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Identifying changes in irrigation return flow with gradually intensified water-saving technology using HYDRUS for regional water resources management

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ABSTRACT

Irrigation return flow is critical for both surface and groundwater resources in downstream catchments. However, studies sufficiently clarifying the dynamics of hydrological processes in relation to irrigation return flow are scarce. In this study, HYDRUS-2D/3D model was used to analyze four irrigation development scenarios in Aksu River Basin, a major tributary of Tarim River. The study determined the effect of agricultural water saving on the dynamics of irrigation return flow in the basin. The results showed that for the 1990s, the irrigation return flow coefficient for flood irrigation was 0.50. This suggested that 50% of the water used in irrigation returned as discharge in the lower reaches. With increasing water scarcity, irrigation amount dropped while drip irrigation with plastic mulch was intensified. Accordingly, the irrigation return flow coefficient dropped from 0.44 in the 2000s to 0.34 in the 2010s under flood irrigation and from 0.42 to 0.23 under drip irrigation. With the drastic drop, irrigation was no longer enough to stabilize soil salinity in the region. The recent irrigation plan requires further reduction in irrigation amount. Based on the projected effects of the new irrigation scheme on soil salt build-up, an optimized irrigation scheme showed that the irrigation return flow coefficient should remain at 0.25. And with the use of water-saving technology, irrigation return flow has dropped from 594.01 mm in the 1990s to 164.62 mm in the 2010s, which should be maintained at 186.37 mm for the sustainability of the optimized irrigation scheme. The study also suggested that salinity was increasing in the downstream water systems due to irrigation return flow from land reclamation and water saving. This was a potential threat to the fragile riparian ecosystems in the study area.

1. Introduction

The accelerated depletion of groundwater and surface water systems due to warming climate and increasing food demand has resulted in a continuous decline of available water resources over our lifetimes (Pekel et al., 2016). Freshwater demand to support the ever-growing global population is highest in agricultural sector (Bruinsma, 2003). The current pace of agricultural development in Northwest China has aggravated water scarcity in Tarim River, the largest inland river in the region. Studies show that the expansion of farmlands is the primary cause of dwindling flow in Tarim River, resulting in ecological degradation in the downstream regions (Hao et al., 2008; Tao et al., 2011). As one of the three main tributaries of Tarim River, Aksu River feeds a large area of cropland in Tarim River Basin. Irrigated area in Aksu River Basin increased from 1.0×10^5 ha in 1949 to 2.1×10^5 ha in 1989 and then to 3.6×10^5 ha in 1998 (Zhang et al., 2008). Studies again show that cultivated area in the basin has since increased further by 20% (Huang et al., 2015). The increase in cultivated/irrigated area increased water use from 4.6×10^9 m^3/yr in the 1950s to 6.7×10^9 m^3/yr in the 2000s and then to 9.8×10^9 m^3/yr in 2010 (Feike et al., 2015; Shen et al., 2008). Thus despite the 6.7% increase in runoff in the headwater region (driven by increasing precipitation), discharge from Aksu River into Tarim River has decreased in the last half century (Xu et al., 2005;

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Xu et al., 2013). The flow decline in the lower reaches of Tarim River has also caused severe degradation of riparian ecosystems in the basin (Feng et al., 2005).

With the worsening water shortage, there is need to improve water use efficiency for sustainable agricultural development. Because drip irrigation with plastic mulch increases water use efficiency by maintaining sufficient water in the root zone, it is fast spreading across arid and semi-arid regions in China. However, high water use efficiency does not necessarily translate into high water saving. For instance, Scott et al. (2014) observed an “efficiency paradox”, where improvements in water use efficiency led to an increase in cultivated land area which in turn increased crop water use.

Irrigation return flow refers to the irrigation excess not used by plants or held as soil water that eventually returns to an aquifer system or surface water body (Dewandel et al., 2008). It is an important source of recharge in arid regions (Simons et al., 2015). Crosa et al. (2002) noted that over 80% of water flow in the lower reaches of Amu Darya River was from irrigation return flow. Similarly in Tarim River Basin, Aksu River which is the only tributary with a perennial flow of 73.2% to the total flow in Tarim River (Chen et al., 2003), 39.9% of that flow is irrigation return flow (Li et al., 1999).

Irrigation return flow coefficient is defined as the ratio of irrigation return flow to total applied water (Jafari et al., 2012). It is used to quantify the effects of irrigation on groundwater recharge and/or stream flow. Traditional methods of determining irrigation return flow include the use of lysimeter, water mass balance, chloride mass balance, environmental isotopes and Darcy’s law (Jafari et al., 2012; Scanlon et al., 2002). Field experiments on irrigation return flow are only feasible at limited scales under specific conditions. However, model simulations offer cost-effective and time-saving analyses of irrigation return flow coefficient under different water-saving scenarios.

Dewandel et al. (2008) successfully estimated irrigation return flow coefficients at watershed and seasonal scales for different crops using a hydraulic model that combines both water balance and unsaturated/saturated flow analyses. Using HYDRUS-1D model Jiménez-Martínez et al. (2009) estimated irrigation return flow coefficient of 0.22–0.68 for a summer-melon and fall-lettuce crop rotation system. Similarly, Poch-Massegú et al. (2014) used HYDRUS-1D to estimate irrigation return flow at 37% of total applied water under lettuce-melon crop rotation system. With agricultural development, irrigation methods have gradually changed from low-efficiency flood irrigation to high-efficiency irrigation technologies (e.g., drip irrigation) with heterogeneous soil water distribution in the soil profile. HYDRUS-2D/3D is appropriate for the simulation of irrigation return flow because it can capture water flow under drip irrigation conditions (Šimůnek et al., 2012; Skaggs et al., 2004).

Soil salinization is a major issue in cultivated arid regions and salt transport is closely related to water flow. Salt content at the soil surface decreases with the infiltration of irrigation or precipitation water into the soil profile. Under strong evaporation, however, salt accumulates at the soil surface. HYDRUS-2D/3D can capture such salt distribution patterns under drip irrigation (Phogat et al., 2012; Wang et al., 2014).

Despite the extensive studies on irrigation (Jafari et al., 2012; Lecina et al., 2010), the effect of changes in irrigation on irrigation return flow coefficient is not entirely clear. Farmland hydrological processes are greatly altered by changes in water allocation and irrigation regimes. For high efficiency in integrated water resources management, it is important to quantify the trends and variations in irrigation return flow coefficient due to changes in irrigation modes at different developmental stages. The objectives of this study were to: 1) analyze and compare the characteristics of water use under different irrigation regimes; 2) evaluate the effects of different irrigation technologies on irrigation return flow coefficient and soil salinity; and 3) provide suggestions for high efficiency in integrated water resources management in irrigated drainage basins.

2. Material and methods

2.1. Experimental site

Field experiments were conducted at the Soil and Water Conservation Monitoring Station in Alaer. The station is located in Aksu River Basin in Northwest China at 81°11′E, 40°37′N and elevation of 1013 m above sea level. Average annual precipitation in the study area is 49.2 mm, 87% of which falls in May through September. Strong open pan surface evaporation of ~1987 mm/yr in the region induces heavy build-up of soluble salts in the soil profile. According to the USDA classification system (Soil Survey Staff, 1975), the dominant soil texture is sandy loam. Observed salt contents in the land before reclamation at 0–10, 10–20, 20–30, 30–60, 60–90, 90–120 and 120–150 cm soil depths were 55.9, 30.1, 22.9, 15.14, 14.45, 16.8 and 16.9 g/kg, respectively. Based on lab-tested relationship between salt concentration (C, g/L) and electrical conductivity (EC, mS/cm) of $C = 0.8775 \times EC - 2.0803$ ($R^2 = 0.985$) and on the assumption that soil salts completely dissolve in soil water, the calculated electrical conductivities of the soil water (EC_{sw}) were 290.85, 165.39, 142.46, 97.38, 88.07, 104.20 and 109.02 mS/cm, respectively. In the strongly irrigation-driven agriculture, cotton (*Gossypium hirsutum* L.) is by far the most cultivated cash crop because of its high salt tolerance.

2.2. Experimental design

Irrigation return flow includes bypass water, surface runoff or tail water and subsurface drainage (Aragüés and Tanji, 2003). However, due to water scarcity in arid areas, water delivered to farmlands is not always enough to produce bypass water or surface runoff. Thus irrigation return flow in such regions is limited to drainage below crop root zone (Jafari et al., 2012).

The experiments were conducted in drainage lysimeters with backfilled soil in impermeable concrete walls and bottom. The lysimeters (3.33 m in length and 2 m in width, the equivalent of 0.01 Chinese mu or 6.67 m^2, and 2 m in vertical depth) were set up at the center of a homogeneous, flat cotton field. During the construction of the lysimeters, the 0–150 cm depth of soil was carefully excavated and every 10 cm depth of dugout soil piled separately. Then the backfilling of the pits was done in the sequence of occurrence of the native soil at the site. The 150–200 cm soil was replaced by coarse sand and gravel, which created a filter layer beneath the soil profile. Each lysimeter was equipped with a perforated PVC drainage pipe (diameter of 25 mm) at the bottom of the filter layer to route drainage water, namely irrigation return flow, from the bottom of the lysimeter to a graduated bucket (Fig. 1).

The lysimeter experiments lasted for four years from 2011 to 2014. Due to high soil salinity in the newly reclaimed farmland, the experiments in 2011 and 2013 were discarded because of low and sparse seedling growth. To leach soil salts out of the lysimeters, pre-sowing flood irrigations of 339 mm and 300 mm were done in 2012 and 2014, respectively. Because the amount of irrigation was so large, it was done in several bits over two days to prevent overflow from the lysimeter. However, pre-sowing irrigation by the local farmers is done in a single flood irrigation and left to leach over the following days. This irrigation also provides the necessary water to support cotton growth at the early stage. In the study, a flow meter was used to measure irrigation amount and a graduated bucket used to measure drainage amount.