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Investigating seawater intrusion due to groundwater pumping with schematic model simulations: The example of the Dar es Salaam coastal aquifer in Tanzania

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A B S T R A C T

Water supply requirements in Dar es Salaam city (Tanzania) are rising rapidly by population growth and groundwater is increasingly used to fullfill the needs. The groundwater is taken from the Dar es Salaam Quaternary coastal aquifer (DQCA), stretching inland from the coastline. As thousands of wells have been drilled in the coastal strip and pumping rates are uncontrolled, seawater intrusion is deteriorating the quality of fresh groundwater. To investigate the response of the fresh/salt water interface to coastal pumping, simulations with a schematic two-dimensional cross-sectional model have been done. Depending on the depth of the wells in the 150 m thick DQCA and their distance from the coastline, different pathways of seawater intrusion and shifts of the interface can be recognized. The local presence of a semi-pervious layer can have a significant impact on the fresh/salt water distribution. Although the modeled section is not related to a specific location along the coastline but rather represents an average aquifer buildup, the results of the simulations can be used to formulate recommendations when drilling new wells and for a better monitoring of the salinisation process along the coast. It proves that even simple schematic models can give meaningful contributions.

1. Introduction

The problem of coastal aquifer salinisation as a result of seawater intrusion occurs in many countries and cities located in coastal areas. This problem is mainly associated with high groundwater exploitation due to population growth and industrial developments. When groundwater is pumped from coastal aquifers, freshwater that is discharging into the sea is intercepted, disrupting the natural equilibrium. This causes the fresh/salt-water interface to migrate landward and/or locally upward (upconing). The latter is expressed as the movement of saltwater from a deeper saltwater zone into the fresh groundwater in response to pumping at a single well (Reilly and Goodman, 1987). The greater the drawdown at the extraction point, the greater the potential for upconing. Saltwater upconing is a widespread problem reported globally: for example, in Japan (Hosokawa et al., 1990), USA (Krause and Clarke, 2001), Germany (Diersch et al., 1984; Diersch and Nillert, 1987), the Netherlands (Huisman, 1954), Israel (Dagan and Bear, 1968; Schmorak and Mercado, 1969) and Belgium (Walraevens et al., 1993). Intrusion of saline water occurs where saline water dislocates or mixes with fresh water in an aquifer. Groundwater overexploitation through the wells that are located near the shoreline is a major cause of seawater intrusion. Seawater, because of its higher density (1.025 g/ml), goes inland under a relatively low density freshwater (1.000 g/ml).

The seawater intrusion forms a saline wedge below a transition zone, mainly due to the dispersion effect (Polemio et al., 2009).

The risk for saltwater intrusion in the study area was recognized since 1986 (Mnzava, 1986). The few data available prior to 1980 indicate that increases in chloride concentration were not yet a problem in Dar es Salaam Quaternary coastal aquifer (DQCA) (unpublished records from the files of the Ministry of Water). In the 1980s, some increase of chloride concentration thought to be influenced by various sources was reported (Mnzava, 1986;

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Msindai, 1988). Substantial increases in chloride concentrations were documented following heavy pumping, which DQCA experienced since 1997, when boreholes drilling began to expand quickly following the weakening of the surface water supply and rapid population growth. A study made by the Ministry of Water (URT, 2007) and Mjemah (2007) reported an increase of groundwater salinity in several boreholes in the coastal area of the city. Chloride ion concentrations in the range 1000–10,000 mg/l have been recorded in several points and a value higher than 10,000 mg/l has been measured in seven points (Mtoni, 2013).

Groundwater salinization and abandonment of several boreholes/wells in the areas close to the coastline are clearly the result of seawater intrusion initiated by excessive groundwater pumping (Mtoni et al., 2013). Since 1997, the Tanzanian Government, Non-Governmental Organizations (NGOs), Community Based Organizations (CBOs) and international aid organizations have promoted the drilling of boreholes to try to meet the demand of water supply in the city (Mtoni et al., 2011, 2012). The cumulative effect of pumping since then is likely to have influenced the fresh/saline interface given the close proximity of the communities to the sea shore and the high pumping rates.

2. Objective of the study

The objective of the paper is to demonstrate how simulations with a schematic cross-section model of a coastal strip can be used to compare different general development scenarios regarding localisation and depth of the pumping wells and to evaluate the risk of increased aquifer salinisation by intrusion of seawater. This research presents simulation of seawater intrusion in a coastal aquifer in response to groundwater abstraction, inspired by the case of Dar es Salaam aquifer. The simulations do not refer to specific well configurations. Average conditions in the Dar es Salaam Quaternary Aquifer system were input to the model, which uses a representative hydrostratigraphy for the simulated area. The schematic model studies the impact of distance between pumping and shoreline, depth of pumping wells and the role of the existence of a semi-pervious layer in the aquifer system on the fresh/salt water distribution.

3. Geology and hydrogeology of the Dar es Salaam region

The geological formations of Dar es Salaam region consist mainly of Quaternary and Neogene deposits (Fig. 1) (GST, 1963). The DQCA consists of Quaternary sediments which fill up a palaeo valley eroded in an underlying thick Neogene deltaic sequence (the so-called "clay bound sands"), which also surround the DQCA aquifer to the north and the south.

The Quaternary deposits are subdivided into: (1) alluvial deposits comprising clay, silt, sand and gravel, which are recent deposits occurring in river valleys; (2) coral reef limestone; and (3) sands of Pleistocene to Recent age with Holocene so-called "white buff sands" at outcrop; these sands constitute the main aquifers of the study area (Mjemah et al., 2009, 2011; Van Camp et al., 2013).

The presence of a local semi-pervious unit (clay, sandy clay and silt) within the Quaternary sand deposits allows two productive aquifers to be distinguished, both of Quaternary age: an upper unconfined sand aquifer and a lower semi-confined sand aquifer. The lower aquifer overlies the substratum formed by Mio-Pliocene clay-bound sands. The latter has more than 750 m thickness and is considered as the base of the groundwater reservoir (Mjemah, 2007; Van Camp et al., 2013).

The underlying Neogene deposits at and around the study area are classified into two main groups: (1) the Mio-Pliocene "clay-bound sands" and gravels formation outcropping in the northwest, south-east and to the south, and underlying the Pleistocene to Recent deposits in most of the study area. They appear to be more clayey near their top whereas in deeper parts, the clay content may decrease, leading to a deep aquifer; and (2) the Lower Miocene Pugu Kaolinitic Sandstone occurring in the west. The latter consists of reddish brown, thick-bedded sandstone inter-bedded with minor siltstone, shale, and limestone.

4. Methodology

4.1. Modeling of seawater intrusion in coastal aquifers

Seawater intrusion is a common contamination problem in coastal areas. It affects, mainly, arid and semi-arid zones, where high population and urbanisation are coupled to scarce water resources and resorting to intensive exploitation of groundwater. Numerical models provide effective tool to understand groundwater problems.

Density dependent flow or variable density flow is the term that classifies the flow pattern influenced by density differences in the fluid system (Lebbe, 1996; Vandenbohede, 2008). Proper simulation of density-dependent phenomena in groundwater flow and transport relies on coupled models that incorporate the constitutive relationship between solute concentration and density (Paniconi et al., 2001). Darcy's law presented in Eq. (1.1) is the foundation of groundwater flow models.

$$q = -K\nabla h \tag{1.1}$$

where q = the flow rate, K = hydraulic conductivity, and ∇h = the hydraulic gradient.

The horizontal and vertical components q_{hi} and q_{vi} of the Darcian velocity at a point i are presented in Eq. (1.2) (Lebbe, 1996).

$$q_{hi} = K_{hfi}\frac{\mu_f}{\mu_i}\frac{\partial h_{fi}}{\partial x} \quad q_{vi} = K_{vfi}\frac{\mu_f}{\mu_i}\left(\frac{\partial h_{fi}}{\partial z} + \frac{\delta_i - \delta_f}{\delta_f}\right) \tag{1.2}$$

K_{hfi} and K_{vfi} are the horizontal and vertical conductivity for freshwater, δ_f and δ_i are the densities of the freshwater and of the water at point i and μ_f and μ_i are their dynamic viscosities, $\partial h_{fi}/\partial x$ and $\partial h_{fi}/\partial z$ are the vertical and the horizontal freshwater head gradients and $(\delta_i - \delta_f)/\delta_f$ is the buoyancy at point i.

Under natural conditions, aquifer recharge is in equilibrium with groundwater discharge (Buddemeier, 1996). Near the shoreline, this equilibrium shows a salt-water wedge inland, under the freshwater, because of the higher density of the seawater. When groundwater is pumped from coastal aquifers, freshwater that is discharging into the sea is intercepted, disrupting the natural equilibrium. In order to manage saltwater intrusion, it is important to first understand, among others, the physical mechanisms by which saltwater intrusion occurs. The understanding of saltwater intrusion mechanisms will help to establish sustainable groundwater development scenarios. Saltwater intrusion causes the fresh/saltwater transition zone (mixing zone between fresh and saltwater) to migrate landward and/or locally upward.

4.1.1. Ghyben–Herzberg relation

According to the Badon Ghyben–Herzberg principle (Badon-Ghyben, 1888; Herzberg, 1901), the thickness of the freshwater lens below sea level (z) is 40 times larger than the thickness of the lens above sea level (h), due to difference in density between fresh water (ρ_f = 1.000 g/cm^3) and sea water (ρ_s = 1.025 g/cm^3):

$$z = \frac{\rho_f}{(\rho_s - \rho_f)}h = 40h$$