Journal of Hydrology 528 (2015) 206–216

Contents lists available at ScienceDirect

Journal of Hydrology

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

Quantifying water and energy budgets and the impacts of climatic and human factors in the Haihe River Basin, China: 1. Model and validation

Ying Guo, Yanjun Shen *

Key Laboratory of Agricultural Water Resources, Hebei Key Laboratory of Agricultural Water-Saving, Center for Agricultural Resources Research, Institute of Genetics and Developmental Biology, Chinese Academy of Sciences, Shijiazhuang 050021, China

ARTICLE INFO

Article history:
Received 31 December 2014
Received in revised form 13 May 2015
Accepted 16 June 2015
Available online 24 June 2015
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Magdeline Laba, Associate Editor

Keywords:
Evapotranspiration
Energy balance
Water budget
Modeling
Haihe River Basin

SUMMARY

We have developed an operational model to simulate water and energy fluxes in the Haihe River Basin (231,800 km^2 in size) for the past 28 years. This model is capable of estimating water and energy fluxes of irrigated croplands and heterogeneous grids. The model was validated using actual evapotranspiration (ET_a) measured by an eddy covariance system, measured soil moisture in croplands, groundwater level measurements over the piedmont plain and runoff observations in a mountainous catchment. A long-term time series of water and energy balance components were then simulated at a daily time step by integrating remotely sensed information and meteorological data to examine the spatial and temporal distribution and changes in water and energy fluxes in the basin over the past 28 years. The results show that net radiation (R_n) in the mountainous regions is generally higher than that in the plain regions. ET_a in the plain regions is higher than that in the mountainous regions mostly because of higher air temperature and larger areas of irrigated farmland. Higher sensible heat flux (H) and lower ET_a in the urban areas are possibly due to less vegetation cover, an impervious surface, rapid drainage, and the heat island effect of cities. During the study period, a water deficit continuously occurred in the plain regions because of extensive pumping of groundwater for irrigation to meet the crop water requirements. Irrigation has led to significant groundwater depletion, which poses a substantial challenge to the sustainability of water resources in this basin.

1. Introduction

Climate change and human activities potentially have substantial impacts on land surface processes at various spatial and temporal scales and have attracted considerable attention from the hydrological and ecological communities (Piao et al., 2010). At a basin scale, changes in both climatic and human dimensions directly affect the hydrological cycle and water yield, which would in turn have an important influence on ecosystems and society. In semi-arid, semi-humid and drought-prone areas, ecosystems are more vulnerable to climate change and human disturbance (Liu and Xia, 2004; Xia and Zhang, 2008). Regional water and energy budgets are important to determine water resources and environmental conditions. Quantification of water and energy budgets and their changes at the basin scale is essential for a better understanding of the mechanisms of changes in the hydrological cycle and water yield and can be greatly beneficial in improving basin water management and safeguarding food security in populated and cultivated regions.

The Haihe River Basin (hereafter HRB), with a total population of ~140 million including ~20 large- and medium-sized cities, is the political, economic, and cultural center of China. It is also the main grain production area in China, producing ~10% of China's total grain and accounting for ~30% of wheat and ~20% of corn production in China. However, the HRB is facing severe water crisis issues (Xia and Zhang, 2008), characterized by water shortage and degradation of ecosystems. In this basin, runoff is mostly generated in the mountainous regions and water consumption is concentrated in the plain regions that contain the main agricultural areas, industries, and cities. Agriculture depends largely on groundwater exploitation (Weng et al., 2010) in the HRB, similar to the US High Plains and Indus plain, and has become one of the three major groundwater depletion areas in the world (Siebert et al., 2010). Over the past several decades, groundwater pumping has experienced a continuous increase due to the rapid agricultural and urban development. As a result, water tables are dropping dramatically at a rate of ~1 m/yr in the piedmont plain (Li and Ding, 2012;

* Corresponding author. Tel./fax: +86 311 85800019.
E-mail addresses: guoy@sjziam.ac.cn (Y. Guo), yjshen@sjziam.ac.cn (Y. Shen).

http://dx.doi.org/10.1016/j.jhydrol.2015.06.039
0022-1694/

Shen et al., 2005), primarily due to groundwater overdraft (Liu et al., 2001; Qin et al., 2013; Zhang et al., 2003). Meanwhile, almost all major rivers in the plain regions are drying up and becoming ephemeral streams (Xia and Zhang, 2008). A significant reduction in runoff in the mountainous region was also detected in the past few decades (Yang and Tian, 2009). The conflict between the supply and demand of water resources has become serious. Sustainability of water resources is extremely important for maintaining the food production and ecosystems in this region. Therefore, quantification of water and energy budgets and their implications to water resources yielding in the HRB would greatly facilitate decision-making for water resources management.

Numerous studies have investigated water and energy budgets at basin scales using different methods, such as large-scale observation experiments, remote sensing, and modeling, to obtain a better understanding of the hydrological cycle (Berbery et al., 2003; Boulet et al., 2000; Feng and Houser, 2008; Pan et al., 2008; Saux-Picart et al., 2009; Yao et al., 1996). Quantification of major components in hydrological and energy fluxes and their changes in time and space can help to understand hydrological trends (Kumar and Merwade, 2011; Leblanc et al., 2012; Moran-Tejeda et al., 2011). However, observations provided by traditional field experiments are generally constrained to field and landscape scales. Most studies have investigated individual hydroclimatic variables using data from a few hydrometeorological stations, which may not be able to provide a complete picture of changes in water and energy budgets, or water resource availability over a region, making the implications to ecology and hydrology unclear. Since the late 1970s, satellite remote sensing data have been widely used for water and energy fluxes monitoring at regional scales (Ahmad et al., 2006; Bastiaanssen et al., 1998; Loukas et al., 2005) and have also recently been used to monitor ET_a for the HRB (Hu et al., 2011; Li et al., 2008; Long and Singh, 2012; Shu et al., 2011; Wu et al., 2012). In these satellite-based water or energy flux monitoring and analyses, daily and/or annual fluxes were extrapolated by using limited scenes of quality images (Long and Singh, 2010). Cloud-free images are rarely available most of the time in the basin. Large uncertainties could be involved in the flux estimates from remote sensing, which may not provide precise information regarding water and energy fluxes at river basin scales (Allen et al., 2011; Jia et al., 2012; Kalma et al., 2008; Li et al., 2009).

Integration of ground-based meteorological observations and remote sensing data with modeling provides a promising way to fulfill the requirement of evaluating large-scale water and energy budgets (Qin et al., 2013). Although many land surface models have been proposed or used, such as BATS (Seth et al., 1994), SiB2 (Sellers et al., 1996a,b), LSM (Bonan, 1996), CLM (Dai et al., 2003) and so on, there still is a need for modeling studies because a major drawback of most previous land surface models is their relatively high data demand. Most land surface models need hourly atmospheric forcing data and the input of a large number of parameters. Model calculation processes are also complex and time consuming, and the availabilities of these models at regional scales differ for studies in different regions because of their different modeling purposes. Thus, these land surface models may not be suitable for this study because we have limited data at high time resolution in the HRB. Therefore, we need to develop an operational model to simulate water and energy fluxes in the HRB that has both good operability and accuracy.

The objectives of this study were therefore (1) to develop an operational model in combination with satellite- and ground-based observations to simulate the effects of human activities, e.g., land use change, irrigation operations, etc.; (2) to validate the model using multi-source and multi-scale observations, such as measurements of water and energy fluxes at the field scale and groundwater level monitoring and streamflow observations at the sub-basin scale; (3) to evaluate the spatial and temporal variations in water and energy budgets in the HRB over the past 28 years; and (4) to investigate the implications of the changes in water/energy budgets from climate change and human activities on water resource availability in this basin. In the current paper, we present the first component of this work, i.e., modeling and validation. The second component concerning trends and impact factors of water and energy budget changes is presented in a companion paper.

2. Model description and parameterization

The model was developed based on land surface energy and water balances and is capable of simulating the effect of irrigation activities on water and energy budgets in the irrigated croplands, as well as the effect of different land cover/use on water and energy budgets of a heterogeneous grid at a daily scale. We describe the model processes and structure in the following sessions.

2.1. Net radiation (R_n)

The land surface energy balance can be expressed as

$$R_n = H + G + \mathrm{LE} \tag{1}$$

where R_n is the net radiation (MJ m^{-2} day^{-1}); H is the sensible heat flux (MJ m^{-2} day^{-1}); G is the soil heat flux (MJ m^{-2} day^{-1}), which can be ignored at the daily timescale (Allen et al., 1998); LE is the latent heat flux (MJ m^{-2} day^{-1}).

The net radiation is calculated as

$$R_n = R_{ns} - R_{nl} \tag{2}$$

where R_{ns} and R_{nl} are the net shortwave and net longwave radiation, respectively. The net shortwave radiation (R_{ns}), is the fraction of the incoming solar radiation (R_s) that is not reflected from the surface. The fraction of the solar radiation reflected by the surface is known as the land surface albedo (α). R_{ns} is calculated by

$$R_{ns} = (1 - \alpha)R_s \tag{3}$$

The land surface albedo, α, is highly variable for different surfaces and is calculated from satellite data according to the method proposed in Wang et al. (2004). The incoming solar radiation (R_s) depends on atmospheric conditions (e.g., humidity, dust) and solar declination (e.g., latitude and month) because as the radiation at the top of atmosphere (TOA) penetrates the atmosphere, some of the radiation is scattered, reflected or absorbed by the atmospheric gases, clouds and dust. However, it is difficult to measure at a regional scale. Here, it is calculated with the Angstrom formula, which relates TOA radiation, R_a, and the relative sunshine duration:

$$R_s = \left[a_s + b_s \frac{n}{N}\right] R_a \tag{4}$$

where n is the actual sunshine duration (hour), N is the maximum duration of sunshine or daylight hours (hour), and n/N is the relative sunshine duration. In different atmospheric and solar declination conditions, the Angstrom values a_s and b_s will vary. Here, no actual solar radiation data are available, and the values $a_s = 0.25$ and $b_s = 0.50$ are used (Allen et al., 1998).

The TOA radiation R_a is calculated by

$$R_a = \frac{24 \times 60}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \tag{5}$$

where G_{sc} is the solar constant (0.0820 MJ m^{-2} min^{-1}); d_r is the inverse relative Earth–Sun distance; ω_s is the sunset hour angle (rad); φ is the latitude (rad); and δ is the solar declination (rad).

The maximum duration of sunshine or daylight hours N (hour) can be calculated by the formula in Allen et al. (1998):