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Groundwater pumping effects on contaminant loading management in agricultural regions

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ABSTRACT

Groundwater pumping changes the behavior of subsurface water, including the location of the water table and characteristics of the flow system, and eventually affects the fate of contaminants, such as nitrate from agricultural fertilizers. The objectives of this study were to demonstrate the importance of considering the existing pumping conditions for contaminant loading management and to develop a management model to obtain a contaminant loading design more appropriate and practical for agricultural regions where groundwater pumping is common. Results from this study found that optimal designs for contaminant loading could be determined differently when the existing pumping conditions were considered. This study also showed that prediction of contamination and contaminant loading management without considering pumping activities might be unrealistic. Motivated by these results, a management model optimizing the permissible on-ground contaminant loading mass together with pumping rates was developed and applied to field investigation and monitoring data from Icheon, Korea. The analytical solution for 1-D unsaturated solute transport was integrated with the 3-D saturated solute transport model in order to approximate the fate of contaminants loaded periodically from on-ground sources. This model was further expanded to manage agricultural contaminant loading in regions where groundwater extraction tends to be concentrated in a specific period of time, such as during the rice-growing season, using a method that approximates contaminant leaching to a fluctuating water table. The results illustrated that the simultaneous management of groundwater quantity and quality was effective and appropriate to the agricultural contaminant loading management and the model developed in this study, which can consider time-variant pumping, could be used to accurately estimate and to reasonably manage contaminant loading in agricultural areas.

1. Introduction

In many agricultural regions both agriculture and municipal water users rely heavily, or often exclusively, on clean, reliable sources of groundwater. However, certain agricultural activities have sometimes had detrimental effects on the environment as results of groundwater contamination (Chae et al., 2004; Jiang and Somers, 2009; Masetti et al., 2008; Peña-Haro et al., 2009, 2010; Roseta-Palma, 2003; Skinner et al., 1997; Spalding and Exner, 1993; Wang et al., 1996; Wei et al., 2009). In particular, the excessive use of nitrogen-based fertilizer and manure often results in nitrate contamination to the groundwater, which may be harmful to human health, damage crop productivity, and lead to eutrophication of surface water (Almasri and Kaluarachchi, 2005; Chae et al., 2004; Hayashi and Rosenberry, 2002; Lee et al., 1991; Newbould, 1989; Peña-Haro et al., 2009; Spalding and Exner, 1993; Wick et al., 2012). The deterioration of agricultural groundwater quality can affect the sustainability of groundwater use, limiting the supply of available water and imposing remediation costs. Nevertheless, these activities cannot arbitrarily be restricted for only the groundwater quality protection and thus it is necessary to find a way to manage the activities which can prevent groundwater contamination as well as guarantee agricultural productivity.

Several integrated approaches for agricultural contaminant loading management have been explored in order to incorporate hydrological, environmental, and economic considerations in estimating nitrate leaching and determining appropriate on-ground fertilizer application (Almasri and Kaluarachchi, 2005; Peña-Haro et al., 2009, 2010; Shaffer et al., 1991; Wei et al., 2009). However, these studies did not take into account any potential influences of groundwater pumping, even though groundwater has been used

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commonly in many agricultural regions. Generally, groundwater pumping lowers the water table and distorts groundwater flow. Consequently, it could have significant impacts on the fate of contaminants in the subsurface, such as its leaching to the water table and transport in the aquifer (Almasri and Kaluarachchi, 2004; Taghavi et al., 1994; Willis and Yeh, 1987). Eventually, the effects of groundwater pumping will have a decisive influence even on the contaminant loading management. A few studies have given comprehensive insights into managing groundwater quantity and quality together economically (Roseta-Palma, 2002, 2003) and hydrologically (Gharbi and Peralta, 1994; Keshari and Datta, 1995). In particular, Roseta-Palma (2002, 2003) emphasized the importance of this integrated management, indicating that the value of water depended on the quantity of water available based on its quality. However, the former studies were based solely on the economic values of groundwater quantity and quality, without considering the physical processes of groundwater flow and solute transport, and the latter studies focused on the indirect management of groundwater quality, by controlling pumping rates and/or scheduling, rather than contaminant loading from on-ground sources. In a broad sense, many studies about groundwater quality management might also belong to the latter. For example, they determined the optimal pumping control to remove the contaminant plume (e.g., Ko et al., 2005) or to prevent the saltwater intrusion (e.g., Park and Aral, 2004). The unexceptional fact that pumping can spread or shrink a contaminant plume, which these studies were based on, must be another reason that groundwater quantity should be considered in its quality management and it is necessary to manage the both together.

In agricultural regions where pumping has been concentrated in a specific period of time, it is particularly important to consider pumping conditions in managing contaminant loading. For example, rice farming requires a significant amount of water during the growing season, and most or a large portion of the required water has often come from groundwater because of its spatial proximity and availability. As a result, groundwater level and flow field in those regions tend to change from season to season, and so does the fate of contaminant. This indicates that contaminant loading management in those regions should be performed with consideration of the fate of contaminants under time-variant pumping condition.

Objectives of this study were to demonstrate the effects and importance of considering the existing groundwater pumping conditions on contaminant loading management, and to develop the contaminant loading management model more appropriate and practical for agricultural regions. A simulation–optimization model was developed to optimize both the permissible on-ground contaminant loading mass and the pumping rates simultaneously and to consider time-variant pumping. Several observations from field investigations in an agricultural region in Icheon, Korea, were used for the model development and demonstration, which will be introduced in the next chapter.

2. Observations from field work

Field investigation and monitoring of agricultural groundwater use and nitrate contamination were carried out in an agricultural field of about 9 km^2 in Icheon, Korea (Fig. 1). Although the greenhouse area has been expanding, occupying fields that were previously rice paddies, the majority of the study area remains covered by rice paddies. In the study area, which requires a significant amount of water supply during every rice-growing season, groundwater is the main water supply, despite concerns of a groundwater shortage caused by over-extraction. The recent increase in the number of greenhouse facilities, which typically use a significant amount of fertilizers, could be a threat to the groundwater quality in the study area.

In the study area, most agricultural groundwater wells located near rice paddies and greenhouses were installed within 10 m depth from the ground surface. Redox potential and dissolved oxygen measured in these wells were in the range of 200–300 mV and 5–6 mg/L, respectively. Thus, the aquifer is under oxidizing and aerobic conditions, implying that nitrate leached from a nitrogen-based fertilizer would be transported with groundwater flow, without undergoing mass reduction by denitrification (Tesoriero et al., 2000). Nitrate concentrations measured in these wells were mostly above 3 mg NO_3–N/L (Fig. 2(a)).

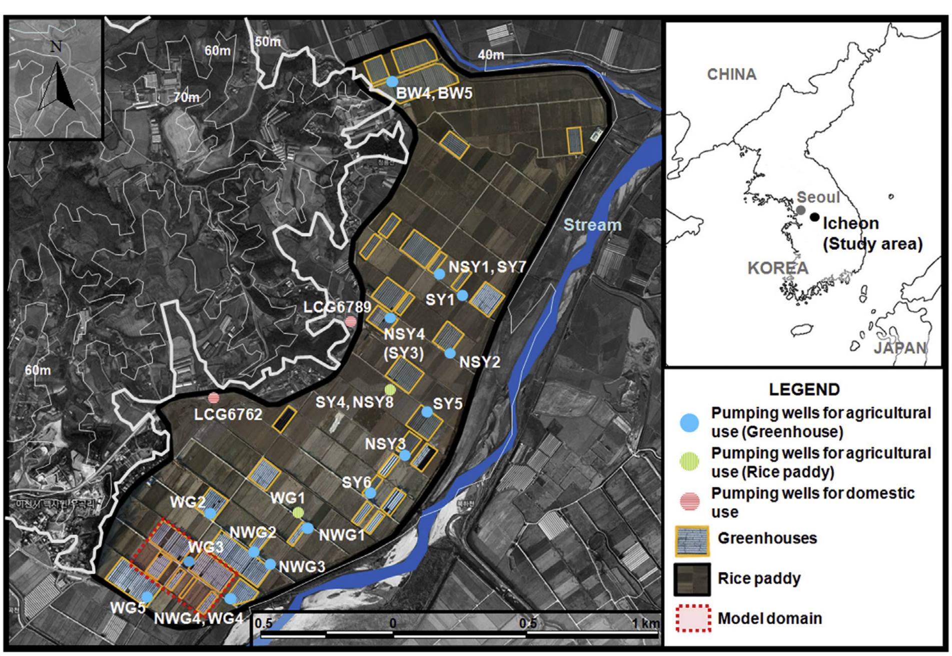

Fig. 1. Site description for field investigation and modeling.