Journal of Hydrology 546 (2017) 515–525

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Variations in annual water-energy balance and their correlations with vegetation and soil moisture dynamics: A case study in the Wei River Basin, China

Shengzhi Huang [a,*], Qiang Huang [a], Guoyong Leng [b], Menglong Zhao [a], Erhao Meng [a]

[a] State Key Laboratory Base of Eco-Hydraulic Engineering in Arid Area, Xi'an University of Technology, Xi'an 710048, China
[b] Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD 20740, USA

ARTICLE INFO

Article history:
Received 9 August 2016
Received in revised form 3 November 2016
Accepted 31 December 2016
Available online 7 January 2017
This manuscript was handled by A. Bardossy, Editor-in-Chief, with the assistance of Saman Razavi, Associate Editor

Keywords:
Watershed water-energy balance
Vegetation dynamics
Soil moisture dynamics
Fu's equation
The Budyko hypothesis
The cross wavelet analysis

ABSTRACT

It is of importance to investigate watershed water-energy balance variations and to explore their correlations with vegetation and soil moisture dynamics, which helps better understand the interplays between underlying surface dynamics and the terrestrial water cycle. The heuristic segmentation method was adopted to identify change points in the parameter ω series in Fu's equation belonging to the Budyko framework in the Wei River Basin (WRB) and its sub-basins aiming to examine the validity of stationary assumptions. Additionally, the cross wavelet analysis was applied to explore the correlations between vegetation and soil moisture dynamics and ω variations. Results indicated that (1) the ω variations in the WRB are significant, with some change points identified except for the sub-basin above Zhangjiashan, implying that the stationarity of ω series in the WRB is invalid except for the sub-basin above Zhangjiashan; (2) the correlations between soil moisture series and ω series are weaker than those between Normalized Difference Vegetation Index (NDVI) series and ω series; (3) vegetation dynamics show significantly negative correlations with ω variations in 1983–2003 with a 4–8 year signal in the whole WRB, and both vegetation and soil moisture dynamics exert strong impacts on the parameter ω changes. This study helps understanding the interactions between underlying land surface dynamics and watershed water-energy balance.

1. Introduction

Actual evapotranspiration is a vital component of watershed water balance (Liu and Yang, 2010; Matin and Bourque, 2013; Camporese et al., 2014), which is commonly estimated based on evaporation capability (Huang et al., 2014a). Penman (1956) reported that actual evapotranspiration is proportional to evaporation capacity, whereas Bouchet (1963) and Brutsaert and Parlange (1998) stated that actual evapotranspiration exhibits a complementary relationship with evaporation capacity. Evapotranspiration is primarily controlled by precipitation and evaporation capacity at annual timescale (Yang et al., 2007). Hence, Budyko (1974) established watershed coupled water-energy balance equation, which is called as the Budyko hypothesis. A large number of researchers have fitted the empirical relationship of water-energy balance in various basins based on hydrological and meteorological data (Budyko, 1974; Fu, 1981; Choudhury, 1999; Zhang et al., 2004; Yang et al., 2006, 2007; Yang et al., 2008; Xiong and Guo, 2012), and verified the validity of the Budyko hypothesis. The empirical equations were widely adopted to investigate the regional distribution characteristic of annual water-energy balance in watershed, predict interannual variations of watershed water balance, as well as quantify the effects of climate change and human activities on runoff variations (Budyko, 1974; Milly and Dunne, 2002; Sankarasubramanian and Vogel, 2002). Fu (1981) provided the boundary conditions of the Budyko hypothesis according to the physical meaning of watershed hydrology and meteorology, and obtained its analytical expression via dimensional analysis and mathematical derivation, thus providing a solid theoretical basis for the application of the Budyko hypothesis. Yang et al. (2006) investigated the effectiveness of the Budyko hypothesis, Penman hypothesis, and Bouchet's complementary hypothesis based on Fu's equation, and pointed out that Fu's equation based on the Budyko hypothesis can be well used to describe coupled water-energy balance at annual timescale.

From then on, the Budyko hypothesis, as an effective tool for studying watershed annual water-energy balance, has been exten-

* Corresponding author.
E-mail address: huangshengzhi7788@126.com (S. Huang).

http://dx.doi.org/10.1016/j.jhydrol.2016.12.060
0022-1694/

sively applied in hydrology (Li et al., 2007; Ma et al., 2008; Xu et al., 2014; S.Z. Huang et al., 2015a). For example, Shao et al. (2011) used the Budyko's water balance model to analyze the regional soil-vegetationatmosphere interaction; Xiong and Guo (2012) evaluated the performance of the Budyko formula in calculating long-term water balance in humid watersheds of southern China; Wang and Hejazi (2011) employed the Budyko hypothesis to quantify the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States; Xu et al. (2014) adopted the Budyko hypothesis to detect the dominant cause of runoff decline in Haihe basin. Previous studies provided a new idea for analyzing watershed change characteristic and quantifying the impacts of climate change and human activities on runoff changes. Most of them built the relationship between the long-term mean values of the parameter ω in the Budyko-type formulas and factors including climate, vegetation cover, geomorphology, or proportions of wasteland and irrigated land (Yang et al., 2007; Han et al., 2011; Li et al., 2013), which are frequently treated as constant. In practice, the irrigated land area and vegetation cover among others in a specific watershed can be altered over years. Consequently, the shape of the Budyko curve in the watershed is possibly changed, and the stationarity of watershed water-energy balance may be invalid, thereby leading to errors. Hence, it is necessary for studies using the Budyko hypothesis to determine whether the stationarity of its parameter ω series is still effective.

Some studies found that the parameter ω of the Budyko framework is associated with land surface characteristics such as soil types, vegetation cover, climate seasonality, as well as topography (Milly, 1993, 1994; Shao et al., 2012; Williams et al., 2012; Yang et al., 2007, 2009; Zhang et al., 2001, 2004). Several studies have explored the role of vegetation cover in the Budyko framework. For instance, leaf area index has exhibited strong correlations with the parameter ω in Fu's equation at the 10 day timescale (Yang et al., 2008). Shao et al. (2012) adopted a multivariate adaptive regression spline model to calibrate the model parameter and found strong influences of forest coverage on ω. Although these studies have revealed the relationship between vegetation cover and ω to a certain extent, they only reflected their linear characteristics due to the application of multivariate linear regression models, thus failing to capture their nonlinear characteristics. Building upon previous studies, we attempt to introduce the cross wavelet analysis to explore the linkages between vegetation dynamics and ω variations, aiming to better understand the interplays between the terrestrial water cycle and vegetation dynamics under the context of changing environment. The cross wavelet analysis is a technique combining the cross spectrum analysis with wavelet transform, and it can fully reveal the correlations between two time series in both time and frequency domains (Hudgins and Huang, 1996; Torrence and Compo, 1998). It provides the distribution laws of the energy resonance and covariance of two time series in both time and frequency fields, thus being able to capture the nonlinear characteristics in their relationships (Torrence and Compo, 1998). Several studies have stated that annual water balance is sensitive to soil water storage capacity in watershed (Zhang et al., 2001; Potter et al., 2005; Cong et al., 2014). However, these previous studies did not explore the detailed correlations in both time and frequency fields, thereby failing to reflect the changing characteristics of the relations. Therefore, the cross wavelet analysis is also employed to explore the correlations between soil moisture and ω, with the purpose of revealing the role of soil water storage capacity in the variations of the parameter ω in the Budyko framework in both time and frequency fields.

The primary objectives of this study are: (1) to determine whether the stationarity of the parameter ω of Fu's equation in the Budyko framework is valid in a changing environment; (2) to investigate the effects of vegetation dynamics on the variations of the parameter ω; (3) to examine the correlations between soil moisture dynamics and ω variations. The first objective is to determine whether the parameter ω series of the Budyko framework is non-stationary, whereas the second and third objectives are to explore possible reasons behind the changes in the parameter ω series from the perspectives of vegetation and soil moisture dynamics, respectively. In this study, the primary novelties lie in (1) identifying the non-stationarity of the parameter ω series of the Budyko framework; (2) exploring the correlations between ω and vegetation/soil moisture dynamics in both time and frequency fields. To the best of our knowledge, both of them have not been investigated yet.

2. Study area and data

2.1. The Wei River Basin

The Wei River Basin (WRB), the largest tributary of the Yellow River in China, is selected as the study area in this study (Fig. 1). The Wei River is located between 33.5–37.5°N and 103.5–110.5°E, covering a total area of nearly 1.35×10^5 km^2. Topographically, the altitude increases from the lowest Guanzhong Plain in the southeast and southern portion of the basin to the highest mountainous areas in the northwestern basin. Situated in a continental monsoon climate zone, the WRB experiences rich precipitation and high temperature in summer but sparse precipitation and low temperature in winter. Its annual precipitation is approximately 559 mm (Zhang et al., 2008). Furthermore, its precipitation has a noticeable seasonality, with approximately 60% of its annual precipitation occurring in flood season (from June to September). The mean air temperature in the coldest month ranges from −3 °C to −1 °C, whereas that in the hottest month varies from 23 °C to 26 °C (Zhang et al., 2008). The primary vegetation type in the WRB is temperate deciduous broad-leaved forest. Farmlands are mainly distributed in the Guangzhong Plain (Fig. 1). As an important agricultural and economic zone, the WRB has been remarkably impacted by human activities such as irrigated agriculture, urbanization, and water and soil conversion projects, especially in recent decades. These activities have exerted large impacts on the hydrological processes in the WRB (Zuo et al., 2014; S.Z. Huang et al., 2015b). Therefore, the WRB is a suitable test case to investigate the non-stationarity of the parameter ω of the Budyko framework and explore the correlations between ω and vegetation and soil moisture dynamics.

2.2. Data

Daily precipitation, wind speed, sunshine duration, air temperature, vapour pressure, and relative humidity data obtained from 21 meteorological stations in the WRB and its surroundings are utilized in this study (Fig. 1). Each station has meteorological data spanning January 1, 1960–December 31, 2010. Meteorological data are obtained from the National Climate Center (NCC) of China Meteorological Administration (CMA). Potential evapotranspiration (PET) data are computed using the Penman-Monteith equation (Allen et al., 1998). In addition, daily runoff data at Linjiacun, Zhangjiashan and Huaxian hydrological stations in the WRB are obtained from the hydrologic manual. Each station has runoff data spanning January 1, 1960–December 31, 2010. Linjiacun station is situated in the middle reach of the basin with catchment area of 3.3×10^4 km^2, and the basin above Zhangjiashan station has catchment area of nearly 4.2×10^4 km^2, whilst Huaxian station is located in the lower reach of the basin, and its catchment area accounts for 97.16% of the entire basin. Hence, the runoff at Huax-