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Water quality impacts of irrigation return flow on stream and groundwater in an intensive agricultural watershed

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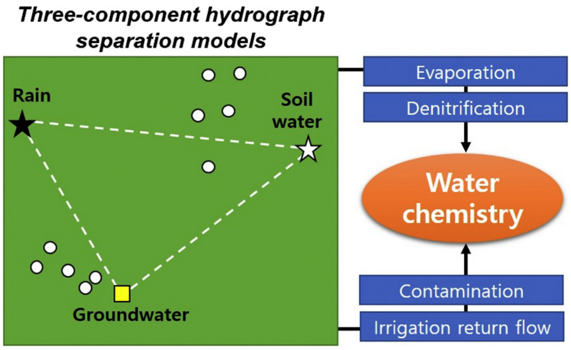
HIGHLIGHTS

- Chemistry in stream water near rice paddy field is not entirely explained by THSMs.
- Plot of Cl/NO_3 and NO_3/HCO_3 indicates natural and anthropogenic sources.
- $\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$ values indicate that manure is dominant source in many samples.
- Water chemistry is deciphered by combination of THSMs, multi-isotopes and elements.

GRAPHICAL ABSTRACT



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ABSTRACT

Irrigation return flow can include contaminants derived from agricultural practices, and then deteriorate the quality of surface and subsurface water within the watershed. Thus, it is important to estimate the effect of irrigation return flow on water chemistry/quality. To do that water samples were collected between November 2004 and December 2005 from stream and groundwater in a small watershed that contains extensive rice paddy fields. The water isotopic compositions represented seasonal variation, particularly in downstream of main channel and the tributary. In April and May, water samples in the downstream and tributary could not be explained by three-component (soil water, groundwater and rainfall) hydrograph separation models (THSM). These results indicated that the stream water was affected by high evaporation and that another water body (e.g. quick return flow) impacted on THSM. Plot of Cl/NO_3 and NO_3/HCO_3 showed that the water chemistry of all water samples was mainly regulated by soil water and groundwater. In addition, the water chemistry was related to water derived from rice paddy fields (WR) and manure. Manure impacted the water chemistry in tributary, one of the shallow groundwaters and the deep groundwaters, whereas that water in downstream was affected by WR. On a plot of $\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$ values, many samples were in a cluster indicative of manure and on a denitrification line. These imply that irrigation return flow characterized by denitrification processes was involved in determining the water chemistry. We suggest that chemical and multi-isotopes approach combined with the THSM is useful to elucidate the sources and processes controlling water chemistry in stream associated with rice paddy fields.

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1. Introduction

Rice is a staple food throughout the world, especially in Asia, which accounts for >90% of the world's total rice production (Food and Agriculture Organization of the United Nations, FAOSTAT: http://faostat3.fao.org/download/Q/QC/E). Population growth has continuously led to a greater demand of rice production, and global rice production has substantially increased from 259 million tons in the 1960s to 454 million tons in the 1980s to over 655 million tons in the 2000s (FAOSTAT). This rice production increase frequently required the use of greater amounts of irrigation water. Water is not completely consumed in a rice paddy field during the growing season and is subsequently discharged to streams and infiltrated to groundwater; this is referred to as irrigation return flow. Because potential contaminants such as pesticides, fertilizers, and manure are frequently applied in the rice paddy field, discharge of flooded water in the rice paddy field can deteriorate water quality of surface water within watershed. According to numerous monitoring studies, paddy rice cultivation caused surface/subsurface water contamination (Ferrero et al., 2001; Nakano et al., 2004; Stigter et al., 2008; Rajmohan and Elango, 2007). Thus, water samples collected from drainage stream receiving irrigation return flow included elevated physical and chemical parameters such as EC, Ca, Na, COD (Mhlanga et al., 2006). Impact of irrigation return flow on water quality was also examined on the input of nutrients to estuary, with spatial and temporal variation of EC, nitrate and total phosphorus concentration in groundwater (Pearce and Schumann, 2001). In addition, recent study showed that contribution of irrigation return flow to river water quantity and quality could be simulated, and that irrigation return flow significantly increased the salinity and quantity of Arkansas River (Lin and Garcia, 2012). River has dilution capacity and nutrient levels in the estuary are generally low, probably, due to sedimentation of phosphorus and nitrogen, and denitrification/volatilization of nitrogen. Effect of irrigation return flow on water chemistry/quality would be relatively important in a small stream than in river and estuary.

According to the Rural Development Administration (www.rda.go.kr) in South Korea, compost/manure is added to rice paddy fields in late winter and chemical fertilizer is added in late spring and mid-summer; thereafter, irrigation water is discharged in early summer to early fall. The drained irrigation water is likely incorporated into other water bodies in the watershed. In practice, Kim et al. (2009) estimated that approximately 26% of irrigation water in a 313 ha watershed in South Korea was discharged as irrigation return flow. The impact of irrigation return flow on groundwater and stream water should be assessed to properly manage water quality.

Irrigation return flow originates from irrigation water, which is typically stagnant for a long period of time, and thus, water isotopic compositions and chloride could be inferred to be indicators of irrigation return flow. Irrigation return flow tends to be enriched in $\delta^{18}O$ and $\delta^{2}H$ and shows elevated Cl concentrations relative to stream water and groundwater in a given watershed (Simpson and Herczeg, 1991; Kattan, 2008). In particular, in rural regions, $\delta^{18}O$ and $\delta^{2}H$ values are more useful to ascertain whether irrigation return flow contributes to stream and groundwater because the stable isotope ratios are less vulnerable to anthropogenic sources compared to Cl. Recent studies reported the contribution of irrigation return flow to stream and groundwater in watersheds using $\delta^{18}O$ and $\delta^{2}H$ values (Kattan, 2008; Dochartaigh et al., 2010). In more recent study, Keesari et al. (2017) reported that shallow groundwater, not deep groundwater, was affected by irrigation return flow using water isotopes, and furthermore estimated whether shallow and deep zone groundwaters were interconnected using tritium (^{3}H). In addition to $\delta^{18}O$ and $\delta^{2}H$ values, the isotopic compositions of nitrate are available as a suitable tool to trace the effect of irrigation return flow on stream and groundwater because irrigation water during the growing season may include distinct isotopic signals of manure/chemical fertilizer applied in paddy fields. For example, nitrate in the rice paddy field can be removed by denitrification process, resulting in the elevated $\delta^{15}N$ and $\delta^{18}O$ values (approximately 15‰ and 10‰, respectively) of nitrate in groundwater in the rice paddy field (Kim et al., 2015a).

The objective of this study was to estimate the effects of irrigation return flow on stream and groundwater in a watershed and to identify the main sources influencing stream and groundwater chemistry. To focus on the properties and contributions of irrigation return flow, this study was implemented in a small catchment with extensive rice paddy fields, and physicochemical and multi-isotope data were employed. In addition, each portion of soil, groundwater, and rain water in stream water were calculated using graphical technique such as three-component hydrograph separation model.

2. Sites and methodology

2.1. Site description

The Tanbang stream, which is located in Yesan, Chungcheongnam-do, South Korea, originates from the forest upstream and flows through agricultural areas in the middle/lower stream (Fig. 1). Of the discharge area of the stream (ca. 3.7 km^2), the forest and agricultural areas are ca. 58% (2.15 km^2) and 33% (1.22 km^2), respectively, and the rest (<10%) of the area is used as residential area. In this discharge area, rice and dry paddy farming intensively occurred from April to October (agricultural season; AS), but typically not from November to early March (non-agricultural season; NAS). Rice and dry paddy fields show distinct distribution patterns in the discharge area; rice paddy fields are mainly around streams, whereas dry paddy fields are located at the base of a mountain. Many wells that were constructed for agricultural practices, not for human drinking water, have not been strictly managed. Furthermore, the irrigation water taken from the groundwater and stream water flows into streams and/or is infiltrated without proper treatment after irrigation; there is no information on how much groundwater and stream water was used for irrigation water.

The study area is temperate with four distinct seasons. The annual average temperature is 11.8 °C. The precipitation is approximately 1100 mm/yr and ca. 80% of precipitation is concentrated in the rainy season (June to September) (http://www.kma.go.kr).

2.2. Sampling and analysis

The sampling campaign was conducted by periodically collecting water samples from stream water (3 sites) and groundwater (4 sites); here, groundwater was subdivided into shallow groundwater (2 sites; <20 m depth) and deep groundwater (2 sites; 100 to 120 m depth), based on the depth of wells, during the period of November 2004 to December 2005 (Fig. 1); Most wells were developed near rice paddy field. In addition, stream water in the upper reaches was temporally collected during rainy days from April 9 to 11 and from July 8 to 10. With stream water and groundwater sampling, soil water was collected from lysimeters installed at a depth of 15, 30, 60 and 90 cm in forest in the uppermost part of the catchment (Fig. 1). Precipitation was taken from a 20-L container preloaded with liquid paraffin to avoid evaporation. For anion analysis, water samples were transferred to a 60-ml high-density polyethylene bottle through a 0.45-μm membrane filter, and the oxygen and hydrogen isotope values ($\delta^{18}O$ and $\delta^{2}H$) were collected in the same manner. For the nitrogen and oxygen isotopic compositions of nitrate ($\delta^{15}N_{NO3}$ and $\delta^{18}O_{NO3}$), water samples were transferred into 4-L containers and a concentrated $HgCl_2$ solution was added to restrain the microbial activity. The water samples for cations were acidified with ultrapure HNO_3 until reaching a pH of approximately 2 after filtering in the field. During the collection of water samples, the water temperature, pH and electric conductivity (EC) were measured on site using a portable meter (Orion, Thermo Scientific, USA). All water samples were stored in a refrigerator until analysis.