed to include both capital and operational costs. The total costs are then compared to projected costs of satisfying demands using alternate strategies.

Results from the comprehensive preliminary study will lead to recommendations regarding the implementation of subsequent ASR phases.

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