Journal of Hydrology 519 (2014) 3531–3540

Contents lists available at ScienceDirect

Journal of Hydrology

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

Interannual variability of regional evapotranspiration under precipitation extremes: A case study of the Youngsan River basin in Korea

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ARTICLE INFO

Article history:
Received 21 March 2014
Received in revised form 29 September 2014
Accepted 18 October 2014
Available online 6 November 2014
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Venkat Lakshmi, Associate Editor

Keywords:
Evapotranspiration
Budyko curve
Water balance
MODIS
Climate extremes

SUMMARY

Understanding basin-scale evapotranspiration (ET) is an important issue for the management of regional water resources, especially with the recent trend of intensified precipitation (P). This study assessed the spatial and temporal variations of regional ET in response to P extremes, for various types of land-cover across the Youngsan River basin in Korea.

The spatial distribution of monthly P and ET from 2001 to 2009 were estimated using rainfall records from 40 weather stations located across the basin and a satellite-derived, process-based ET model Breathing Earth System Simulator (BESS) (Ryu et al., 2011), respectively. The study periods were focused on the recent years with abnormally large, small and normal P, which were identified from anomalies in the z-sores of long-term (1973–2011) rainfall records. The variation of regional ET was assessed in terms of: (1) the controlling factors, using the statistics of related meteorological and geographical data, (2) a water-energy balance, using Budyko's framework, and (3) the water balance of four selected watersheds in the region, using the partitioning of annual P into ET and riverflow discharge (Q).

The total annual ET of this region decreased in abnormally large-P year and increased in small-P year, because the ET in July to August (which accounts for more than 36% of annual ET) was limited by the available energy rather than available water due to the summer monsoon. In terms of land cover types, forests showed larger interannual variability in ET than paddy fields or cropland, with the differences in ET between large and small-P years being 108 and 82 mm yr^{-1}, respectively. The sensitivity of annual ET to P extremes was significantly related to the leaf area index (LAI), rather than soil properties, topography, or specific land-cover type ($p < 0.05$, generalized linear model). However, the interannual variations of ET were not large (15–18%) compared to those of annual P (51–62%) and Q (108–232%) during 2002–2009. Thus, vegetation played a consistent role in releasing water back to the regional atmosphere through ET, regardless of P extremes.

1. Introduction

Vegetation plays a key role in the regional water cycle through evapotranspiration (ET). A number of recent observations have suggested that 40–60% of precipitation (P) can be lost through ET in temperate deciduous and coniferous forests (Jassal et al., 2009; Komatsu et al., 2007; Kosugi and Katsuyama, 2007; Wilson and Baldocchi, 2000), even in drought conditions (Brümmer et al., 2012; Oishi et al., 2010). In future conditions with more intensified heavy precipitation and drought events (IPCC, 2013), it is critical to understand the variations in ET in relation to extreme P, because of the implications for regional water resource management.

It is widely recognized that ET is controlled by complex processes and interactions between the atmosphere, soil, and vegetation, which are characterized by the climatic, vegetation cover, and catchment features of the region (Baldocchi et al., 2004; Marc and Robinson, 2007; Ryu et al., 2008a; Zhang et al., 2004). Climatic factors such as precipitation, solar radiation, air temperature, humidity, and wind speed are primary influences on ET (Oishi et al., 2010; Penman, 1948; Zhang et al., 2004), because the

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http://dx.doi.org/10.1016/j.jhydrol.2014.10.048
0022-1694/

regional vegetation is exposed to similar atmospheric conditions. Coupled with the weather conditions, variations in ET depend on surface conductance (Monteith, 1965; Wever et al., 2002; Wilson and Baldocchi, 2000), leaf area index (LAI) (Zha et al., 2010), stand age (Jassal et al., 2009; Komatsu et al., 2007; Murakami et al., 2000), and the accessibility of roots to the water table (Lafleur et al., 2005; Paço et al., 2009; Ryu et al., 2008a). Moreover, catchment characteristics affect ET because soil properties such as water storage capacity or permeability, and topographical factors such as slope or elevation, can determine the accessibility of water resources by plants (Zhang et al., 2001, 2004). However, most of these findings were made at selected sites, and therefore represent only the situation for plots in specific ecosystems, and not across the wider-scale heterogeneous landscape.

Spatially continuous maps of ET at a regional scale have been produced by incorporating satellite remote sensing imagery (Jung et al., 2010; Ryu et al., 2011). The methodology for deriving an “ET map” is still being advanced, from empirical/statistical approach using vegetation indices (Jin et al., 2011; Lu and Zhuang, 2010; Nagler et al., 2005) which would be limited in site-specific and incomplete understanding of biophysical process, to the process-based models (Miralles et al., 2010; Mu et al., 2011; Ryu et al., 2011) which would be possible for the geospatial analysis of controlling factors across atmosphere, soil and vegetation. Advances in the spatial and temporal resolution of the regional ET estimates can be accomplished by using Moderate-resolution Imaging Spectroradiometer (MODIS) satellite data. The MODIS imagery from Terra or Aqua platforms, provided with less than 1-km spatial resolution and 1–8 daily revisit frequency since 2000 (Masuoka et al., 1998), is a potential data resource for the monitoring of inter- and intra-annual variability of regional ET (Jin et al., 2011; Lu and Zhuang, 2010; Mu et al., 2011). Thus, these advantages of process-based ET estimation using MODIS data should be highlighted in the regional water cycle assessment at monthly to yearly time scales, in relation to P extremes.

The goal of this study was to assess the seasonal and interannual variability of ET at a basin scale, in extremely large and small-P years. Using the remote sensing and process-based model for regional ET estimation, we attempted to identify the temporal and spatial characteristics of variations in ET in response to abnormal P. The driving factors resulting in changes to ET were analyzed in terms of various climatic, vegetation and catchment features. Furthermore, the implications of the variability in ET for the regional water-energy balance are discussed.

2. Materials and methods

2.1. Study site

The Youngsan River is one of the four major rivers in South Korea, and its river basin (3469 km^2) was selected for this study because of its importance for regional water-resource management (Fig. 1). This region is under the East Asian Monsoon climate, characterized by intensive, long periods of rainfall during the summer season (Hong and Kim, 2011; Kang et al., 2009). Coniferous, deciduous and mixed forests dominate the landscape (45% of the land cover) and cultivated areas—including paddy fields and crop land—occupy 37% of the region (Fig. 1), emphasizing the role of ET in the regional water cycle. To analyze the regional water balance (Section 2.6), we selected four watersheds in the upper basin (2154 km^2) according to the riverflow discharge (Q) monitoring sites in Fig. 2: Gwangju (Watershed A, 493 km^2), Seonam (Watershed B, 564 km^2), Nampyong (Watershed C, 664 km^2), and Youngsan-po (Grand upper basin, 2154 km^2). The annual Q at each

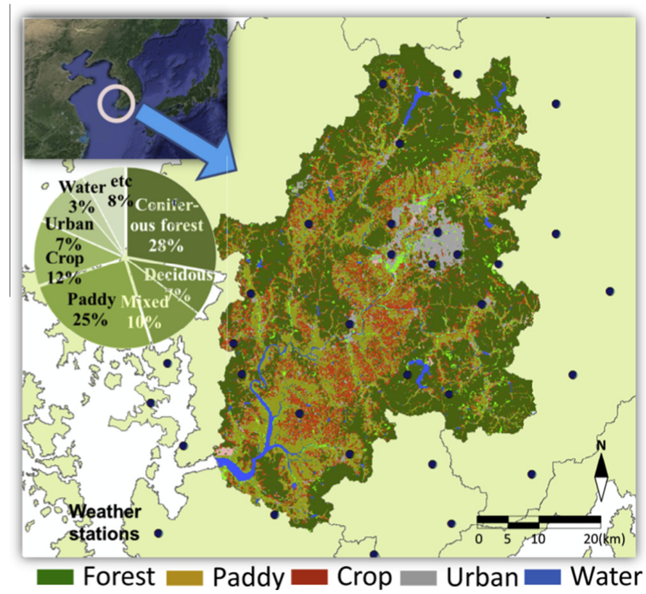

Fig. 1. Study site and land use. The upper-left and lower-right coordinates of the panel are 35°37′27.54″N, 126°14′22.74″E and 34°44′02.86″N, 127°14′39.33″E, respectively.

watershed was estimated from daily flow-rate records (WAMIS, 2013).

2.2. Study periods and annual precipitation (P) anomalies

To identify “normal” and “extreme” P periods, we computed the standard scores (i.e., $z = (x - \mu)/\sigma$; where μ and σ are the mean and standard deviation of the population (see Fig. 3) of annual P, from long-term (1973–2011) annual P records at nine meteorological monitoring stations within the Youngsan River basin. In the recent period (2002–2009), which was covered by the Breathing Earth System Simulator (BESS, see Section 2.4) output using MODIS, we selected the following periods as a benchmark of abnormal weather conditions: 2003 as an abnormally large-P year (1879 mm, $z = 1.8$), 2008 as an abnormally small-P year (958 mm, $z = -1.4$), and the average of 2005, 2006 and 2009 as a normal P year (1282, 1411, and 1330 mm; the z-values were close to 0 at -0.3, 0.2, and -0.1, respectively). The study periods included not only the selected extreme P years but also continuous trends in P from 2002 to 2009, for the analysis of interannual ET variation and water balance (Section 2.6).

2.3. Meteorological dataset

An annual P distribution map was derived from the P data recorded at the 40 locations in the study area (Fig. 1) (Korea Meteorological Administration, 2012), by interpolating the point-based observations using an inverse distance weighted technique (Watson and Philip, 1985). Additionally, we used the daily records of solar radiation, rainfall, wind speed, air temperature and vapor pressure measured at the nine meteorological monitoring stations (Korea Meteorological Administration, 2012) to identify the climatic characteristics of P extremes (Section 2.6).

2.4. Mapping ET based on BESS

The spatial distribution of daily based ET from canopy and soil surfaces was estimated at a 1-km × 1-km spatial resolution using BESS (Hendrix et al., 2013; Ryu et al., 2011). This model is designed