Agricultural and Forest Meteorology 151 (2011) 314–327

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Simulation of the effect of irrigation on the hydrologic cycle in the highly cultivated Yellow River Basin

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ARTICLE INFO

Article history:
Received 8 April 2010
Received in revised form
10 November 2010
Accepted 16 November 2010

Keywords:
Irrigation
Hydrologic cycle
TINDVI
Integrated Catchment-based Eco-hydrology Model
Water availability
Sustainable development

ABSTRACT

To account for complex and diverse water system involving river dry-up, groundwater degradation, agricultural/urban water use, and dam/canal effects in heavily irrigated Yellow River Basin, this study coupled NIES Integrated Catchment-based Eco-hydrology (NICE) model series with more complex sub-models involving various factors (NICE-DRY). The model reproduced reasonably evapotranspiration, irrigation water use, groundwater level, and river discharge during spring/winter wheat, summer maize, and summer rice cultivations. Scenario analysis predicted the impact of irrigation on both surface water and groundwater, which had previously been difficult to evaluate. The simulated discharge with irrigation was improved in terms of mean value, standard deviation, and coefficient of variation. Another scenario analysis of conversion from dryland to irrigated fields predicted that the effect of groundwater irrigation was predominant in the middle and downstream and the resultant groundwater degradation predominantly, where surface water was seriously limited. Simulated dry biomasses of wheat and maize were linearly related to Time-Integrated Normalized Difference Vegetation Index (TINDVI) estimated from satellite images. Temporal gradient of TINDVI during 1982–1999 showed spatially heterogeneous distribution and increasing trends in the wheat and maize fields, indicating that the production increases were related to irrigation water and the resultant hydrologic changes. This integrated approach could help to estimate a close relationship between crop production, hydrologic cycle, and water availability, and predict heterogeneous vulnerability of water resources. Because this region experienced substantial river dry-up and groundwater degradation at the end of the 20th century, this approach would help to overcome substantial pressures of increasing food demand and declining water availability, and to decide on appropriate measures for whole water resources management to achieve sustainable development under sound socio-economic conditions.

1. Introduction

With the development of regional economies, the water use environment in the Yellow River Basin has changed greatly (Fig. 1). This region is heavily irrigated, and combinations of increased food demand and declining water availability are creating substantial pressures. Tang et al. (2008a) indicated that climate change is the dominant contributor to annual streamflow changes in the upper and downstream of the basin, whereas human activities such as irrigation water withdrawals dominate annual streamflow changes in the downstream. The North China Plain (NCP), located in the downstream area of the Yellow River, is one of the most important grain cropping areas in China, where water resources are also the key to agricultural development, and the demand for groundwater has been increasing. Groundwater has declined dramatically over the previous half century due to over-pumping and drought, and the area of saline-alkaline land has expanded (Brown and Halweil, 1998; Shimada, 2000; Chen et al., 2003b; Nakayama et al., 2006). Since the completion of a large-scale irrigation project in 1969, noticeable cessation of flow has been observed in the Yellow River (Yang et al., 1998b; Fu et al., 2004) resulting from intense competition between water supply-and-demand, which has occurred increasingly often. The ratio of irrigation water use (defined as the ratio of the annual gross use for irrigation relative to the annual natural runoff) having increased continuously from 21% to 68% during the last 50 years, indicating that the current water shortage is closely related to irrigation development (Yang et al., 2004). This shortage also reduces the water renewal time (Liu et al., 2003) and renewability of water resources (Xia et al., 2004). This has been accompanied by a decrease of precipitation in most parts of the basin (Tang et al., 2008b). To ensure sustainable water resource use, it is also important to understand the contributions of human

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doi:10.1016/j.agrformet.2010.11.006

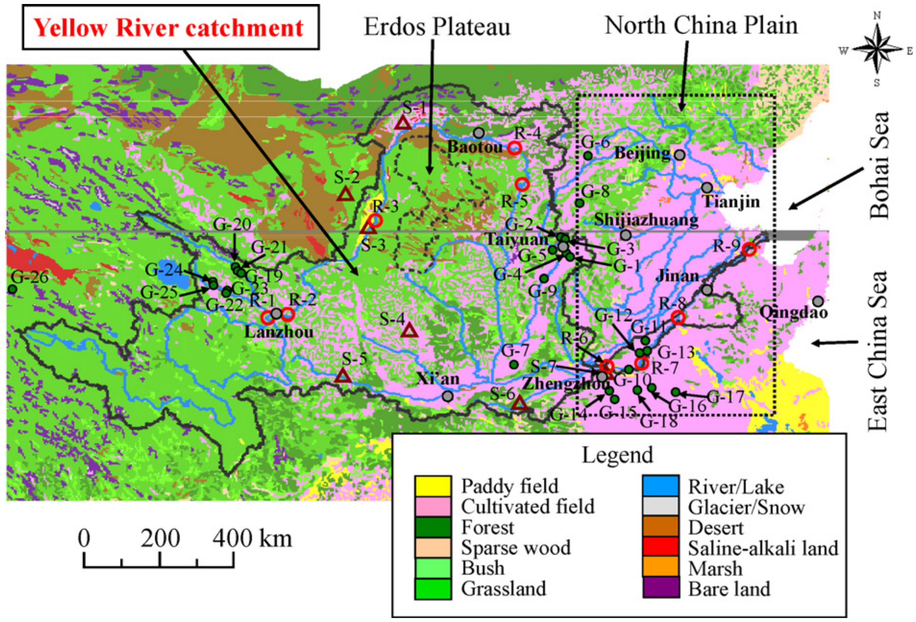

Fig. 1. Land cover in the study area of the Yellow River Basin in China. Bold black line shows the boundary of the basin. Black dotted line is the border of the North China Plain (NCP), which includes the downstream of the Yellow River Basin. Verification data are also plotted in this figure: river discharge (open red circle; nine points; Yellow River Conservancy Commission, 1987–1988), soil moisture (open brown triangle; seven points of the Global Soil Moisture Data Bank; Entin et al., 2000; Robock et al., 2000), and groundwater level (green dot; 26 points; China Institute for Geo-Environmental Monitoring, 2003). Details of the observation stations are shown in Table 1.

intervention to climate change in this basin (Xu et al., 2002), in addition to clarifying the rather complex and diverse water system in the highly cultivated region.

The research described here focuses on the impact of irrigation on the hydrologic cycle in the Yellow River Basin, an arid to semi-arid environment with intensive cultivation. Combination of the NIES Integrated Catchment-based Eco-hydrology (NICE) model (Nakayama, 2008a,b, 2010, in press; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2010; Nakayama and Watanabe, 2004, 2006, 2008a,b; Nakayama et al., 2006, 2007, 2010, revised) with more complex components (sub-models) such as irrigation, urban water use, and dam/canal systems has led to the NICE-DRY model, which simulates the balance of both water budget and energy in the entire basin with a resolution of 10 km. The objective of this study was to evaluate the complex hydrological processes of river dry-up, agricultural/urban water use, groundwater pumping, and dam/canal effects, and to reveal the impact of irrigation on both surface water and groundwater in the basin. Based on the relationship between satellite images of the Normalized Difference Vegetation Index (NDVI) and Time-Integrated NDVI (TINDVI), and the simulated dry biomasses of wheat and maize, a temporal gradient of TINDVI during 1982–1999 was estimated, and this was linearly correlated with changes in the production of both crops and indirectly correlated with changes in irrigation water use and the resulting hydrologic changes. This integrated approach will help to clarify how the substantial pressures of combinations of increased food demand and declining water availability can be overcome, and how effective decisions can be made regarding sustainable development under sound socio-economic conditions in the basin.

2. Site description

The Yellow River is 5464 km long and has a basin area of 794,712 km^2 if the Erdos inner flow area is included (Fig. 1). The basin is divided between the upper region (3472 km, 428,235 km^2) from the headwater to Toudaoguai in Inner Mongolia (R-4 in Table 1); the middle region (1206 km, 343,751 km^2) from Toudaoguai to Huayuankou in Henan province (R-6 in Table 1); and the lower region (786 km, 22,726 km^2) from Huayuankou to the estuary. The upper region can be divided into two sub-regions, the source area (upstream of Tangnaihai) and downstream (between Tangnaihai and Toudaoguai). The Yellow River is well known for its high sediment content, frequent floods, unique channel characteristics in the downstream (where the river bed lies above the surrounding land), and limited water resources. In the downstream, it is confined to a levee-lined course as it flows across the NCP, which is one of the most important grain cropping areas in China because of its large area (about 13,600 km^2) and huge population (about 112 million). The NCP is a giant alluvial plain formed by deposition by the Yellow, Hai, and Luan rivers and their tributaries. Many palaeochannels of different stages form various geomorphologic features (Chen, 1996).

3. Model structure of NICE-DRY

3.1. NICE model series describing natural regions

The NICE series of models (Nakayama, 2008a,b, 2010, in press; Nakayama and Fujita, 2010; Nakayama and Hashimoto, 2010; Nakayama and Watanabe, 2004, 2006, 2008a,b; Nakayama et al., 2006, 2007, 2010, revised) include surface-unsaturated–saturated water processes and assimilate land-surface processes describing variations in phenology from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data. The surface hydrology model of NICE consists of a hillslope hydrology model based on kinematic wave theory and a distributed stream network model based on both kinematic and dynamic wave theories. NICE also solves a partial differential equation describing three-dimensional groundwater flow for both unconfined and confined aquifers. The models connect sub-models from beneath the surface to the surface by considering water and heat fluxes; for example, (i) recharge calculated from the gradient of hydraulic potential between the deepest layer of unsaturated flow and the groundwater level, (ii) effective precipitation calculated from precipitation, infiltration into the upper