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Nitrate fluxes to groundwater under citrus orchards in a Mediterranean climate: Observations, calibrated models, simulations and agro-hydrological conclusions

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ABSTRACT

Nitrate contamination of groundwater under land used for intensive-agriculture is probably the most worrisome agro-hydrological sustainability problem worldwide. Vadose-zone samples from 0 to 9 m depth under citrus orchards overlying an unconfined aquifer were analyzed for variables controlling water flow and the fate and transport of nitrogen fertilizers. Steady-state estimates of water and NO_3-N fluxes to groundwater were found to vary spatially in the ranges of 90–330 mm yr^{-1} and 50–220 kg ha^{-1} yr^{-1}, respectively. Calibration of transient models to two selected vadose-zone profiles required limiting the concentration of NO_3-N in the solution that is taken up by the roots to 30 mg L^{-1}. Results of an independent lysimeter experiment showed a similar nitrogen-uptake regime. Simulations of past conditions revealed a significant correlation between NO_3-N flux to groundwater and the previous year's precipitation. Simulations of different nitrogen-application rates showed that using half of the nitrogen fertilizer added to the irrigation water by farmers would reduce average NO_3-N flux to groundwater by 70%, decrease root nitrogen uptake by 20% and reduce the average pore water NO_3-N concentration in the deep vadose zone to below the Israeli drinking water standard; hence this rate of nitrogen application was found to be agro-hydrologically sustainable. Beyond the investigation of nitrate fluxes to groundwater under citrus orchards and the interesting case-study aspects, this work demonstrates a methodology that enables skillful decisions concerning joint sustainability of both the water resource and agricultural production in a common environmental setting.

1. Introduction

1.1. Groundwater contamination by nitrate originating from agricultural practices and the research scope

Groundwater contamination by nitrate is a drinking-water problem of great concern worldwide (e.g. Burow et al., 2010; Glen and Laster, 2010; Jin et al., 2012; Liu et al., 2005; Orban et al., 2010; Oren et al., 2004; Thorburn et al., 2003). Only nitrate and bacteria are regarded by the American Environmental Protection Agency (EPA) as requiring immediate action whenever their concentration exceeds drinking-water standards (US EPA, 1994). Nitrate contamination has disqualified drinking-water wells in Israel (local standard — 70 mg L^{-1} NO_3^- or 15.8 mg L^{-1} NO_3-N) more than any other contaminant in the beginning of the 21st century (Elhanany, 2009). Hence, investigations of nitrate fluxes to groundwater and actions that can be taken to reduce them are of interest to the community of water-resource experts as well as to the general public.

The world population has doubled in the last century, and most peoples' diets are richer, due to the ability to form reactive species of nitrogen (NH_4^+, NO_3^-) from atmospheric nitrogen (N_2) inexpensively. This ability was developed at the beginning of the 20th century by F. Haber, earning him the Nobel Prize in chemistry in 1918 (Erisman et al., 2008; Haber, 1920). Reactive

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nitrogen is the form of nitrogen that most crops can take up, and therefore its inexpensive synthesis has enabled the rapid development of intensive agriculture and food richness (including dairy and meat products). However, concomitantly, contamination of groundwater resources by nitrate has become by far the most troublesome agriculture-related contamination in the 21st century (e.g. Burow et al., 2010; Jalali, 2005; Kourakos et al., 2012; Vitousek et al., 2010).

Nitrogen uptake by roots and leaching below the root zone have been investigated with the use of transient mechanistic models of water flow and nitrogen-species transport concentrated in the root zone or relatively shallow vadose zone (e.g. Doltra and Munoz, 2010; Hanson et al., 2006). On the other hand, regional assessments of groundwater contamination with nitrate make use of varying degrees of simplification of vadose-zone processes (e.g. de Paz and Ramos, 2004; Kourakos et al., 2012; Mercado, 1976). The current study is based mainly on deep vadose zone data (below the root zone). It provides a novel agro-hydrological approach in which methods and perspectives from both groundwater hydrology and agricultural sciences are combined to form an assessment that is of interest both to the farmers and water-resource managers. More particularly, the term agro-hydrology is used in this work in the context of sustainability of both intensive agriculture and water quality of the aquifer beneath the agricultural land. Before defining the research objectives we bring here a background (containing some new analysis) which puts the current research in context of a broader view of the nitrate problem in the Israeli Coastal Aquifer.

1.2. Background: nitrate in the Israeli Coastal Aquifer and the current research sites

The spatial distribution of nitrate concentration in the groundwater of the generally unconfined Israeli Coastal Aquifer (Gvirtzman, 2002; Issar, 1980; Kurtzman and Scanlon, 2011; Kurtzman et al., 2012) was examined jointly with soil type and land-use maps (Fig. 1a–d). Regional problems of high nitrate concentrations in the groundwater are found under agricultural land (that is still cultivated today or was cultivated in the near past) in the sandy-loam Hamra soils (mostly Inceptisols and Alfisols). Problems of high nitrate concentration in groundwater are much smaller below cultivated Vertisols (clay) (Fig. 1a–c).

An agricultural area overlying one of the nitrate-problematic regions of the aquifer was selected for the survey of three citrus orchards (oranges are grown in orchards O1 and O2 and grapefruits in O3, Fig. 1e); in addition, an orchard of red grapefruits (O4) in the clayey Vertisols was surveyed for comparison (Fig. 1b). Note the relatively short range of variability (or short correlation length) of nitrate concentration in groundwater under the agricultural land (Fig. 1e), which suggests that local nitrate fluxes from the vadose zone to the aquifer are important.

To summarize the temporal variability of groundwater nitrate in the selected area, 30 wells, from which at least one nitrate observation was made every 5 years between 1972 and 2011, were selected. The 5-year averages of all nitrate observations in each well were compiled and the average of the 30 wells for each 5-year interval is shown in Fig. 2 (historical groundwater nitrate concentrations were obtained from the Israeli Water Authority). Under the investigated sandy-loam agricultural land, the rate of nitrate contamination has increased since the 1970s (Fig. 2). This trend is discordant with the slowing rate of increase of nitrate concentrations in the aquifer after 1970 suggested by Ronen et al. (1983). The latter study may have reduced the interest in studying nitrate behavior in this aquifer compared with the intense work performed in the 1970s on this topic (e.g. Avnimelech and Raveh, 1976; Mercado, 1976). However, the relatively recent disqualification of many drinking-water wells due to the above-standard concentrations of nitrate (Elhanany, 2009; Goldberg, 2009) has triggered new studies (including the current one) on this problem.

1.3. Research objective and workflow

The overall objective of this study was to find a sustainable path for both protecting the aquifer from nitrate pollution and providing intensive citrus growing. This objective was achieved through the following steps: (i) survey of the vadose zone under citrus orchards overlying a zone in the aquifer where high concentrations of nitrate are common, and assessment of the spatial variability of water and nitrate fluxes; (ii) calibration of 1D models of transient water flow and nitrogen-species transport from land surface down to the water table using selected data profiles; (iii) analysis of a controlled lysimeter experiment to verify the relations between root nitrogen uptake and nitrogen concentration in the soil solution and a comparison of the results with the independent calibrated models; (iv) use of the calibrated models to investigate nitrate fluxes to groundwater; and (v) simulation of different surface applications of nitrate to citrus and suggestions for adequate and sustainable application rates.

2. Materials and methods

2.1. Field sampling and lab analysis of vadose zones beneath orchards

In each of the four citrus orchards that were selected for the survey (three in sandy-loam and one in clay (vertisol) soils, 50 km south, Fig. 1b), three sampling boreholes were drilled using the direct push technique, and a continuous core was obtained from 0–9 m depth. Cores were extracted into 150-cm long PVC liner of 43 mm ID, using a Geoprobe-6610DT® rig. Two boreholes were drilled relatively close, at a distance of <30 m, and the third was drilled more than 100 m away from the first two, but still within the same orchard. Soil (and sediment) cores were cut into 30-cm segments. All segments were analyzed in the top 3 m and every second segment was analyzed between 3 and 9 m.

Drillings were done during 5 days between June and September 2010. Core segments were sealed with caps and tape and kept in a cooler until reaching the lab, and then put in a refrigerator for the night. The next morning all samples were weighted and subsamples for chloride, nitrate and ammonium analysis were put to dry in the oven (40 °C) for 3 days, and then sieved to 2 mm before extractions. Soil extracts were kept refrigerated until the analysis (maximum 2 weeks).

The following variables were analyzed for the core segments (hereafter “samples”): bulk density (core dry mass per volume), gravimetric water content (105 °C), and gravimetric particle-size distribution (hydrometer, 4–7 samples per