Assessing managed aquifer recharge (MAR) for coastal aquifer management in Asia, South America and Europe in a changing climate

K. Hinsby[1], Z. Ma[2], J.C. Wu[3], H.W. Liu[2], S. Montenegro[4], G. C. da Silva Jr.[5], D. Postma[1],
A.R. Johnsen[1], C.S. Jacobsen[1], and S.R. Sørensen[1].

[1]Geological Survey of Denmark and Greenland,
[2]China Geological Survey,
[3]Nanjing university,
[4]Federal University of Pernambuco,
[5]Federal University of Rio de Janeiro.

ABSTRACT

Population growth in coastal regions, climate change and sea level rise pose increasing challenges to the sustainable management of coastal aquifers and ecosystems and the conjunctive use of groundwater and surface water globally. The project Water4Coasts, which includes partners from Brazil, China and Denmark, seeks to develop and apply new innovative monitoring, data handling, modeling and management solutions, and share experiences on sustainable management of coastal water resources and ecosystems in a changing climate. In this paper we present selected preliminary results and conclusions from the case study sites in Recife (Brazil), Laizhou Bay (China) and the Island of Falster (Denmark).

INTRODUCTION

Sustainable management of coastal water resources and ecosystems face increasing problems globally (Wu *et al.* 1993, 2008, da Silva Jr. *et al.*, 2010, Hinsby *et al.*, 2011, 2012, 2013 Montenegro *et al.*, 2012, Sonnenborg *et al.* 2012, Rasmussen *et al.*, 2013). The main objectives of the project Water4Coasts, from the “ecoinnovation” program of the Danish Ministry of Environment, are to evaluate and promote innovative solutions within: 1) Techniques for controlling saltwater intrusion and land subsidence; 2) Efficient methods for early warning and flood risk reduction from streams and canals; 3) Methods for reducing nutrient loadings to surface waters and 4) New efficient monitoring, data handling and visualization techniques. The study focuses on investigations in three coastal aquifers at Laizhou Bay, China; Recife, Brazil and Marielyst/Falster, Denmark. The three study sites are located in very different climatological and hydro(geo)logical settings in the northern and southern hemisphere, with annual precipitation ranging from around 600 mm (evaporation greater than 1600 mm and drought conditions in Laizhou, China) up to more than 2000 mm (Recife, Brazil), and at three different seas: The Pacific ocean, the Atlantic ocean and the Baltic Sea.

METHODS

In Water4Coasts evaluation of different methods for controlling saltwater intrusion are considered, such as managed aquifer recharge of rainwater and/or recycled water for development of positive hydraulic barriers to control saltwater intrusion. Such systems have been in operation in, for instance, California (e.g. Reichard and Johnson, 2005) and Northern Spain (Ortuño *et al.* 2012) for decades, while managed aquifer recharge in coastal dunes is well known from the Netherlands (Karlsen *et al.*, 2012). Rainwater harvesting and injection is a relevant option for the Recife site with annual precipitation of up to more than three meters in wetter years, but it may also be a relevant option at both of the other sites. For the Danish site at the Baltic Sea, regional climate models have estimated that the current winter precipitation may increase by about 50% in this century. Rainwater harvesting, storage and injection in aquifers may be an option both for controlling saltwater intrusion and for flood risk reduction. Likewise, direct injection of recycled water to coastal aquifers (managed aquifer recharge) is considered to be a realistic option to control saltwater intrusion in all three investigated sites, in order not only to control saltwater intrusion and reduce flooding risks, but also to further reduce nutrient loadings to coastal waters and, in some cases, mitigate or reduce the risk of land subsidence. The Water4Coasts project considers different options for all three study sites and compares experiences for monitoring and controlling saltwater intrusion gained at the three study sites in Brazil, China and Denmark.

RESULTS

Results from the three study sites presented here include: 1) Initial assessment of the feasibility of rainwater harvesting and MAR in Recife, Brazil; 2) Monitoring, local and regional modelling of current saltwater intrusion from seawater and old marine sediments in Laizhou Bay area, China; and 3) Assessment of the chemical and microbiological quality of drain water potentially used for injection in possibly horizontal saltwater barrier wells on the Island of Falster, Denmark.

Recife, Pernambuco State, Brazil

Recife Coastal Plain multi-aquifer system consists of two deep semi-confined aquifers, Cabo and Beberibe, covered by a phreatic aquifer, Boa Viagem. The excessive drawdown of the potentiometric heads in the deep aquifers due to overexploitation is aggravated by the high urbanization level, which highly decreases the chance of natural recharge of the system. Thus, the importance of evaluating the potential of managed aquifer recharge using rainfall as an alternative for recovering the potentiometric heads in the confined aquifers is increasing. In this context, an artificial recharge experiment simulating the use of rainfall volume storage was performed. The experiments were carried out in a region where the highest drawdowns in Cabo aquifer have been observed, in order to verify the artificial recharge results. Different scenarios were analyzed with numerical analysis by the finite element program CODE_BRIGHT (Olivella, 1995). The results suggest that managed aquifer recharge by injection wells in the site studied is feasible. Nevertheless, experiments with long-term injection and analysis should be carried out to further evaluate the potentiometric head variations caused by long-term managed aquifer recharge.

Laizhou Bay, Shandong Province, China

Different scenarios including change in abstraction (reducing water exploitation 30% and increasing brine-water mining 30%), sea level rise（rise of 0.3 m）and managed aquifer recharge along the “Yellow River to Qingdao canal” (injection volume is $1.8\times10^{5}m^{3}/d$) are currently being modeled at two scales. The modeled areas, located between Weifang city and the southern coastline of Laizhou Bay are shown in Figure 1.

Two density-dependent groundwater flow models have been established for the Chinese study area between The City of Weifang and the coastline of Laizhou Bay 1) A regional model covering all of the area shown in Figure 1 is set up in SEAWAT (Langevin *et al.*, 2007) and 2) A smaller more detailed model is established about 1020 km^2 in northwestern part of the area. The model is set up in FEMWATER (Lin *et al.*, 1997). The models are established by China Geological Survey and Nanjing University. Based on the data of groundwater level, chloride and TDS concentration, regional scale and small scale models are identified and validated.

Figure 1. Laizhou Bay study area in China.

The migration of the saltwater intrusion interface was analyzed in a variety of modelling schemes in order to assess the impact of different scenarios. According to the modeling results, the seawater intrusion speed is about 450 m/a during the 1980s and 1990s, and then it slows down to 50 m/a or less in recent years. In addition, they show that the intrusion speed will increase by approximately 5% and 18% as having 50% more pumping and 0.3m sea level rising, respectively. Additional results show that the sea level rise has relatively little effect on the interface under current conditions. However, changes in aquifer recharge and abstraction have a conspicuous effect on the seawater intrusion interface, and can significantly affect the seawater intrusion interface migrating southwards. Consequently, change in abstraction scheme is the simplest and more practical way to avert seawater intrusion, because the Municipal Government is able to implement effective management quickly, while managed aquifer recharge may the best way to prevent saltwater intrusion. However, the feasibility of such actions must be further identified according to hydrogeological conditions, drilling technology and injection water quality.

Marielyst, Falster, Denmark

Saltwater intrusion and the impact of climate change and sea level rise has been modelled with SEAWAT (Rasmussen *et al.*, 2013). Currently the model is improved and recalibrated and prepared for the evaluation of different design of saltwater intrusion barriers, which may include both vertical and horizontal barrier wells (Rasmussen *et al.*, this volume). Results from parallel studies on the organic, inorganic and microbiological quality of water from drainage canals in the study area, which potentially may be used for managed aquifer recharge in injection barrier wells, show that a rather high number of different types of pharmaceuticals (e.g. cardiovascular medicine, psychopharmica, anti-inflammatory painkillers and antibiotics) and some pathogens are currently present in drain waters, and that these therefore would need efficient pre-treatment before injection. Finally, geochemical modelling demonstrates that the evolution of groundwater chemistry and the significance of redox processes may differ significantly between single and dual porosity media.

DISCUSSION AND CONCLUSIONS

The preliminary results and assessments demonstrate that MAR may contribute to control and mitigate salt water intrusion problems in the investigated aquifers, as has also been demonstrated in several MAR systems successfully operating mainly in the U.S. and Europe. However, the studies also demonstrate that MAR requires strict control with the quality of the recharged waters and efficient treatment before recharge/injection, especially to ensure efficient removal of e.g. pathogens and potential emerging contaminants (e.g. pharmaceuticals) from sewage systems and agricultural practices etc. In addition, injection of oxic surface water into anoxic groundwater environments may mobilize trace elements such as As and Ni, e.g. from oxidation of pyrite, and create other severe groundwater quality or well clogging problems. Hence, required pretreatment, subsurface hydraulics, chemical processes and solute transport, as well as transport and fate of contaminants and naturally occurring trace elements in groundwater, need to be carefully assessed before designing and installing full scale operating MAR systems.

REFERENCES

Hinsby, K., Ma, Z., Wu, J.C., Montenegro, S., Silva G. C. da et al. Managing coastal aquifers in Asia, South America and Europe in a changing climate – exchanging experiences and recommendations. 3rd Asia-Pacific Coastal Aquifer Management Meeting, October 21-24, Beijing, China, 2013.

Hinsby, K., Markager, S., Kronvang, B., Windolf, J., Sonnenborg, T. O., and Thorling, L.. 2012. Threshold values and management options for nutrients in a catchment of a temperate estuary with poor ecological status, Hydrol. Earth Syst. Sci, 16, 2663-2683.

Hinsby, K., E. Auken, G. H. P. Oude Essink, P. de Louw, F. Jørgensen, B. Siemon, T. O. Sonnenborg, A. Vandenbohede, H. Wiederhold, A. Guadagnini, and J. Carrera. 2011. Assessing the impact of climate change for adaptive water management in coastal regions. Hydrol. Earth Syst. Sci, 149, special issue.

Karlsen, R.H., F.J.C. Smits, P.J. Stuyfzand, T.N. Olsthoorn, B.M. van Breukelen. 2012. A post audit and inverse modeling in reactive transport: 50 years of artificial recharge in the Amsterdam Water Supply Dunes. J. Hydrol., 454–455, 7–25.

Langevin, C.D., Thorne, D.T., Dausman, A.M., Sukop, M.C. and Guo, W. 2007. SEAWAT Version 4: a computer program for simulation of multi-species solute and heat transport. US Geological Survey, Techniques and methods, Book 6, Chapter A22, US Geol. Survey, Reston, VA.

Lin, H.C.J, Richards, D.R., Talbot, C.A. *et al.* FEMWATER. 1997. A Three-Dimensional Finite Element Computer Model for Simulating Density-Dependent Flow and Transport in Variably Saturated Media. U.S. Army Corps of Engineers etc, Technical Report CHL-97-12.

Montenegro, S., and Ragab, R.: Impact of possible climate and land use changes in the semi-arid regions. 2012. A case study from North Eastern Brazil, J. Hydrol., 434, 55-68.

Olivella, S., 1995 Nonisothermal Multiphase Flow of Brine and Gas Thorough Saline Media. Tesis Doctoral, Universitat Politècnica de Catalunya, Departament D'Enginyeria del Terreny i Cartográfica.

Ortuño, F., Molinero, J., Garrido, T., and Custodio, E.. 2012. Saltwater injection barrier recharge with advanced reclaimed water at Llobregat delta aquifer (Spain), Water Sci. Techn. 66, 2083-2089.

Rasmussen, P., Sonnenborg, T. O., Goncear, G., and Hinsby, K.. 2013. Assessing impacts of climate change, sea level rise, and drainage canals on saltwater intrusion to coastal aquifer, Hydrol. Earth Syst. Sci., 17, 421-443.

Rasmussen, P., Sonnenborg, T.O. and Hinsby, K. Evaluating hydraulic barriers for reducing and controlling saltwater intrusionin a changing climate. SWIM23, pp. ??, this volume.

Reichard, E.G. and Johnson, T.A. 2005. Assessment of Regional Management Strategies for Controlling Seawater Intrusion. Journal of Water Resources Planning and Management, 131(4):280-291.

Silva Jr., G. C., Bocanegra, E., Custodio, E., Manzano, M., and Montenegro, S. 2010. State of knowledge and management of Iberoamerican coastal aquifers with different geo-hydrological settings, *Episodes*, 33, 91-101.

Sonnenborg, T. O., Hinsby, K., van Roosmalen, L., and Stisen, S. 2012. Assessment of climate change impacts on the quantity and quality of a coastal catchment using a coupled groundwater-surface water model, Clim. Change, 113.

Wu, J. C., Meng, F. H., Wang, X. W., and Wang, D.. 2008. The development and control of the saltwater intrusion in the eastern coastal of Laizhou Bay, China, Environ. Geol., 54, 1763-1770.

Wu, J.C., Xue, Y., Liu, P., Wang, J., Jiang, Q. and Shi, H. 1993. Sea-Water Intrusion in the Coastal Area of Laizhou Bay, China .2. Sea-Water Intrusion Monitoring, Ground Water, 31, 740-745.

Contact information: Klaus Hinsby, Geological Survey of Denmark and Greenland, Department of Hydrology, O. Voldgade 10, 1350 Copenhagen, Denmark, tel.: +45 91 333 618, e-mail: khi@geus.dk