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Assessing the effects of indirect wastewater reuse on paddy irrigation in the Osan River watershed in Korea using the SWAT model

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ABSTRACT

In the case of indirect wastewater reuse, which accounts for most of the wastewater reuse for agriculture, the influence of effluent from a wastewater treatment plant (WWTP) on irrigation water should be assessed prior to analyzing the effects of indirect wastewater reuse on soil-plant systems and agricultural environments. The objective of this study was to assess the effects of indirect wastewater reuse on irrigation water for paddy fields using the Soil and Water Assessment Tool (SWAT) model in a wastewater reused watershed in Korea. The model was calibrated and validated using four years (2010–2013) of hydrological and water quality data from the same watershed before the assessment. The model exhibited good performance for predicting daily streamflow, suspended solids (SS) and total nitrogen (T–N) loads from the calibration and validation procedures using statistical and graphical model evaluation. The verified model and historical weather data from 1981 to 2010 (30 years) were used to assess the effects of considering the effluent discharge from a WWTP. Effluent discharge was assessed as an important alternative for emergency agricultural water, as it largely contributes to available irrigation water for paddy fields during the drought season. Effluent discharge was also evaluated as a significant impact on irrigation water quality because the exceedance probability for a tolerable concentration and a water quality standard for T–N concentration increased more than 60 and 40%, respectively, due to its influence. The amount of wastewater reuse for indirect reuse was found to account for 27% of the total agricultural water supply using the reuse ratio proposed as an intuitive criterion to quantify the degree of influence of indirect wastewater reuse on stream water irrigation.

1. Introduction

The agricultural paradigm is changing to achieve agricultural productivity and environmental sustainability concurrently (Foley et al., 2011). Wastewater reuse for agriculture could be an alternative that meets both challenges because it provides an improvement to productivity and environmental benefits (Jeong et al., 2014), and consuming agricultural products irrigated with wastewater is a common practice for more than 10% of the world population (WHO,2006). In Korea, treated wastewater is also widely used for paddy irrigation because its volume is relatively constant throughout the year, and it has abundant fertilizer ingredients (Jang et al., 2012). The use of treated wastewater in paddy irrigation is expected to increase as wastewater treatment plants (WWTPs) influencing irrigation water increase (MOE, 2012).

Wastewater reuse for agriculture can be categorized as direct and indirect reuse. The terms direct and indirect refer to the conditions under which wastewater is applied in irrigation (Rutkowski et al., 2007). Direct wastewater reuse means that farmers directly take the treated effluent from a WWTP through an irrigation system, whereas indirect wastewater reuse is defined as when farmers take the treated effluent diluted with fresh water from streams or reservoirs after a WWTP discharges it downstream. Most wastewater reuse in agriculture is indirect, which means that the wastewater is disposed of into streams and the diluted wastewater is used for irrigation (Blumenthal et al., 2000). Investigations have found that 63 out of 505 WWTPs with a wastewater treatment capacity of more than 500 $m^3 d^{-1}$ irrigate their effluent onto farmland, predominantly on paddy fields, and more than 130 WWTPs affect irrigation water in Korea (Kim et al., 2009; Ministry of Environment (MOE), 2012).

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There have been abundant studies focusing mainly on the effects of direct wastewater reuse on soil-plant systems (Mohammad and Mazahreh, 2003; Stevens et al., 2003; Palese et al., 2009; Pereira et al., 2011a) and comparative studies on crop growth and environmental impacts according to irrigation water including conventional irrigation water, reused water, and reused water diluted artificially (Gori et al., 2000; Mohammad and Ayadi, 2004; Kang et al., 2007; Banon et al., 2011; Pereira et al., 2011b). Despite the wealth of studies on the subject of wastewater irrigation, few studies on the influence of effluent from a WWTP on irrigation water have been performed on the situation where indirect wastewater reuse accounts for most of the wastewater reuse. In both direct and indirect wastewater reuse, the irrigation water quality is affected by disposal levels of WWTPs. Especially in the case of indirect wastewater reuse, the hydrological conditions in which the treated wastewater is diluted also affect irrigation water in addition to the disposal levels. Therefore, it is important to address how irrigation water is affected by effluent from a WWTP on irrigation water prior to any analysis of the impacts of indirect wastewater reuse.

The purpose of this paper is to assess the effects of indirect wastewater reuse on paddy irrigation considering the river flow conditions and effluent from a WWTP to provide better programs for a sustainable indirect wastewater reuse. To carry out the objective of the assessment, we have used the semi-distributed river basin model, the Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2002; Arnold and Fohrer, 2005). The SWAT model has gained international acceptance as a robust interdisciplinary watershed modeling tool as evidenced by hundreds of SWAT-related papers (Gassman et al., 2007). Its applicability for flow predictions and water quality simulations, including nitrogen studies, has been verified (Santhi et al., 2006; Saleh and Du, 2004; Singh et al., 2005; Kang et al., 2006; Nasr et al., 2007; Ullrich and Volk, 2009).

2. Materials and methods

2.1. SWAT model

The SWAT model is a physically based, continuous model that was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch et al., 2005). The model can predict hydrologic components, sediment load and water quality including total nitrogen (T–N). It can assist land and water managers in assessing the impact of land management practices in hydrology, erosion and nonpoint source pollution. A more detailed description of the model can be found in Neitsch et al. (2005). In this study, the ArcSWAT version of SWAT2005 was used.

In the SWAT model, a watershed is divided into multiple subwatersheds, which are then divided into homogeneous spatial units characterized by similar geomorphologic and hydrological properties called hydrological response units (HRUs) (Flugel, 1995). User-specified land cover, soil area, and slope thresholds can be applied that limit the number of HRUs in each subwatershed (Ficklin et al., 2009). For this study, land use, soil properties and slopes that comprise over 5% of the subbasin were used for HRU definition.

2.2. Study watershed

The SWAT model was applied to the Osan River watershed located in central Korea with latitude and longitude ranging from N 37°05′56″ to N 37°14′05″ and from E 127°01′29″ to E 127°09′38″, respectively. The Osan River watershed is appropriate for the study watershed because it includes the Osan WWTP,

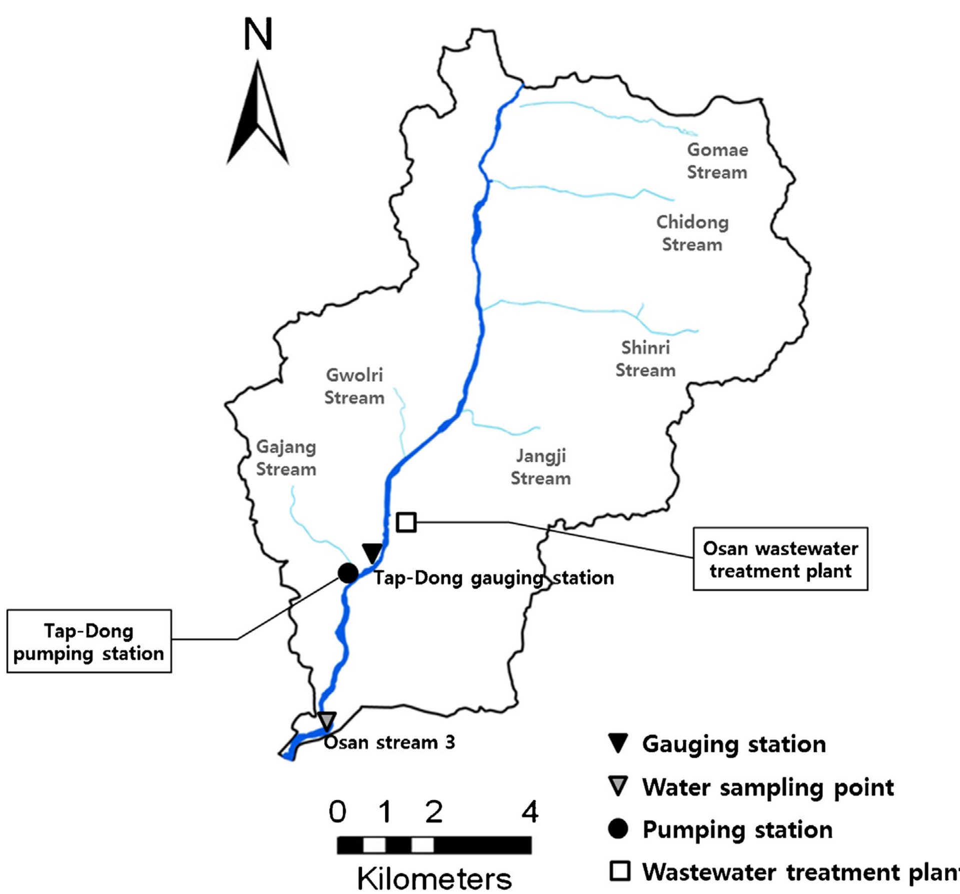

Fig. 1. The study watershed and monitoring networks including the streamflow gauging station and the water sampling point.