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Groundwater resource vulnerability and spatial variability of nitrate contamination: Insights from high density tubewell monitoring in a hard rock aquifer

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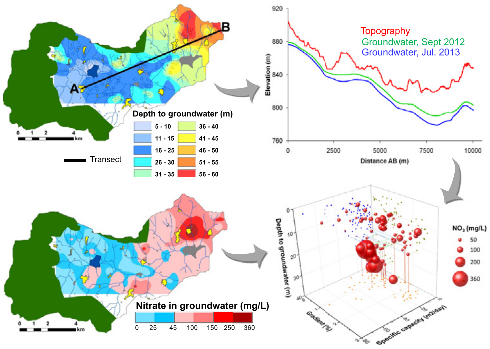
HIGHLIGHTS

- Tube well irrigation induces groundwater depletion in semi-arid areas.
- An irrigated catchment in India shows high spatial variability of groundwater NO_3.
- Extreme NO_3, up to 360 mg/L, is related to areas of severe groundwater depletion.
- Irrigation with NO_3 rich groundwater induces a “hidden” input of N to the crop.
- Considering it would help optimizing fertilizer and mitigating groundwater quality.

GRAPHICAL ABSTRACT



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ABSTRACT

Agriculture has been increasingly relying on groundwater irrigation for the last decades, leading to severe groundwater depletion and/or nitrate contamination. Understanding the links between nitrate concentration and groundwater resource is a prerequisite for assessing the sustainability of irrigated systems. The Berambadi catchment (ORE-BVET/Kabini Critical Zone Observatory) in Southern India is a typical example of intensive irrigated agriculture and then an ideal site to study the relative influences of land use, management practices and aquifer properties on NO_3 spatial distribution in groundwater. The monitoring of >200 tube wells revealed nitrate concentrations from 1 to 360 mg/L. Three configurations of groundwater level and elevation gradient were identified: i) NO_3 hot spots associated to deep groundwater levels (30–60 m) and low groundwater elevation gradient suggest small groundwater reserve with absence of lateral flow, then degradation of groundwater quality due to recycling through pumping and return flow; ii) high groundwater elevation gradient, moderate NO_3 concentrations suggest that significant lateral flow prevented NO_3 enrichment; iii) low NO_3 concentrations, low groundwater elevation gradient and shallow groundwater indicate a large reserve. We propose that mapping

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groundwater level and gradient could be used to delineate zones vulnerable to agriculture intensification in catchments where groundwater from low-yielding aquifers is the only source of irrigation. Then, wells located in low groundwater elevation gradient zones are likely to be suitable for assessing the impacts of local agricultural systems, while wells located in zones with high elevation gradient would reflect the average groundwater quality of the catchment, and hence should be used for regional mapping of groundwater quality. Irrigation with NO_3 concentrated groundwater induces a “hidden” input of nitrogen to the crop which can reach 200 kgN/ha/yr in hotspot areas, enhancing groundwater contamination. Such fluxes, once taken into account in fertilizer management, would allow optimizing fertilizer consumption and mitigate high nitrate concentrations in groundwater.

1. Introduction

Irrigated agriculture has large impacts on groundwater resources, both in terms of quantity and quality (Foster and Chilton, 2003; Scanlon et al., 2010; Böhlke, 2002; Scanlon et al., 2007). Among agricultural-borne non-point source pollutants, nitrogen has been the focus of many studies due to its ubiquitous impact on ecosystems, sometimes referred as the “Nitrogen cascade” (Galloway et al., 2003). Long-term impact of agriculture on nitrogen loads to rivers has been demonstrated at large basin scale (Agrawal et al., 1999; Billen et al., 2001; Howden et al., 2010). However, many recent studies showed that the stream water quality is not a good proxy to assess N losses from different types of agricultural systems, as solute transit times in catchments are highly variable (Kirchner et al., 2000) and on average very long (Haag and Kaupenjohann, 2001; Ruiz et al., 2002; Basu et al., 2010; Hrachowitz et al., 2015). As agricultural practices are expected to impact more directly the quality of the groundwater (Aquilina et al., 2012), many studies have used the spatial variations of groundwater quality to evaluate the impacts of agricultural systems (Lockhart et al., 2013; Zhang et al., 1996; Zhao et al., 2016). However, adequate modelling of groundwater flow and solute transport is often limited by the lack of information on the spatial variations of aquifer characteristics (Foster and Chilton, 2003; Kinzelbach et al., 2003) due to low density of observation wells (Zhou and Li, 2011), especially in developing countries (Singh, 2014).

National or regional monitoring network implemented by government agencies are often the only available information for mapping groundwater resources, in quantity and quality, but is generally of very limited density, ranging from about 0.1 to 0.001 well/km^2 (Schot and Pieber, 2012). Use of sophisticated geostatistics (e.g. Krigging, neural network) can allow estimating the quality of the interpolation (Bárdossy et al., 1997) and use of ancillary information can improve the mapping (Bárdossy, 2006). However, due to the uncertainty on actual well source area, this approach usually allows to classify only broad types of land use, like agriculture, grasslands, forests (Lockhart et al., 2013). Indeed, in the case of sedimentary aquifers, which are usually homogeneous and/or in the case of industrial agriculture, characterized by large plots, monoculture and standardized agricultural practices, low density measurements of groundwater quality might reasonably reflect the impact of dominant agricultural systems. In such cases, the system is often considered as “1D” (Almasri and Kaluarachchi, 2007). To the contrary, in the case of hard rock aquifers, which properties display large spatial variability and/or for family farming, characterized by small plots and large diversity of crops and practices, such lumped approaches are likely to be inadequate.

This is the case in India where agriculture is largely dominated by small and marginal farmers, with average farm size being about 1 ha (Dorin and Aubron, 2016), and where the agricultural practices are highly diverse (polyculture and large variability of fertilization practices). The “pump revolution” (Molle et al., 2003) which started four decades ago with the development of low-cost submersible pump technologies in the 80s, allowed millions of small farmers to own individual tube wells. India accounts for one third of world's total irrigated area, about 60% of which is from groundwater (Thenkabail et al., 2009; Bhaduri et al., 2012). In addition, fertilizer input has dramatically increased since the green revolution, reaching about 30 Megatons of NPK per year i.e. about twice the European consumption. Combination of tube well irrigation and fertilizer input allowed to increase the food production but induced groundwater depletion, and led to what is now identified as a major “groundwater crisis threatening the food security of the country (Smilovic et al., 2015): groundwater decline is the fastest in the world (Fishman et al., 2011) and contamination is widespread, with tremendous impacts on water resources and ecosystems.

In Peninsular India, the low transmissivity of hard rock aquifers (Sekhar et al., 1994; Dewandel et al., 2012) limits the area irrigated by one well typically to <1 ha. This led to a dramatic increase in the number of farm tube wells in the past decades (>20 million in India; Shah, 2014). This unique density of tube wells makes this system an ideal observatory to assess the variability of impacts of agriculture on groundwater quality. However, only very few studies have exploited the potential of using farmer tube wells as high-density monitoring networks. They have highlighted the fact that the large variability of agricultural practices can induce over short distances large variations in groundwater depletion (Anuraga et al., 2006; Maréchal et al., 2006) and in groundwater quality, especially due to solute recycling by pumping (Perrin et al., 2011). All these observations suggest that due to the low permeability of aquifer, the system is dominated by vertical fluxes and lateral groundwater flow can be neglected (Perrin et al., 2012). However, it was recently shown that the spatial transport processes are more complex than commonly thought (Alazard et al., 2015) and that lateral flow can have a significant impact on groundwater resource (Mangiarotti et al., 2012).

The objective of this paper is to develop proxies for the assessment of water resource vulnerability in the context of hard rock aquifer in a tropical catchment and assess its relationship with groundwater nitrate concentrations. For this, we use a dense network of farmer tube wells in an agricultural catchment. We first assess the groundwater resource variability at the catchment scale, then we examine the relationships between the local groundwater resource and the nitrate concentration in groundwater, particularly regarding the occurrence, or not, of lateral flows. Finally, we discuss the implication of vertical recycling of groundwater irrigation on the crop nitrogen budget.

2. Materials and methods

The Berambadi catchment (84 km^2) is a sub-catchment of South Gundal, located in the Deccan Plateau of Southern India (Fig. 1). It belongs to the Kabini basin Environmental Research Observatory BVET (http://bvet.obs-mip.fr/en), and AMBHAS observatory (Sekhar et al., 2016; Tomer et al., 2015, www.ambhas.com).

The bedrock is a granitic gneiss traversed by east-west dykes ranging from 0.5 to 1.5 km length and 5 to 15 m width (Sekhar et al., 2006). The aquifer, typical of hard rock granitic areas (Wyns et al., 2004) is composed of two layers, one fissured layer of a few meter thickness at the surface of the fresh bedrock, with high hydraulic conductivity but low porosity and one weathered layer (gneissic saprolite) with low

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