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The influence of fish ponds and salinization on groundwater quality in the multi-layer coastal aquifer system in Israel

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ABSTRACT

This study focuses on the impact of surface reservoirs (fish ponds) on a multi aquifer coastal system, and the relation between the aquifer and the sea. The study was conducted in an Israeli Mediterranean coastal aquifer, which includes a sandy phreatic unit and two confined calcareous sandstone units. The geological description is based on 52 wells, from which 33 samples were collected for stable isotope analysis and 25 samples for organic and inorganic parameters. Hydraulic head and chemical measurements suggest that there is an hydraulic connection between the fish ponds above the aquifer and the phreatic unit, whereas the connection with the confined units is very limited. The phreatic unit is characterized by a low concentration of oxygen and high concentrations of ammonium and phosphate, while the confined units are characterized by higher oxygen and much lower ammonium and phosphate concentrations. Organic matter fluorescence was found to be a tool to distinguish the contribution of the pond waters, whereby a pond water signature (characterized by proteinaceous (tryptophan-like) and typical humic-matter fluorescence) was found in the phreatic aquifer. The phreatic unit is also isotopically enriched, similar to pond waters, with $\delta^{18}O$ of −1‰ and δD of −4.6‰, indicating enhanced evaporation of the pond water before infiltration, whereas there is a depleted isotopic composition in the confined units ($\delta^{18}O$ = −4.3‰, δD = −20.4‰), which are also OM-poor. The Phreeqc model was used for quantitative calculation of the effect of pond losses on the different units.

The Dissolved Inorganic Nitrogen (DIN) in the upper unit increases downstream from the ponds toward the sea, probably due to organic matter degradation, suggesting contribution of DIN from shallow groundwater flow to the sea. $^{87}Sr/^{86}Sr$ and Mg/Ca in the brackish and saline groundwater of the lower confined units increase toward seawater value, suggesting that the salinization process in the region is connected to seawater intrusion and not to old brine from the underlying Cretaceous aquitard.

1. Introduction

The interrelation between the sea and multi-layered coastal aquifers is an important issue in many parts of the world, mainly due to the problem of seawater intrusion (e.g., Bear et al., 1999; Post, 2005) or to the contribution of SGD to coastal water quality (Moore, 1999; Mayfield et al., 2014).

In some coastal areas there are surface reservoirs (i.e., fish ponds) above the aquifer, which make the hydrogeological condition more complex. Worldwide aquaculture has been annually increasing by 8.7% over the past 40 years, the fastest-growing food-producing sector (Herbeck et al., 2013). Decreasing fish stocks in the oceans and the rapid growth of human population will most probably lead to a further increasing reliance on farmed seafood as a source of protein (Naylor et al., 2000). China is by far the largest producer of aquaculture goods, accounting for 62% of global production in terms of quantity (FAO, 2010).

One of the key environmental concerns about aquaculture is water degradation, due to discharge of effluents with high levels of nutrients and suspended solids into adjacent waters, causing eutrophication, oxygen depletion and siltation (e.g., Burford et al., 2003). The majority of studies on pond aquaculture focus on water quality assessments in the ponds themselves or the quantification of effluent fluxes from ponds (e.g., Alongi et al., 2000; Briggs and Funge-Smith, 1994; De Silva et al., 2010; Islam et al., 2004; Jackson et al., 2003; Páez-Osuna et al., 1997; Wahab et al., 2003).

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It has been shown that high loads of nitrogen, phosphorus and suspended solids are released from fish ponds. However, only very little is known about the effects of effluents from fishponds on groundwater, particularly in multilayer aquifer. Leaking surface reservoirs can significantly affect the water quality and the water balance of coastal aquifers (e.g., Bear, 1979; Sophocleus, 2002). Fishponds are usually overloaded with organic matter and have a high potential for antibiotic contamination (Jacobsen and Berglind, 1988; Scribner et al., 2004; Lalumera et al., 2004). Avisar et al. (2009) showed the existence of Oxytetracycline antibiotic in groundwater, although it is generally assumed to be immobile and effectively removed by soil and sediments. Leakage from fishponds to coastal aquifers may also serve as a conveyor of nutrients and other contaminants to the sea, which might cause deterioration of the coastal water quality, leading to algae bloom (Moore, 1999; Li et al., 1999; Corbett et al., 1999; Lee and Kim, 2007; Mayfield et al., 2014). Quantitative evaluation of the seepage/infiltration from surface reservoirs into a multi-layer aquifer is complicated, since most of the possible chemical tracers are not conservative and change in the subsurface, affected by chemical and microbiological processes (Sophocleus, 2002; Avisar et al., 2009). The use of stable isotopes to identify leakage from surface reservoirs was found to be a useful tool (Scanlon et al., 2002; Darling et al., 2003; Peng et al., 2007; Guttman et al., 2011). Isotopic fractionation, caused by evaporation in the ponds, results in heavier isotopic composition of oxygen and hydrogen, which can be easily traced in the isotopic-lighter groundwater (Gat et al., 1996). Unlike the chemical composition, the oxygen and deuterium isotopes are not affected by interaction with the solid material or dissolved components, which makes them relatively conservative and usable for mass balance calculation of the seepage fraction in groundwater. Other chemical tracers, such as nutrients and specific organic species (Stedmon et al., 2003; Borisover et al., 2009; Mostofa et al., 2010), may be used as complementary tools as well.

The objective of this research was to study the impact of surface reservoirs (fish ponds) on the water quality of the underlying multilayered aquifer and the nutrient loads carried to the nearby coastal seawater, using chemical and isotopic tracers. We also used stable and radioactive isotopes to study the source of salinity and the rate of processes, such as seawater intrusion.

2. Hydrogeological background and study area

The study area is located in the southern Carmel coastal plain, in the area of Kibbutz Maagan Michael (Fig. 1). The climate in the region is characterized by dry summers and rainy winters (average precipitation of about 600 mm). In this area, the Quaternary aquifer consists of layers of loose sands and partly confined calcareous sandstones (locally called "Kurkar"), which are underlain by almost impermeable Late Cretaceous chalks (Bar Yosef and Michaeli, 2006). Toward the east, the Quaternary rocks are in hydraulic contact with Late Cretaceous dolomites (Fig. 2) at the foot of Mt. Carmel (Bar Yosef, 1974; Dafny, 2009). The facies change between dolomites (east) and chalks (west) prevents the direct flow of groundwater from the Cretaceous aquifer to the sea (Fig. 2), which forces the water to discharge through the Quaternary aquifer in the Taninim springs (Fig. 1) or to flow westwards through the Quaternary aquifer. This water plays an important role in the water balance of the Quaternary coastal aquifer (Michelson and Zeitoun, 1994; Guttman, 1998; Bar Yosef and Michaeli, 2006). The Taninim springs are the natural discharge of the Late Cretaceous Yarkon-Taninim carbonate aquifer whose northern border is located at Mt. Carmel (Dafny, 2009; Fig 1). These springs are the principal source of water for fishponds in this area. The spring water is brackish (1500–2000 mg/l Cl), which is due to the mixing of fresh groundwater with old saline water of marine origin found in the lower part of this aquifer (Bar, 1983).

The western part of the Carmel coast is characterized by two N-S oriented Kurkar ridges. The westernmost ridge is often partly or completely submerged (Michelson, 1970; Almagor, 2000). The depression between the ridges is usually filled with Pleistocene marsh deposits (Sivan et al., 2005), covered by Holocene loose quartz sand. The fishponds are located along the coastline, between the eastern Kurkar ridge and the sea, covering an area of about 2 km^2, mostly on top of the phreatic loose sand unit (Fig. 1).

Water pumping from the Quaternary aquifer in the research area was very small until 1995. With the drilling of "recycling" wells in the vicinity of the fishponds, abstraction from the aquifer increased to 6×10^6 m^3/yr. These wells were named "recycling" because they were supposedly circulating the infiltrating pond water. In 2007, groundwater abstraction already reached nearly 20×10^6 m^3/yr. Because of its high salinity (around 2000 Cl mg/L), the water is used only as raw material for a local desalination plant and for the fishponds. Guttman (1998) argued that the infiltration of water from the fishponds resulted in the local rise of the groundwater table (groundwater "mound"). This was somewhat supported by the enriched isotope (oxygen and deuterium) signature, which was found in one observation well (Taninim T4, Fig 1) in the confined unit (Guttman, 1998). This high water table, combined with the small thickness of the coastal aquifer (20–40 m), counteracts seawater intrusion. Flow model and water balance suggested that water infiltration from the fishpond to the coastal aquifer reaches 8–13 $\times 10^6$ m^3/yr (Michelson and Zeitoun, 1994; Guttman and Kronveter, 2007; Bar Yosef and Michaeli, 2006), although this was not supported by chemical mass balances of the aquifer water. In the Mediterranean Sea, tidal amplitude varies from approximately 0.4 m at spring tide to approximately 0.1 m at neap tide.

3. Field methods

Hydrological data was obtained from four new wells drilled during this study (wells 71 series and 72, Fig. 1), which penetrated the different units in the Quaternary aquifer, and from existing pumping and observation wells in the research area. The new boreholes were drilled without adding any mud or fluid to avoid contamination. After drilling, PVC pipes, perforated at selected depths, were inserted into the holes. Cement plugs were placed at the depth interval of the clayey layers, in order to separate between the sub aquifers. The Quaternary section beneath the fishpond area was analyzed and mapped, based on 52 borehole descriptions.

Temperature, EC, pH, Eh (Oxidation-Reduction potential) and DO (dissolved oxygen) were measured manually in the field with portable meters (WTW MultiLine 3430), and water level was measured both manually (wells T2 and T2a) and continuously by Solinst mini-divers (wells 71-1, 71-2, 71-3). Fishpond water, as well as groundwater from wells, was sampled for chemistry, stable and radioactive isotopes, organic matter and inorganic nutrients. Samples from the observation wells were also collected for chemistry and isotope analysis a few days after drilling. In old observation wells, the sampling procedure followed the standard purging (at least three times the well volume) prior to sampling. Three drops of mercury-chloride solution diluted with distilled water were added to poison the sub-samples taken for ^{14}C analyses. Nitric acid was added before sampling to the bottles of the sub-samples taken for trace elements, which were filtered immediately after sampling through 0.45 μm. Three drops of hydrochloric acid