Journal of Contaminant Hydrology 169 (2014) 123–131

Contents lists available at ScienceDirect

Journal of Contaminant Hydrology

journal homepage: www.elsevier.com/locate/jconhyd

Regional water quality patterns in an alluvial aquifer: Direct and indirect influences of rivers

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ARTICLE INFO

Article history:
Received 19 February 2014
Received in revised form 21 August 2014
Accepted 5 September 2014
Available online 16 September 2014

Keywords:
Dilution
Denitrification
Alluvial aquifer
Flood plain
Stable isotope
Diffuse pollution

ABSTRACT

The influence of rivers on the groundwater quality in alluvial aquifers can be twofold: direct and indirect. Rivers can have a direct influence via recharge and an indirect one by controlling the distribution of fine-grained, organic-carbon rich flood deposits that induce reducing conditions. These direct and indirect influences were quantified for a large alluvial aquifer on the Swiss Plateau (50 km^2) in interaction with an Alpine river using nitrate as an example. The hydrochemistry and stable isotope composition of water were characterized using a network of 115 piezometers and pumping stations covering the entire aquifer. Aquifer properties, land use and recharge zones were evaluated as well. This information provided detailed insight into the factors that control the spatial variability of groundwater quality. Three main factors were identified: (1) diffuse agricultural pollution sources; (2) dilution processes resulting from river water infiltrations, revealed by the $\delta^{18}O_{H_2O}$ and $\delta^2H_{H_2O}$ contents of groundwater; and (3) denitrification processes, controlled by the spatial variability of flood deposits governed by fluvial depositional processes. It was possible to quantify the dependence of the nitrate concentration on these three factors at any sampling point of the aquifer using an end-member mixing model, where the average nitrate concentration in recharge from the agricultural area was evaluated at 52 mg/L, and the nitrate concentration of infiltrating river at approximately 6 mg/L. The study shows the importance of considering the indirect and direct impacts of rivers on alluvial aquifers and provides a methodological framework to evaluate aquifer scale water quality patterns.

1. Introduction

Alluvial plains frequently harbor productive aquifers that play an important role for drinking water supply and irrigation. River sediments often form shallow aquifers composed of gravel, sand, silt or clay deposited in river channels or on floodplains (He and Walling, 1997). Alluvial aquifers close to mountain ranges are often particularly permeable and productive due to the presence of coarse material. Alluvial plains are often also hotspots of human activity with traffic routes, settlements and intense agriculture. Soils formed in organic-rich river deposits are fertile (Schaetzl and Anderson, 2005) and water is abundant for irrigation. Hence, a large fraction of the recharge area might be used for growing crops. As water tables in alluvial aquifers are often shallow and deposits permeable, alluvial aquifers are vulnerable to contamination. Elevated nitrate concentrations can be observed in many aquifers, impacting the quality of drinking water supply wells. It is important to understand the factors that control nitrate levels and groundwater quality patterns in general in view of the long-term exploitation of alluvial aquifers.

Different factors can influence groundwater quality patterns in alluvial aquifers. Here nitrate patterns are discussed although spatial patterns of other substances (e.g. pesticides) are influenced by similar factors. Alluvial aquifers often interact with rivers. In humid areas, nitrate levels in larger rivers are frequently fairly low especially in headwater areas since

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http://dx.doi.org/10.1016/j.jconhyd.2014.09.002

agriculture is usually less intense compared to downstream plains. Hence, groundwater–surface water interactions can lead to a zone of lower nitrate concentration along rivers, in contrast with nitrate-rich groundwater recharged through farmlands (Debernardi et al., 2008; Hosono et al., 2013; Pinay et al., 1998). At locations dominated by direct recharge, evapotranspiration and water input including irrigation are the main physical processes that influence nitrate concentration as shown in a study that compares five agriculture regions throughout the USA (Green et al., 2008). In addition, nitrate levels might also be influenced by biogeochemical processes, especially plant uptake and denitrification (Bohlke et al., 2002; Haycock and Burt, 1993; Kellogg et al., 2005; McMahon and Bohlke, 1996). Numerous studies have investigated denitrification in the riparian zone (Burt et al., 1999; Clement et al., 2003; Kellogg et al., 2005; Maitre et al., 2005) and in aquifers in general (Bohlke et al., 2002; Green et al., 2008; Tesoriero and Puckett, 2011). Denitrification in riparian zones has frequently been attributed to shallow water table conditions and/or soil quality. According to Pinay et al. (2000), soil texture in alluvial sediments, particularly the silt and clay fraction, is closely related to the denitrification potential. Similarly, Schilling and Jacobson (2012) linked the lithology of alluvial sediments to the potential of denitrification. They documented greater organic content in fine-textured materials of swale sediments, known to promote denitrification. Hence, rivers might have a two-fold influence on nitrate concentrations: a direct influence via dilution and an indirect one by controlling on a long time-scale spatial patterns of fine-grain, organic-carbon rich sediments that promote denitrification. While the nitrate behavior in the vicinity of streams and at the scale of agricultural parcels has attracted a great deal of attention so far, there is only limited information on nitrate patterns at the scale of entire alluvial aquifers directly and indirectly influenced by rivers.

Rationalizing the spatial variability of nitrate concentrations in the proximity of rivers can be challenging since both biogeochemical and dilution processes affect the concentration, independently of the spatial variability of land use. Several studies have analyzed stable isotopes in nitrate to demonstrate denitrification and to differentiate it from dilution (Hosono et al., 2013; Mariotti et al., 1988). In another study, chemical parameters (e.g., chloride; Pinay et al., 1998) were used to quantify the mixing of surface water and groundwater.

The aim of this study is to identify and quantify the various factors that influence the spatial distribution of nitrate concentrations at the scale of an alluvial aquifer, with a special focus on the effect of a river crossing the aquifer. More specifically, the goal of the study is to evaluate the relative role of dilution vs. denitrification on spatial patterns of nitrate at the aquifer scale, to evaluate how denitrification was related to alluvial plain characteristics and to provide a methodological framework to differentiate the two effects.

The northern part of the Seeland aquifer, located in central Switzerland, was chosen as a study site. The site is well suited since land use is relatively homogeneous throughout the catchment area of the aquifer, fertilizer input rates are constrained by agricultural regulations and irrigation has a negligible effect on the aquifer water balance. Therefore, variations in nitrate concentrations at the scale of the aquifer are expected to be predominantly related to direct or indirect influences of the river rather than due to variations in fertilizer and water inputs. Furthermore, a dense network of monitoring wells is available throughout the aquifer. The direct influence of river water was mapped based on the stable isotope composition of water as direct recharge by precipitation and river water are expected to have a distinctly different isotope signature due to the origin of the river from a high altitude. Based on the mixing ratios, expected nitrate concentrations due to dilution only were calculated and compared to measured concentrations in order to locate denitrification zones. These zones were related to the alluvial soil quality and processes that control the architecture of the alluvial plain. This approach could be applicable in future studies to better understand the sources and the attenuation mechanisms of groundwater nitrate pollution in alluvial aquifers.

2. Study area

The Seeland region is located in the northwestern part of Switzerland (Fig. 1). The unconfined North-Seeland aquifer was formed by the deltaic depositional system of the Aare River, which took place after the last Pleistocene glaciations (Würm). Basement rocks underlying the aquifer are composed of the Tertiary Molasse of the Swiss Plateau, which constitutes most of the reliefs surrounding the aquifer. During the Riss glacial period, the Rhone Glacier carved out this bedrock valley that is partly filled by ground moraines. These deposits are covered with a series of glacio-lacustrine sediments, represented mostly by clay with locally gravelly lenses, exceeding a thickness of 200 m. During the last glaciations, large amounts of glaciofluvial gravel ('Seeland gravel' in Fig. 1) were deposited in front of the Rhone Glacier. The successive avulsions of the meandering Aare River led to a variable lithology of the unconsolidated Quaternary sediments ('Aare deposits' in Fig. 1), which varies from well-sorted gravels to clay. The average thickness of these deposits in the alluvial plain is approximately 25 m and can reach 50 m in the Aarberg–Kappelen region. Up to 10 m of flood deposits ('fine sediments' in Fig. 1) are observed in the northeast border of the plain. The deltaic depositional system has led to a strong heterogeneity of the sediments, but on a larger scale, the aquifer is relatively homogeneous (Kozel, 1992). Until the 19th century and the first river engineering works (Jura water corrections, 1868–1891), this large area was a floodplain of the Aare River (Kozel, 1992), limiting its exploitation for human activities. After the river engineering works, the swamps and marshes were drained and turned into farmlands.

The Seeland aquifer is the largest aquifer in the Bern region. It is crossed by the Hagneck Canal that divides the aquifer into two main parts. The study area, known as the North-Seeland aquifer, is located in the northern part of the Seeland region and covers a total area of some 50 km^2 (Fig. 1). The upstream boundary of the aquifer consists of the Hagneck Canal (Kellerhals and Haefeli, 1988), which corresponds to a water divide caused by the strong infiltration of water. From this southern boundary, groundwater flows to the northeast. Along the eastern boundary, piezometric levels show that exchanges may occur between groundwater and stream water of the Alteaare River, which corresponds to the former course of the Aare River before the Hagneck Canal was constructed. The aquifer discharges into the Nidau-Büren Canal in the north. Several pumping wells are located in the aquifer, a series of five