Journal of Environmental Management 209 (2018) 426–439

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Piezometric level and electrical conductivity spatiotemporal monitoring as an instrument to design further managed aquifer recharge strategies in a complex estuarial system under anthropogenic pressure

Victor Hugo R. Coelho [a, b, *, 1], Guillaume F. Bertrand [a, 1], Suzana M.G.L. Montenegro [a], Anderson L.R. Paiva [a], Cristiano N. Almeida [b], Carlos O. Galvão [c, d], Luís Romero Barbosa [b], Larissa F.D.R. Batista [a], Eduardo L.G.A. Ferreira [a]

[a] *Geosciences and Technology Center, Federal University of Pernambuco, Recife, PE 50670-901, Brazil*
[b] *Water Resources and Environmental Engineering Laboratory, Federal University of Paraíba, João Pessoa, PB 58051-900, Brazil*
[c] *Technology and Natural Resources Center, Federal University of Campina Grande, Campina Grande, PB 58429-900, Brazil*
[d] *Cities Research Institute, Griffith University, Nathan Campus, Queensland 4111, Australia*

ARTICLE INFO

Article history:
Received 3 August 2017
Received in revised form
27 December 2017
Accepted 30 December 2017

Keywords:
MAR
Paleo-channels
Deep aquifer
Infiltration
Injection
Brazil

ABSTRACT

Recife Metropolitan Region (RMR, NE Brazil) lies over a multi-layered aquifer system located in an estuarial area. The region has experienced fast population growth and repeated droughts in the last three decades, which led to unprecedented anthropogenic pressure on groundwater resources because of intense water pumping. Accordingly, scientific and stakeholder communities have been challenged to ensure the maintenance of sustainable groundwater resource by managing all water cycle. Because controlling pumping rates is difficult due to the large number of illegal wells, the Managed Aquifer Recharge (MAR) strategies are now under consideration. The RMR presents a tropical climate and an annual average rainfall rate of approximately 2450 mm year^{-1}, providing great potential volumes of water to be used for piezometric level recovery. However, MAR implementation requires a detailed and in-depth knowledge of the human-impact on the hydrogeological behavior of the resource over the long-term, in order to find out the most appropriate recharge strategy. Therefore, the present study illustrates how routine data monitoring, i.e., piezometric level and electrical conductivity (EC), in combination with the geological knowledge, may allow proposing further MAR strategies. Two contrasted behaviors were observed in RMR: (i) groundwater level decrease and stable EC in the North and Southernmost areas of Recife; and (ii) stable groundwater level and high/varying EC values next to the estuarial zone. Although aquifers are undergoing over-abstraction, this spatiotemporal heterogeneity suggests that a recharge is possibly locally favored next to the estuarial area of the RMR thanks to hydraulic connections between surface and deep aquifers throughout extended paleo-channels. Thus, based on this typology, MAR implementation through controlled infiltration close to the estuarial area seems to be more appropriated, whereas the direct deep injection appears to be more relevant in more distant zones.

1. Introduction

Groundwater is a key natural resource supporting socioeconomic development worldwide (Foster et al., 2013) as well as ecological service sustainability (Bertrand et al., 2012; Kløve et al., 2014, 2011). However, the anthropogenic disturbances faced by this resource may lead to negative consequences such as dramatic reduction of the stored water volume (Brkić et al., 2013; Chaudhuri

* Corresponding author. Geosciences and Technology Center, Federal University of Pernambuco, Recife, PE, 50670-901, Brazil.
E-mail addresses: victor-coelho@hotmail.com (V.H.R. Coelho), guillaume.bertrand@email.com (G.F. Bertrand), suzanam.ufpe@gmail.com (S.M.G.L. Montenegro), andersonlrpaiva@gmail.com (A.L.R. Paiva), almeida74br@yahoo.com.br (C.N. Almeida), carlos.galvao@ufcg.edu.br (C.O. Galvão), luisromero.eng@gmail.com (L.R. Barbosa), larissafbatista@gmail.com (L.F.D.R. Batista), eduardolgaferreira@hotmail.com (E.L.G.A. Ferreira).
[1] The authors have equally contributed to the present study and share the first authorship.

https://doi.org/10.1016/j.jenvman.2017.12.078
0301-4797/

and Ale, 2014a; Weinthal et al., 2005), possible salt-water intrusion into coastal aquifers (Cary et al., 2015; Chaudhuri and Ale, 2014b; Loáiciga et al., 2012), contamination risks (Bertrand et al., 2016; Chatton et al., 2016; Chaudhuri and Ale, 2014b; Montenegro et al., 2006), and soil subsidence hazards (Cao et al., 2013; de Luna et al., 2017; dos Santos et al., 2012; Pardo et al., 2013). The magnitude of these threats is particularly accentuated in megacities of developing countries due to rapid demographic growth, since it has seriously outstripped these cities' capacity to provide adequate basic services for their citizens (Cohen, 2006). Studies conducted by Silva Jr. et al. (2010) and Bocanegra et al. (2010) have identified quality and quantity issues in the heavily populated coastal areas of South America, which point out the unsustainable groundwater abstraction in the region.

Two strategies, i.e., discharge or recharge managements, may be implemented in densely populated areas to minimize the influence of this pressure on the subsurface resource and to limit groundwater shortage. Pumping limitation policies, along with a severe legislation, must focus on the development of extensive domestic water supply networks on controlling the pumping rate and the drilling of new wells (Carrera-Hernández and Gaskin, 2007; Custodio et al., 2017a, 2017b). Such strategy implies strong public policies to assure proper network operation procedures and strict groundwater abstraction control. Alternatively, the Managed Aquifer Recharge (MAR) may be implemented through rainwater and/or wastewater collection to be further used in groundwater system supplying (Vanderzalm et al., 2010; Zuurbier et al., 2017). This type of management requires good knowledge about the long-term hydrogeological functioning, besides the awareness of the human impact on such functioning, in order to make sure that the additional recharge allows further groundwater pumping, therefore, limiting the abovementioned adverse effects.

The groundwater monitoring time series in developing countries are usually scarce and just comprise few variables, which could be seen as a limitation to the knowledge about aquifer behaviors (Mogheir et al., 2005; Triki et al., 2013). However, although routinely monitored variables such as potentiometric levels and electrical conductivity (EC) can be rich information sources and provide insights on long-term aquifer behaviors, in many cases their uses are limited to the functioning control of the well and are neglected for the aquifer scale process knowledge acquisition. Additionally, sound hydrogeological surveys and consistent knowledge about well drilling and abstraction provided by experienced hydrogeologists are often available (Dillon, 2005; Newman et al., 2016).

The Recife Metropolitan Region (RMR, Pernambuco, NE Brazil) lies over a multi-layered aquifer system located in an estuarial area (Cary et al., 2015; Petelet-Giraud et al., 2017). The region constitutes a typical climatic hotspot facing demographic and groundwater over-abstraction pressures in Southern Hemisphere countries (Bertrand et al., 2016; Cary et al., 2015; Chatton et al., 2016; Petelet-Giraud et al., 2017). The RMR is the fourth largest urban area in Brazil and hosts ~3.9 million inhabitants. Like many Southern cities, Recife faces a set of serious structural issues such as precarious access to public water (losses, pressure drawdown, and lack of investment in water-supply network management), water rationing, and poor sewage-collection system (~40% coverage) (Chatton et al., 2016). These structural issues were worsened by repeated droughts since the late 1990s.

The aforementioned conditions have resulted in the increased number of newly drilled wells in the region (Montenegro et al., 2010), mainly in the deepest good-quality groundwater aquifers. Such scenario led to dramatic piezometric drawdowns (up to 70 m in some places), which have increased the risks of saline intrusion and contamination due to the hydraulic connection with the superficial aquifers (Bertrand et al., 2016; Cary et al., 2015; Montenegro et al., 2006). This large number of abstraction wells (most of them illegal) also presents large pumping rates, which probably impacts the natural recharge due to the low transmissivity of the system. This situation highlights the great difficulty in limiting the discharge compartment of the system, since water scarcity and management failures may favor the uncontrolled use of groundwater (Cary et al. in press; Cary et al., 2014; Petelet-Giraud et al., 2017).

The RMR is characterized by tropical climate and, although it has been facing repeated droughts for the last 20 years, large amount of annual rainfall (2450 mm) has been recorded, as well as frequent extreme events generating urban drainage issues. Such condition implies relevant water volumes to be virtually available to recharge local aquifers. Moreover, it suggests the possibility of implementing MAR projects to provide a sustainable strategy to limit the adverse effects from climatic and anthropogenic pressures. However, as previously mentioned, such potential should be assessed by integrating the historical human impact on the resource conditions.

Accordingly, the challenge to stakeholders lies on delineating the potential points for the implementation of MAR strategies, i.e., relevant places and techniques. Thus, in order to address this problematic, the present paper illustrates how the analyses applied to frequently underrated data (e.g., potentiometric level and EC) may provide the historical hydrological background of the aquifer reactivity under abstraction process. Finally, this study shows how these information, along with the geological knowledge, may allow proposing further MAR strategies to be applied to a complex estuarial and urban system, which is typically an over-abstraction hotspot presenting recharge pattern issues.

2. Study site

2.1. Site description

The RMR is located along the Atlantic coast of the Brazilian Northeastern region, 7° 41′–8° 36′ S latitude and 34° 49′–35° 16′ W longitude; it covers 2769 km^2 (Fig. 1). The region includes Recife City and thirteen other neighboring counties, most of them at mean altitude 5 m above sea level. The most populated areas in RMR are located close to the estuarine area of the Capibaribe River, which also comprises mangroves and receives water from streams fed by the dense drainage network in the metropolis (Cabral et al., 2004; Cary et al., 2015; Chatton et al., 2016). According to Köppen's classification, RMR presents hot and humid tropical monsoon climate, with mean temperature above 25 °C. The average annual rainfall (1961–1990) is approximately 2450 mm (Sobrinho et al., 2015), most of which recorded from March to July.

Historically, the public water supply in the RMR relies mainly on surface water and dams (Chatton et al., 2016). Cabral et al. (1999) have estimated that the public supply service provided by the groundwater system represented ~18% of the total demand in the region. Nevertheless, repeated droughts have caused groundwater abstraction increase in the last few decades, and it was identified as a risk for the groundwater quality and quantity (Cavalcanti and Montenegro, 2009). Accordingly, Costa et al. (2002) reported that the 1998–1999 drought led to water rationing and this phenomenon was followed by a large and uncontrolled groundwater abstraction in Recife. More than 13000 wells, most of them illegal private boreholes, were drilled in the city, which led to one of the highest well densities in Brazil (Batista, 2015). Two “hotspots” could be identified in the RMR: (i) Boa Viagem avenue; and (ii) Northwestern “Bacia do Pina”, in Espinheiro neighborhood. The current study was carried out in these two highly-impacted sites.