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Research papers

Impact of leaky wells on nitrate cross-contamination in a layered aquifer system: Methodology for and demonstration of quantitative assessment and prediction

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ABSTRACT

Poorly constructed wells can cause deterioration of groundwater quality by carrying surface contaminants into a deep subsurface aquifer system. In this study, the impact of leaky wells on groundwater contamination was quantitatively evaluated in a layered aquifer system of the Gosan agricultural fields, Jeju Island, Korea, where degradation in groundwater quality by nitrate has been reported. We introduce a leaky-well module and a double-domain integration method to compute nitrate cross-contamination through a layered aquifer system. The simulation results clearly revealed that the leaky wells rapidly degraded the water quality of the underlying aquifer by acting as a direct pathway for nitrate-rich shallow groundwater. The model results predicted that in order to decrease the NO_3-N concentration at the regional groundwater wells below the maximum contamination level (MCL), the maximum allowable fertilizer amount of Gosan would be 45–65% of the currently applied fertilizer level, whereas sealing of the regional groundwater wells would rapidly decrease the NO_3-N concentration below the MCL without reducing fertilizer usage. Our study demonstrated that the well conditions and hydrogeological system play major roles in the occurrence of nitrate in the underlying aquifer in Gosan; therefore, a proper groundwater management plan against nitrate contamination should be established on the basis of a comprehensive understanding of the hydrogeologic system of the area.

1. Introduction

Nitrate contamination has been a global issue in terms of groundwater quality for a long time, because extensive fertilizer usage on agricultural land may induce excessive N-leaching into subsurface aquifer systems (Postma et al., 1991; Widory et al., 2004; Koh et al., 2006; Stadler et al., 2008). Nitrate components are easily exported into the aquatic system because of their high solubility into water and low sorption capacity on soil particles. When humans drink water that contains high levels of nitrate, health problems such as methemoglobinemia in infants and stomach cancer can result (Wolfe and Patz, 2002). Therefore, many countries regulate the maximum content of nitrate to <50 mg/L as NO_3^- or <10 mg/L as NO_3-N in drinking water (Goodchild, 1998; EPA, 2010; WHO, 2011; ME, 2014).

The occurrence of nitrate in groundwater is highly influenced by the hydrogeologic setting of the area. In general, shallow groundwater is more susceptible to nitrate contamination than deep groundwater because shallow aquifers are readily affected by leaching of surface contaminants (Spalding and Exner, 1993; Nolan and Stoner, 2000; Böhlke, 2002). In a layered aquifer system consisting of an upper shallow and a lower deep aquifer interbedded with an aquitard, nitrate barely reaches the underlying aquifer because the intervening aquitard acts as a barrier to prevent downward migration of surface contaminants. However, when the middle aquitard is penetrated, or when the shallow groundwater travels vertically through improperly constructed wells, additional contamination of nitrate can occur in the underlying aquifer (Spalding and Exner, 1993; Santi et al., 2006).

Improperly constructed wells can rapidly degrade the water quality of an underlying aquifer by acting as a conduit for surface contaminants (Fig. 1; Spalding and Exner, 1993; Church and Granato, 1996; Jiménez-Martínez et al., 2011; Koh et al., 2012). Several studies have discussed the influence of leaky wells on con-

Abbreviations: MCL, maximum contamination level.

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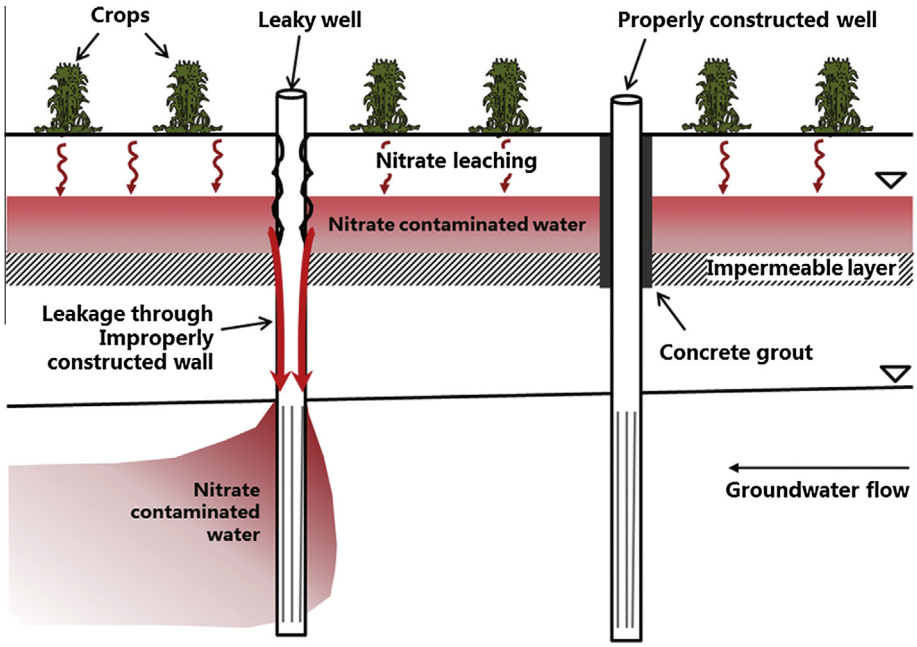

Fig. 1. Schematic diagram of nitrate transport pathways in leaky and properly constructed wells in the layered aquifer system.

taminant transport in multi-layered aquifer systems based on numerical interpretation (Reilly et al., 1989; Avci, 1992; Lacombe et al., 1995; Elci et al., 2001; Konikow and Hornberger, 2006; Landon et al., 2010). These studies noted that the amounts of water and solutes passing through a leaky well were significant and could result in cross-contamination of aquifers. However, there has been less effort on quantitative assessment of the effects of leaky wells on the groundwater contamination at the field scale. A complex hydrological setting of the layered aquifer system and leaky well hydraulics has restricted field-scale applications of numerical approach. Dragon et al. (2009) applied a numerical approach to explain aquifer cross-contamination via a leaky well at the field scale; however, in their model, the water leakage rate through the leaky well was simply inferred on the basis of the amount of groundwater usage, and the hydraulic connection between upper and lower aquifers via the leaky well was not considered in detail.

The Gosan area of Jeju Island, South Korea, is characterized by a layered aquifer system consisting of upper perched and lower regional aquifers separated by an impermeable clay layer. Intensive cultivation activities in this area have led to severe nitrate contamination of both the perched and the regional aquifer (Koh et al., 2012). Elevated nitrate concentration in groundwater is a major issue, especially in the regional aquifer because it is the main source of potable and agricultural water for Jeju Island. A previous study (Koh et al., 2012) in the Gosan area observed great improvement of water quality in the regional aquifer after re-grouting a leaky well, and it concluded that aquifer cross-contamination through improperly constructed wells is the main cause of highly elevated nitrate concentrations.

To suggest an efficient management plan to protect the aquifer environment against nitrate contamination in the Gosan area, it is necessary to quantify the process of nitrate migration through the leaky wells. However, it was impossible to measure the leakage rate directly because all the groundwater wells in the study site were in use for supplying water to agricultural activities. In this case, an integrated investigation combining field measurements and a numerical approach can provide an alternative method to identify the sources of nitrate and to suggest an adequate groundwater management plan.

The objectives of this study are (1) to develop a new numerical model (double-domain approach) to simulate nitrate transport considering well leakage in the layered aquifer system; (2) to evaluate the impacts of the leaky wells on contamination of the underlying aquifer; and (3) to suggest a reasonable management direction to lower the nitrate concentrations of the Gosan area. This study initially adopted a double-domain integration approach to represent leaky well dynamics in a layered aquifer system. The developed model was calibrated using field measurements and applied to assess the pathway of nitrate movement in the study site. Finally, the model was applied to predict the distribution of nitrate contamination under different remediation scenarios. This study will provide a useful tool for sustainable management of groundwater resources against cross-contamination by nitrate in multi-layered aquifer systems.

2. Site description

2.1. Study area

The Gosan area is located in the Hankyung watershed in the western part of Jeju Island (Fig. 2a and b). The study area is located on a flat lowland with an altitude of 0–114 m above mean sea level. The average precipitation rate at the Gosan weather station during 1992–2012 was 1151 mm/yr. Significant variation in the seasonal precipitation was observed: on average, 73% of annual precipitation was concentrated during the wet season between April and September (Korea Meteorological Administration, 2014). Previous studies in the Hankyung watershed reported that 39–46% of total precipitation infiltrated into the subsurface to recharge the groundwater (Hahn et al., 1994; Won et al., 2006; KIGAM, 2011).

As a result of readjustment of arable land during the 1970s, agricultural fields are distributed broadly in the Gosan area, covering more than 74% (34.4 km^2) of the study region (Fig. 2b) (KIGAM, 2011). Regional groundwater pumping wells (Fig. 2b) lined with PVC pipes were constructed between 1970 and 1980 in the Gosan area, and most of these wells are currently used for agricultural purpose (Jeju Water Resources Management Office, 2001). With the increase in agricultural fields, more chemical fertilizers have