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Watershed water circle dynamics during long term farmland conversion in freeze-thawing area

Wei Ouyang *, Liu Bing, Haobo Huang, Fanghua Hao, Zengchao Hao

School of Environment, State Key Laboratory of Water Environment Simulation, Beijing Normal University, Beijing 100875, China

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SUMMARY

Water resource is increasingly scarce in agricultural watershed under the pressure of socio-economic development. Long term land use conversion and freeze-thawing process posed additional characteristics to the water cycle. The semi-distributed hydrologic model Soil and Water Assessment Tool (SWAT) was employed for surface runoff, evaporation, and percolation simulations in freeze-thawing agricultural watershed. The interpreted five terms of land use data over three decades demonstrated that the percentage of the farmland area of the whole watershed increased from 23.5% to 62.1% and about half of dryland shifted to the paddy land in the recent ten years. The validated SWAT simulation showed that the spatial distribution of the surface runoff volume and the watershed averaged value increased 60 mm. The correlations of precipitation with surface runoff at monthly and yearly scales decreased from 0.8–0.9 to 0.6–0.7 respectively, which highlighted the impact of land use change over the surface runoff. The watershed evaporation was lower under the freeze-thawing condition, which increased from 363.7 mm to 418.5 mm over three decades. The field monitoring recorded the decreasing groundwater level, which was coincided with the expanding area of the paddy land. The watershed precipitation did not varied intensively in the whole simulation period (CV $\leqslant$ 0.01), but the percolation varied as the result of the cultivation disturbance on soil properties. The analysis showed that the expanding paddy land decreased the groundwater level at 0.17 m/yr during 1997 and 2012, which posed new challenge on regional water management. The evapotranspiration in the extreme size of paddy land was relatively small and the groundwater level also decreased relatively slow. These characteristics demonstrated the impact of freeze-thawing on the water cycle. The proposed method can be used as an effective tool for quantitative prediction of irrigation water amount and identify the impact of land use change on the water cycle at freeze-thawing agricultural watershed.

1. Introduction

Water resource security is the important cell for the agricultural sustainability chain, especially with the combined conflicts with food safety, booming population and climate change (Biemans et al., 2013; Wallace, 2000). Farmland expanding seriously influences the regional watershed water cycles because of the rainfall interception, increased irrigation and the soil infiltration due to the cultivation disturbance (De Pauw et al., 2000). Such variations have the direct implication on the surface runoff volume and groundwater storage (Croke et al., 2000). Irrigation directly controls crop growth and harvest, and land use changes reversely affect the agricultural water management (Vargas-Amelin and Pindado, 2014). The paddy land practices in the northeast China provide some special consideration for the water cycle due to the freeze-thawing process and the extreme big size of farmland field. Therefore, it is of utmost importance to assess water cycle response in the freeze-thawing area with long-term agricultural development.

Agricultural exploitation over natural land covers and intensive tillage activities are recognized as the main reasons of water resource deterioration and in particular of groundwater level decreasing in rural watershed (Goss and Richards, 2008). Expanding paddy land increases the base flow and moisture condition with the variations of soil vertical profile and the soil compactness. The crops canopies disturb the eco-hydrological process, soil erosion exposure and groundwater percolation (Mitchell et al., 2009). Previous studies have demonstrated that the water cycle and farmland eco-hydrological dynamics under long term land use changes in sub-tropical or warm areas, which experienced the bigger transpiration rate and subsequent more groundwater

* Corresponding author. Tel.: +86 10 58804585.
E-mail address: wo43@cornell.edu (W. Ouyang).

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extraction (Milano et al., 2013; Singh, 2010). However, this type of analysis in the freeze-thawing agricultural watershed is still rare and the field monitoring over different types of land use was just started (Liu et al., 2011). The issue of water resource sustainability is more serious with the rapid socio-economic development (Yoo et al., 2013). Therefore it is necessary to investigate how farmland conversions in freeze-thawing region impact watershed water cycle.

Conversion of natural land covers to farmlands frequently affects soil nutrients dynamics, soil organic carbon flux, and tillage practices. Such changes finally impact watershed cycle characteristics by altering the ratio of precipitation interception, percolation, evapotranspiration, and groundwater extraction, which also affect the surface runoff volume (Baron et al., 1998; Foley et al., 2005). Studies have shown that irrigation variations induced by land use shifts and crops rotations directly affect the water allocations (Chhabra et al., 2006). The forest reduction and wetland degradation during the agricultural development could impact the hydrological cycle, which also affects the groundwater recharge, surface runoff and the soil erosion (Dixon and Wood, 2003). Moreover, the farmland expanding and the shifts of dryland to paddy land influence the groundwater level and surface streamflow quantity due to increased irrigation amount (Scanlon et al., 2005). The constructed ditch nets around farmlands benefits the surface water discharge and the extreme big size of paddy land also improves the evaporation, which finally impacts the water allocation and cycles.

To illustrate the impact of long term land use changes on water cycle and ecohydrological process, the physical based hydrologic model is effective and widely applied tool (Narasimhan and Srinivasan, 2005). Previous studies have proved the advantages of hydrologic models on terrestrial hydrological cycle simulation and water resource management. Hydrologic modeling can integrate other historical data to simulate the temporal–spatial processes of watershed hydrology dynamics. Different types of models have been used to estimate the regional water cycle dynamics and the Soil and Water Assessment Tool (SWAT) is the widely utilized one (Jakeman and Hornberger, 1993; Arnold et al., 1998). The SWAT model is effective in simulating hydrological processes, water quantity, water cycle and ecohydrologic dynamics at watershed scale with the consideration of land use impacts (Fohrer et al., 2002).

The physical water scarcity is part of the limiting factor for agricultural development, and the expanding of the paddy land leads to the bigger challenge for the local water management (Ouyang et al., 2013). In this study, the model simulation and field monitoring were applied to identify the impact of long-term land use conversion on water cycle dynamics in the freeze-thawing agricultural area. The objectives of this study were: ① elaborating temporal–spatial patterns of land use conversion in agricultural watershed with five terms of land use data; ② simulating the watershed water cycle response to the long term land use conversion with SWAT; ③ quantifying the water cycle response by combing the simulated surface runoff and percolation with the monitored precipitation and groundwater.

2. Materials and methods

2.1. Study area description

The case study watershed is located in northeast China (Fig. 1), which is the typical agricultural area reclaimed from natural land covers. The watershed elevation drops from 129 m to 38 m and is the cold temperature zone with a continental monsoon climate (Ouyang et al., 2012). The mean annual precipitation at the study area is about 583 mm. The mean annual minimum and maximum temperature is −2.6 °C and 8.0 °C, respectively. This study area is an intensely agricultural developed area, with a great quantity of forests and wetlands converted into farmland since 1970. The patch size of farmland field is around 20,000–50,000 m^2, and these types of extreme big size of farmlands are cultivated with machines.

2.2. SWAT model description

SWAT model is a physically based distributed hydrological model that operates at daily step (Arnold et al., 1998). The SWAT model was developed from the Simulator for Water Resources in Rural Basins (SWRRB) model (Arnold and Williams, 1987), which divides the watershed into many sub-basins with calculations of the spatial data. The HRU (Hydrologic Response Units) is assumed as the smallest unit composition of the subbasin that has homogeneous land management, land use and soil property. The model is capable to simulating the hydrological process and water cycle within a basin and can present the response of land managements on streamflow, water quality and tillage management (Sakaguchi et al., 2014).

2.3. Model data preparation

Five types of input data (Digital Elevation Model, land-use, soil property, weather and agricultural management) were imported to the SWAT database. The land-use data in 1979, 1992, 2000, 2005 and 2010 was imported into SWAT, which were interpreted with Landsat series image at same season following the same procedure (Fig. 2). The soil property database was based on the national database, which was updated with the soil physic-chemical analysis data from 1.5-km grid sampling in 2010 (Ouyang et al., 2013). The daily monitoring weather data (precipitation, maximum and minimum temperature, relative humidity, wind speed and hours of sunshine) were obtained from three local weather gauges from 1970 to 2013. The tillage regulation of two types of farmlands were about the rice and soybean, and there detailed tillage dates were set. For the water resource simulation, the irrigation amount and date of paddy land was also the elemental information, which was predefined based on the field investigation. Based on the spatial data, the whole watershed was divided into 12 subbasins.

In order to improve the water cycle validation process, the evaporation, soil temperature, and soil water content were monitored on site. The Bowen ratio method was introduced to estimate the evaporation (Savage et al., 2009; Zeggaf et al., 2008), which was based on the RR-9310 type transposition Bowen ratio flux measurement system. The temperature gradient and water vapor gradient near surface was automatically measured and stored during the interaction between the surface and the atmosphere. The Bowen ratio, sensible heat flux, latent heat flux and moisture flux can also be measured and calculated. The sampling frequency was set at ten minute interval. The evapotranspiration (ET) data is calculated by the FAO Penman–Monteith equation (Allen et al., 1998). The automated soil volumetric water content sensors (TDR type, Coastal, Seattle, WA, USA) were placed at depths of 15, 30, 60 and 90 cm. The monitoring sensors were repeated double at horizontal 0.5 m space (Ouyang et al., 2014a). The daily groundwater level data was collected from the local groundwater monitoring networks.

2.4. Model validation

There was no long-term hydrological monitoring station in this watershed, but three hydrological stations locate at Naoli watershed on the southern boundary. The SWAT case study in Naoli Watershed was completed and the validated parameters of