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Groundwater recharge and salinization in the arid coastal plain aquifer of the Wadi Watir delta, Sinai, Egypt

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A B S T R A C T

The Quaternary coastal plain aquifer down gradient of the Wadi Watir catchment is the main source of potable groundwater in the arid region of south Sinai, Egypt. The scarcity of rainfall over the last decade, combined with high groundwater pumping rates, have resulted in water-quality degradation in the main well field and in wells along the coast. Understanding the sources of groundwater salinization and amount of average annual recharge is critical for developing sustainable groundwater management strategies for the long-term prevention of groundwater quality deterioration. A combination of geochemistry, conservative ions (Cl and Br), and isotopic tracers ($^{87/86}$Sr, δ^{81}Br, δ^{37}Cl), in conjunction with groundwater modeling, is an effective method to assess and manage groundwater resources in the Wadi Watir delta aquifers. High groundwater salinity, including high Cl and Br concentrations, is recorded inland in the deep drilled wells located in the main well field and in wells along the coast. The range of Cl/Br ratios for shallow and deep groundwaters in the delta (~50–97) fall between the end member values of the recharge water that comes from the up gradient watershed, and evaporated seawater of marine origin, which is significantly different than the ratio in modern seawater (228). The $^{87/86}$Sr and δ^{81}Br isotopic values were higher in the recharge water (0.70,723 < $^{87/86}$Sr < 0.70,894, +0.94 < δ^{81}Br < +1.28‰), and lower in the deep groundwater (0.70,698 < $^{87/86}$Sr < 0.70,705, +0.22‰ < δ^{81}Br < +0.41‰). The δ^{37}Cl isotopic values were lower in the recharge water (−0.48 < δ^{37}Cl < −0.06‰) and higher in the deep groundwater (−0.01 < δ^{37}Cl < +0.22‰). The isotopic values of strontium, chloride, and bromide in groundwater from the Wadi Watir delta aquifers indicate that the main groundwater recharge source comes from the up gradient catchment along the main stream channel entering the delta. The solute-weighted mass balance mixing models show that groundwater in the main well field contains 4–10% deep saline groundwater, and groundwater in some wells along the coast contain 2–6% seawater and 18–29% deep saline groundwater.

A three-dimensional, variable-density, flow-and-transport SEAWAT model was developed using groundwater isotopes (^{87}Sr/^{86}Sr, δ^{37}Cl and δ^{81}Br) and calibrated using historical records of groundwater level and salinity. δ^{18}O was used to normalize the evaporative effect on shallow groundwater salinity for model calibration. The model shows how groundwater salinity and hydrologic data can be used in SEAWAT to understand recharge mechanisms, estimate groundwater recharge rates, and simulate the upwelling of deep saline groundwater and seawater intrusion. The model indicates that most of the groundwater recharge occurs near the outlet of the main channel. Average annual recharge to delta alluvial aquifers for 1982 to 2009 is estimated to be 2.16×10^6 m^3/yr. The main factors that control groundwater salinity are overpumping and recharge availability.

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1. Introduction

Alluvial aquifers in arid to semiarid coastal regions worldwide supply freshwater, such as the coastal plain aquifers in the Nile Delta (Sefelnasr and Sherif, 2014) along the northwestern coast of Egypt (Eissa et al., 2015a;b), the Korba plain in Tunisia (Salma et al., 2010), the Eastern Batinah region in northern Oman (Weyhenmeyer, 2002), and along the Arabian Gulf in northern United Arab Emirates (Alsharhan et al., 2001). In the Wadi Watir delta in Sinai, Egypt, as in many arid coastal regions of the world, potable water is limited to a shallow alluvial aquifer that provides the main potable water supply for Nuweiba Harbor located on the coast of the Gulf of Aqaba (Fig. 1). In this aquifer, a thin lens of groundwater floats over a deep saline layer that is very sensitive to pumping induced stresses (El Kiki et al., 1992; El-Refaei, 1992; Eissa et al., 2010). The aquifer has a thickness of about 90 m and high porosity that exceeds 30% (Khalil, 2010). Excessive groundwater withdrawal, undertaken to meet increasing water demands, has resulted in a declining water table, groundwater salinization from an upwelling of deep saline groundwater beneath the delta aquifer (Ismail, 1998; El Sayed, 2006; Shalaby, 1997; Mabrouk and Nasr, 1997), and seawater intrusion at the coast (Abuelfadl, 2004; Abd El Hafez, 2001). The delta was filled with high-saline water during the Pleistocene epoch and its deep layers are composed of mainly clayey sand and clay intercalations that represent three sequential phases of regression and transgression of gulf water (Abbas et al., 2004; Mabrouk and Nasr, 1997). In the Gulf of Aqaba drainage system, recharge is limited throughout the dry season, and groundwater salinization becomes a severe problem (Himida, 1997; Eissa et al., 2010; Isawi et al., 2016). Therefore, understanding the groundwater recharge sources and the upwelling mechanism of deep saline groundwater are important for groundwater management, and necessary to ensure groundwater sustainability at local and regional scales.

In this study, groundwater chemistry and multiple isotopes ($^{87/86}Sr$, $\delta^{37}Cl$, $\delta^{81}Br$, and $\delta^{18}O$), combined with groundwater modeling, were used to evaluate the water-rock interactions, the origin of groundwater recharge, seawater mixing, and the upwelling of deep saline groundwater in the delta. The isotopes used in this study have been used in previous studies to better understand the origin of deep groundwater salinization and improve the understanding of the hydrogeological system of the Canadian Shield, the Russian Siberian Platform, and deep groundwater from Vienne granitoids in France (Stotler et al., 2010; Shouakar-Stash et al., 2007; Negrel et al., 2002).

The variable density groundwater SEAWAT model is an efficient tool for understanding groundwater hydrodynamics, tracing the upwelling of deep saline water, quantifying seasonal variations in groundwater recharge, and evaluating seawater intrusion along coastal aquifers (Guo and Langevin, 2002). However, the assessment and accuracy of the model's output, including groundwater recharge and solute transport, mainly depend on the uncertainty of the input hydrologic parameters (Sibanda et al., 2009). Therefore, using environmental isotopes in conjunction with a numerical flow model could provide further insights into the hydrogeological model framework and model calibration. Several mathematical flow models have been used for the quantitative evaluation and formulation of isotopic data in a hydrological system (IAEA, 1993; Malosazewski et al., 1989). Isotope tracers have been used to provide further insights into the hydraulic properties of natural hydrogeologic systems in an Alpine catchment in Germany (Plumacher and Kinzelbach, 2000), and to calibrate regional groundwater flow models for carbonate-alluvial groundwater systems in southern Nevada in the United States (Kirk and Campana, 1990). Natural isotope ($\delta^{18}O$ and $\delta^{2}H$) approach models have been used in combination with numerical models to evaluate groundwater recharge in an alluvial aquifer in the Nasunogahara area in central Japan (Liu et al., 2014).

In this study, isotopes were used to provide qualitative data for helping to understand the hydrogeological flow system, such as system boundaries, processes of replenishment, and the origins of groundwater recharge and salinization. Quantitative data were inferred, such as the mixing ratios of different water sources and the evaporation factor for shallow groundwater, from these isotopic data. $\delta^{18}O$ values were used to calculate the amount of groundwater evaporation, which was needed for estimating the normalized groundwater salinity needed for SEAWAT model calibration.

This study aimed to: (1) determine the primary source(s) of groundwater salinization in the main well field and gain a better understanding of the effect of deep saline groundwater, (2) develop a SEAWAT model framework based on the isotopic data and the dominant processes that affect groundwater in the Wadi Watir delta, (3) improve SEAWAT model calibration using groundwater level and normalized groundwater salinity data, and (4) estimate the seasonal groundwater recharge sources and rates in the alluvial coastal aquifer system using a tracer approach and numerical simulations.

2. Study area, geology, and hydrogeology

The Wadi Watir delta is located down gradient of the Wadi Watir watershed on the southeastern part of the Sinai Peninsula, Egypt, between longitude 34° 38′ and 34° 41′ E and latitude 28° 57′ and 29° 03′ N (Fig. 1). The Wadi Watir watershed is considered to be the most important watershed in this region because the city of Nuweiba, a tourist destination, and Nuweiba Harbor are on the coast of this delta. Ships sailing from Nuweiba Harbor connect Egypt, Saudi Arabia, and Jordan.

The Wadi Watir watershed is predominantly composed of Precambrian granitic, metamorphic, and volcanic rocks intruded by acidic to basic dykes (Said, 1962). The watershed formed as a part of the eastern tectonic rift of the Sinai, which is delineated by a series of shear faults that form structurally elongated downfaulted rift valleys (Eyal, 1973; Bartov et al., 1979a,b). The rift is mainly composed of Paleozoic clastic and carbonate rocks and is covered by recent Quaternary alluvial deposits (Issar and Gilad, 1982). The Wadi Watir delta is comprised of alluvial aquifers underlain by an impermeable Precambrian basement (Fig. 2).

Groundwater from El Shiekh Attia, the Main Channel, and Furtaga Springs (site $At_{1,2}$, Mc, and F_1; Figs. 1 and 2) are the main recharge sources of groundwater and are located up gradient of the alluvial aquifers of the delta (El Ghazawi, 1999; Eissa et al., 2013b). The primary potable water supply for the Wadi Watir delta is from a well field located adjacent to the mountain block where the Wadi Watir watershed drainage enters the delta (Fig. 1; sites 17–23). Well pumping began in 1982 and since that time, the pumping rate has varied depending on groundwater availability and recharge (El Ghazawi, 1999). The major source of recharge to the alluvial aquifers of the Wadi Watir delta is infiltration from infrequent, heavy rains and floods in the mountain block area of the Wadi Watir watershed (El-Refaei, 1992).

The delta alluvial deposits are mainly composed of Quaternary fine-to-coarse sands, gravels, and boulders that are often within a silty and clayey matrix. These deposits are primarily derived from carbonate and basement rocks (El-Shazly et al., 1974; Eyal et al., 1980; El Kiki et al., 1992). The Quaternary deposits of the Wadi Watir delta can be divided into five layers (Fig. 2b, modified from Abbas et al., (2004)). The two uppermost layers are generally <10 m thick, grouped as surface layers, and are comprised of heterogeneous alluvial deposits. The third layer is a sandy-clay layer that is