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Assessing the impact of dairy waste lagoons on groundwater quality using a spatial analysis of vadose zone and groundwater information in a coastal phreatic aquifer

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ABSTRACT

Dairy waste lagoons are considered to be point sources of groundwater contamination by chloride (Cl^-), different nitrogen-species and pathogens/microorganisms. The objective of this work is to introduce a methodology to assess the past and future impacts of such lagoons on regional groundwater quality. The method is based on a spatial statistical analysis of Cl^- and total nitrogen (TN) concentration distributions in the saturated and the vadose (unsaturated) zones. The method provides quantitative data on the relation between the locations of dairy lagoons and the spatial variability in Cl^- and TN concentrations in groundwater. The method was applied to the Beer-Tuvia region, Israel, where intensive dairy farming has been practiced for over 50 years above the local phreatic aquifer. Mass balance calculations accounted for the various groundwater recharge and abstraction sources and sinks in the entire region. The mass balances showed that despite the small surface area covered by the dairy lagoons in this region (0.8%), leachates from lagoons have contributed 6.0% and 12.6% of the total mass of Cl^- and TN (mainly as $NO_3^- - N$) added to the aquifer. The chemical composition of the aquifer and vadose zone water suggested that irrigated agricultural activity in the region is the main contributor of Cl^- and TN to the groundwater. A low spatial correlation between the Cl^- and $NO_3^- - N$ concentrations in the groundwater and the on-land location of the dairy farms strengthened this assumption, despite the dairy waste lagoon being a point source for groundwater contamination by Cl^- and $NO_3^- - N$. Mass balance calculations, for the vadose zone of the entire region, indicated that drying of the lagoons would decrease the regional groundwater salinization process (11% of the total Cl^- load is stored under lagoons). A more considerable reduction in the groundwater contamination by $NO_3^- - N$ is expected (25% of the $NO_3^- - N$ load is stored under lagoons). Results demonstrate that analyzing vadose zone and groundwater data by spatial statistical analysis methods can significantly contribute to the understanding of the relations between groundwater contaminating sources, and to assessing appropriate remediation steps.

1. Introduction

Earthen (soil-lined or unlined) dairy waste lagoons are commonly used to store farm effluents. These effluents (solid and liquid slurry) contain high concentrations of chloride (Cl^- from salts, such as halite, added to the cows' feed), nitrogen (N), and other possible contaminants such as pathogens. Evaluation of the long-term impacts of such lagoons on groundwater quality is of interest due to the risk for groundwater contamination (Burkart and Stoner, 2007; UNESCO, 2006). Despite the numerous studies that have been conducted on the subject (e.g., Baram et al., 2012a; DeSutter et al., 2005; Gooddy et al., 1998, 2001, 2002; Ham, 2002; Ham and Baum, 2009; Korom and Jeppson, 1994; Parker et al., 1995, 1999a,b; van der Schans et al., 2009; Withers et al., 1998), estimation and quantification of the direct contribution of these pollution point sources to groundwater salinization and contamination by nitrate (NO_3^-), especially on a regional scale, remain a challenge.

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Leaching of Cl^- and different N-species (i.e., organic, ammonium (NH_4^+) and NO_3^-) into the subsurface under dairy/cattle waste lagoons has been extensively studied based on measurements of infiltration fluxes and on sediment sampling (DeSutter et al., 2005; Gooddy et al., 1998, 2001, 2002; Ham, 2002; Ham and Baum, 2009; Parker et al., 1995, 1999a,b). Measurements of infiltration fluxes can provide accurate direct estimations of the infiltrating TN and Cl^- loads. Conversely, sediment sampling cannot provide accurate estimates of the loads stored in the vadose zone or the loads recharging the groundwater (Amiaz et al., 2011; Rimon et al., 2011). The degree of inaccuracy increases in cases where high spatial and temporal variability exists, such as is observed in the loads of organic-N, $NH_4^+ - N$, $NO_3^- - N$ and Cl^- in the vadose zone under lagoons (Baram et al., 2012a; DeSutter et al., 2005; Gooddy et al., 2002; Ham, 2002; Parker et al., 1999b).

Groundwater sampling is also commonly used for estimations of Cl^- and different N-species leaching from waste lagoons (Baily et al., 2011; Baram et al., 2012a; Gooddy et al., 2001, 1998; Harter et al., 2002; van der Schans et al., 2009; Withers et al., 1998). However, some inaccuracies are associated with estimates based on this method. For instance: (a) the chemical composition of a groundwater sample reflects a dynamic mixture between the chemical properties of the recharging lagoon leachates (vertical flow components) and the chemical properties of the ambient/up-gradient groundwater (horizontal flow components); (b) water sampling leads to mixing of deep and shallow water in a well; (c) it may be difficult to distinguish between lagoon seepage and seepage from fields applied with manure (Baily et al., 2011; Harter et al., 2002); and (d) bio-geochemical interactions in the groundwater can obscure the actual concentrations in the recharging leachates (Singleton et al., 2007). Based on the above, it is difficult to accurately assess the past and the future impacts of lagoon leachates on the underlying groundwater, especially on the regional scale.

Recent works by Baram et al. (2012a,b, 2013), Arnon et al. (2008b) and Sher et al. (2012) have provided new quantitative data on the flow, transport and bio-geochemical interactions in the vadose zone under dairy waste lagoons constructed in clay soils and their near surroundings (hereafter termed "margins"). Their work was based on four years of intensive *in situ* vadose zone monitoring at more than 20 independent locations under a lagoon and its margins, down to 20 m below land surface (bls). The monitoring included: (i) continuous measurements of the temporal variation in the vadose zone water content (using 22 TDR probes); and (ii) frequent sampling of the chemical composition of the vadose zone pore water (using 21 vadose zone pore water sampling probes (VSPs)). Their work was also based on quantitative estimates of the abundance of ammonia-oxidizing bacteria and its activity in the vadose zone under the lagoon. The results of these works have indicated that dairy waste lagoons serve as point sources for groundwater contamination by TN (mainly as $NO_3^- - N$) and Cl^-. In addition, the ionic ratios in the pore water indicated that the Cl^- in the vadose zone under the lagoon originated mainly from the halite added to the cows' diet ($Na^+/Cl^- = 1 \pm 0.1$ eq eq^{-1}). Much of the motivation for the present study arose from the need to evaluate the regional impact of these pollution point sources on the degradation of the underlying groundwater quality. Accordingly, the aim of this study is to introduce a methodology by which a spatial analysis of detailed data from the vadose zone and groundwater can be used to assess the past and future impacts of dairy waste lagoons on groundwater degradation. In this study, the methodology is used for evaluating the relative contribution of leachates from dairy waste lagoons, in the past 50 years, to the Cl^- and TN loads in the vadose zone and groundwater in the Beer-Tuvia region in Israel. The methodology is based on: (i) the temporal and spatial distributions of pollutant concentrations and sediment water content, throughout the entire cross-section of a thick vadose zone (>40 m), underlying dairy waste lagoons (data previously published by Baram et al. (2012a,b, 2013)), (ii) the spatial distribution of pollutants in the region's groundwater, (iii) the lithological structure of the region's subsurface, (iv) the history of dairy farming in the region, and (v) the spatial correlations between Cl^- and $NO_3^- - N$ concentrations in the groundwater and the proximity to dairy farms.

2. Materials and methods

2.1. Study area

The study area is located in the Beer Tuvia region (40 km^2), above the southern part of the Coastal Aquifer in Israel. This phreatic aquifer overlies the impervious marine clays of the Pliocene age, Saqiye Group, and is composed mainly of alternating layers of sandstone, calcareous sandstone and marine clay of the Pleistocene age, Kurkar Group, (Issar, 1968; Tulmatz, 1977; Weinberger, 2007). The land surface area is covered by a clay layer, dominated by 2:1 smectite minerals, with thicknesses that vary from several centimeters to up to 20 m over a distance of tens of meters. Desiccation cracks prevail in the clay throughout the year and enable the preferential infiltration of local runoff (Baram et al., 2012a,b, 2013). The climate is Mediterranean with average summer and winter temperatures of 24.3 °C and 14.2 °C, respectively. The average annual precipitation is ~450 mm, occurring during the winter season (November to March), mostly during five to eight rainy episodes. The main recharge to the aquifer is related to the percolation of seasonal rainwater and agricultural return flow from irrigated and rain-fed fields that have been intensively cultivated in the area for over 60 years. In some locations, the aquifer is subjected to artificial recharge via injection wells and infiltration ponds (up to several hundred meters in diameter). Since the mid-1970s, the natural flow of fresh groundwater from the Coastal Aquifer in the region into the sea was stopped by production wells (Coastal Drainage wells), and since then, the region has acted as a closed basin.

The Beer Tuvia region has been intensively cultivated since the early 1950s. The agricultural activity in the region was originally based on local groundwater and fertilizers (organic and inorganic). However, groundwater salinization over the years has led to the shutting down of many production wells [the Cl^- concentration in the local groundwater has increased from ~200 mg Cl^- L^{-1} in the 1950s to 600–900 mg Cl^- L^{-1}in 2010 (Vengosh and Ben-Zvi, 1994; Weinberger, 2007)]. As a result of the local salinization, the agricultural activity in the region has been based on imported water from the Israeli National Water Carrier, or on mixtures between the locally pumped water and the water from the National Water Carrier. Dairy farming in the region began in the 1950s (a small number of cows per farm) and intensified with time, up until the late 1980s, when the number of cattle in the region stabilized at ~12,000. Currently, the region hosts approximately 12,500 cows in 139 dairy farms, which are located within the villages (the dairy farming history of each village is presented in the supporting information 1 (SI, Table S1-1)). The average stocking density, for the individual villages and for the whole region, is 22.8 and 3.7 cows ha^{-1}, respectively. Most of the dairy farms in the region were constructed on similar clay soils and have been using the same agricultural management practices that include: (a) the use of a free-stall barn with a center feed lane, (b) similar feeding methods, and (c) similar waste disposal systems that utilize unlined earthen lagoons with a drainage channel (field observations and past data stored in the archives of the local municipality and of the