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Evaluation of aquifer recharge and vulnerability in an alluvial lowland using environmental tracers

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SUMMARY

A multi-layered aquifer system (eastern Po plain, northern Italy) was investigated by means of isotopic data, with the goal of quantifying groundwater recharge from different sources and assessing the intrinsic vulnerability of aquifers to surface sources of contamination. The geology of the area is based on a stratigraphic alternation of several sandy aquifers and silty–clayey aquitards, down to a maximum depth of 200 m b.g.s. Water isotopes ($\delta^{18}O$, $\delta^{2}H$), and hydrochemical analyses were performed on groundwater samples collected from a regional network of 70 boreholes distributed on an area of almost 2000 km^2. In addition to the regional sampling, detailed vertical isotopic profiling was performed in one location by means of groundwater and sediment samples collected through the whole sequence of aquifers and aquitards. Water isotopes indicated mixing from different sources of recharge (i.e., vertical recharge, Po river, deeper aquifers). Mixing calculations were used to quantify the contributions to the aquifers from the different sources. The vertical profiling allowed for integrating and validating the interpretations at a regional scale. The recharge pattern defined for the different aquifers was translated into an index of hydrogeologic interconnections with the surface, which represents a physically based proxy of the intrinsic vulnerability of the aquifers to surficial sources of contamination.

The investigated setting can be considered to be representative of many other anthropized and groundwater demanding plain settings around the world. Thus, the proposed method represents a valuable approach for such settings both for recharge quantification (e.g., to be used as input for numerical modeling) and for a physically based assessment of the intrinsic vulnerability.

1. Introduction

Alluvial plains constitute both the most human affected portion of the earth's surface and the main fresh groundwater reservoir of the planet (Jones, 2011; Tockner et al., 2008). Exploitation and protection of alluvial aquifers are two objectives of the sustainable management of groundwater resources that need to be addressed in a strictly coupled way (Aral and Taylor, 2011). At the European level, for example, the Water Framework Directive (WFD; 2000/60/EC) emphasizes the role of parallel and integrated quantitative/qualitative monitoring and evaluation to achieve a good general status of the main European water bodies, including aquifers. Consequently, groundwater budgeting and the vulnerability assessment of the main aquifers should be analyzed using integrated approaches.

Groundwater recharge can be considered to be one of the most important parameters to quantitatively estimate the yield and intrinsic vulnerability of an aquifer at the same time (Foster, 1998; Healy, 2010; Misstear et al., 2009; Robins, 1998). Indeed, recharging water represents the main potential carrier of dissolved contaminants. In alluvial plains, recharge originates partly from rainfall (direct recharge) and partly from surface water (lateral recharge from main rivers, irrigation). A permeable hydrologic connection between the aquifer and the ground surface allows for a high contribution to the aquifer from direct recharge. However, the same permeable connection with the surface increases the intrinsic vulnerability of aquifers to surface sources of pollution (Vrba and Zaporozec, 1994).

Various techniques are available to quantify recharge, either empirically (Scanlon et al., 2002) or through indirect numerical modeling (Mastrocicco et al., 2014), but they are rarely combined with an assessment of intrinsic vulnerability. If the intrinsic vulnerability is considered, subjective index methods are mainly

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applied rather than objective physically based methods (Gogu and Dassargues, 2000). The drawback of subjective methods is that their results strongly depend on interpretation and evaluation, in contrast with objective methods.

Environmental tracers, e.g. the stable isotopic ratios of oxygen ($\delta^{18}O$) and hydrogen ($\delta^{2}H$), are perfect tools to assess the intrinsic vulnerability by identifying the time scales and water sources of groundwater systems (e.g., de Vries and Simmers, 2002; Gemitzi et al., 2014; Gibson et al., 2005; Liu et al., 2004; Liu and Yamanaka, 2012; Mizota and Kusakabe, 1994; Nakaya et al., 2007; Qin et al., 2011; Rietti-Shati et al., 2000; Weyhenmeyer et al., 2002; Wilcox et al., 2004). Among the recharge quantification techniques, the most promising are mixing calculations, which allow for estimating the relative importance of different sources (Tubau et al., 2014; Vázquez-Suñé et al., 2010). For example, End Member Mixing Analysis (EMMA; Christophersen and Hooper, 1992; Christophersen et al., 1990; Hooper et al., 1990; James and Roulet, 2006; Jones et al., 2006; Tubau et al., 2014) is a promising tool to evaluate the contribution ratio of each recharge source of groundwater starting from the stable isotopic composition of the water itself (Liu and Yamanaka, 2012). The approach has been successfully applied in sedimentary plain settings throughout the world (e.g., Kármán et al., 2013; Négrel et al., 2003; Peng et al., 2014; Yuan et al., 2011). Stable isotopic compositions of groundwater recharged through the direct infiltration of precipitation will reflect that of local precipitation (Clark and Fritz, 1997). If rivers retain the depleted isotopic signature of their headwaters, the difference in the stable isotopic signatures of rivers and local precipitation can be used to determine the relative contribution of these two sources of groundwater recharge (Kalbus et al., 2006; Lambs, 2004; Scanlon et al., 2002).

The objective of the presented research is to investigate the use of environmental tracers as a tool to quantitatively assess both recharge and intrinsic vulnerability to surface sources of contamination. This tool is applied to a multilayered aquifer setting in an alluvial lowland. Thus, the water sources and mixing ratios of the individual aquifers are identified and the aquitard integrity is evaluated, which is crucial for the interpretation of recharge and vulnerability assessment. The results represent an advance over the usual limitations of aquifer vulnerability studies. First, suitable methods are commonly unavailable for tracing contaminant pathways. Second, such investigations are characteristically limited to the shallowest aquifer of a study area, even though the most valuable aquifers (as in this case) occur at greater depths.

2. Materials and methods

2.1. Hydrogeological setting

The eastern part of the Po river plain in northern Italy is a classic example of a system of multiple, stacked alluvial aquifers. The investigated area extends for approximately 1400 km^2 along the Southern bank of the Po river, around the city of Ferrara (Emilia–Romagna region), in a topographically flat area with absolute elevations ranging from −2 to 19 m a.s.l. (Fig. 1).

The alluvial sedimentary sequence, down to the local bedrock (located at an averaged depth of 200 m b.g.s.), consists of regular alternations of sandy units related to the channel and channel belt sedimentary facies, with silty–clayey levee, overbank and lagoonal deposits, locally enriched in peat. The succession of aquifers and aquitards was deposited during the Quaternary (Regione Emilia-Romagna and ENI-AGIP, 1998). At least five main aquifer units have been identified from the ground surface to the Miocenic bedrock (LIT). The vertical leakage between the different aquifers is controlled by the lower permeability barriers (i.e., aquitards), depending on the hydraulic conductivity and hydraulic head.

The recharge of such a hydrogeologic system occurs at three levels: (1) direct recharge from rainfall from the ground surface, (2) lateral recharge from the Po river by an active channel eroded approximately 15 m down into the shallow sedimentary sequence, and (3) deep regional ground water flow from the distant borders of the Po plain, where macroclastic permeable deposits outcrop as alluvial fans (i.e., along the foothills of the Alps, 70 km north of Ferrara, and the foothills of Apennines, 40 km south). Along the hydrogeological succession from the shallow unconfined aquifer down to the deeper ones, the relative proportion of direct recharge decreases and the contribution of the regional recharge increases. The different sources of groundwater recharge are expected to have distinct and distinguishable isotopic ratios.

The hydrogeological sketch map of the first 100 m b.g.s., including the four shallowest aquifer units, is shown in Fig. 2. The aquifers are coded as A0, $A1_{sup}$, A1, and A2 from top to bottom. The A0 aquifer is Holocenic and is structured in paleo-river beds or in scattered lenses intermingled with fine-grained overbank deposits; $A1_{sup}$, A1 and A2 are Upper Pleistocenic units deposited as channel belts during glacial events (Amorosi and Colalongo, 2005). A0 is an unconfined to leaky-confined aquifer, whereas the other units are fully confined aquifers. The aquitards interlayered in the sandy bodies act as permeability barriers and are named after the underlying aquifers: Q0, $Q1_{sup}$, Q1 and Q2. The Po river is directly connected through the river bed with aquifer A1.

2.2. Sampling network

Two sampling networks were considered. The first sampling network is based on a regional survey approach (i.e., boreholes scattered throughout the investigated area and screened in different aquifers) and was used to collect groundwater samples. The second network consists of three high-resolution multi-screen vertical profiles, 30–60 m deep; these profiles are arranged along a 60-m horizontal transect located in the central-southern portion of the investigated area (known as Caretti site; Nijenhuis et al., 2013). Here, groundwater and sediment samples (for the analysis of pore water) were collected both from aquifers and aquitards.

Seventy groundwater samples were collected from the 70 sampling points of the regional network during spring 2010 or 2011 (Table 1; Fig. 1). The samples were taken from preexisting boreholes screened in the A0, $A1_{sup}$, A1 or A2 aquifers. Eight of the 70 samples were collected inside the Po riverbed (<12 m b.g.s.; locally coincident with the A0 aquifer). Additionally, a surface water sample was collected from the Po river.

Thirty-four groundwater samples were collected (November 2013) from the three profiles of the second sampling network (Table 1; Fig. 3) via multilevel systems (CMT, Solinst, Canada; Einarson and Cherry, 2002), with an averaged vertical spacing of 3.7 m. Furthermore, 57 sediment core subsamples were collected along one of the profiles during drilling operations (July 2013).

2.3. Sampling and analytical methods

2.3.1. Groundwater samples

Prior to sampling, three borehole volumes were purged from the wells of the regional network. Piezometers of the same network were purged by low-flow pumping with a submersible volumetric pump (pumping rate between 0.1 and 1 L/min, according to the aquifer hydraulic transmissivity, to maintain a drawdown no higher than 0.1 m; Robbins et al., 2009). From the multi-screen piezometers of the local network, triple the volume of water contained in the tubing and drains surrounding the screens was purged using a low flow peristaltic pump suitable for CMT systems (Model 410 Peristaltic Pump, Solinst, Canada).