Global and Planetary Change 143 (2016) 10–20

Contents lists available at ScienceDirect

Global and Planetary Change

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

An agricultural drought index to incorporate the irrigation process and reservoir operations: A case study in the Tarim River Basin

Zehua Li [a,b], Zhenchun Hao [a], Xiaogang Shi [c,*], Stephen J. Déry [d], Jieyou Li [a], Sichun Chen [a], Yongkun Li [e]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China
[b] Guangdong Hydropower Planning and Design Institute, Guangzhou 510635, China
[c] CSIRO Land and Water, Canberra 2601, Australia
[d] University of Northern British Columbia, Prince George, British Columbia V2N 4Z9, Canada
[e] Beijing Water Science and Technology Institute, Beijing 100048, China

ARTICLE INFO

Article history:
Received 26 January 2016
Received in revised form 9 May 2016
Accepted 22 May 2016
Available online 25 May 2016

Keywords:
Agricultural drought index
Tarim River Basin
Irrigation process
Reservoir operation
Soil moisture
Hydrologic model

ABSTRACT

To help the decision making process and reduce climate change impacts, hydrologically-based drought indices have been used to determine drought severity in the Tarim River Basin (TRB) over the past decades. As the major components of the surface water balance, however, the irrigation process and reservoir operations have not been incorporated into drought indices in previous studies. Therefore, efforts are needed to develop a new agricultural drought index, which is based on the Variable Infiltration Capacity (VIC) model coupled with an irrigation scheme and a reservoir module. The new drought index was derived from the simulated soil moisture data from a retrospective VIC simulation from 1961 to 2007 over the irrigated area in the TRB. The physical processes in the coupled VIC model allow the new agricultural drought index to take into account a wide range of hydrologic processes including the irrigation process and reservoir operations. Notably, the irrigation process was found to dominate the surface water balance and drought evolution in the TRB. Furthermore, the drought conditions identified by the new agricultural drought index presented a good agreement with the historical drought events that occurred in 1993–94, 2004, and 2006–07, respectively. Moreover, the spatial distribution of coupled VIC model outputs using the new drought index provided detailed information about where and to what extent droughts occurred.

1. Introduction

As an environmental disaster that can occur in all climatic zones and then cause significant socio-economic losses, droughts have been receiving much more attention from scientists and decision makers. Furthermore, the drought impacts are being aggravated by the rise in water demand and the variability in hydro-meteorological variables due to climate change (Mishra and Singh, 2010). Drought events are identified by their duration, magnitude and severity (Dracup et al., 1980). An agricultural drought is considered to begin when the soil moisture availability to plants drops to such a level that it adversely affects the crop yield and agricultural production (Martínez-Fernández et al., 2015). Quiring and Papakryiakou (2003) concluded that it was important to select an appropriate agricultural drought index for quantifying/monitoring agricultural drought, predicting yield, or determining drought insurance/drought assistance. Soil moisture is found to be a good indicator of droughts and floods using a hydrological model (Lakshmi et al., 2004). Owing to the general scarcity and high heterogeneity of soil moisture measurements, most of the agricultural drought indices are derived from soil moisture deficiency based on a combination of precipitation and air temperature (Palmer, 1965, 1968). Recently, these drought indices have been significantly improved by using hydrologic or/and land surface models, which can represent well the effects of topography, soil and vegetation on surface water fluxes through the landscape (Sheffield et al., 2004; Andreadis et al., 2005; Andreadis and Lettenmaier, 2006; Narasimhan and Srinivasan, 2005; Luo and Wood, 2007; Hao et al., 2014; Mo and Lettenmaier, 2014; Xia et al., 2014). However, as the essential parts of agricultural practices, the artificial irrigation and reservoir operations are widely used to assist in the growth of crops, maintenance of landscapes, and revegetation of disturbed soils in dry areas and during periods of inadequate rainfall (Mishra and Singh, 2010). Thus the soil moisture in irrigated areas relies not only on local precipitation but also the withdrawal of water from upstream regions and reservoirs when available (Jackson et al., 2001). Notably, this kind of impact seems more important in China where large dams are being built increasingly (ICOLD, 2003). Therefore, hydrologic and/or land surface models, including the irrigation process and reservoir operations, can assist interpreting the real agricultural drought conditions. Haddeland et al. (2006a)

---

[*] Corresponding author.
E-mail address: Xiaogang.Shi@csiro.au (X. Shi).

http://dx.doi.org/10.1016/j.gloplacha.2016.05.008
0921-8181/© 2016 Elsevier B.V. All rights reserved.

investigated the effects of irrigation on the water and energy balances in the Colorado and Mekong river basins using a land surface hydrologic model. Within the model, an irrigation scheme based on the simulated soil moisture deficit and streamflow was included to predict irrigation water demands and actual water withdrawals. Compared to other approaches (de Rosnay et al., 2003; Boucher et al., 2004; Fekete et al., 2010), the model takes into account the effects of dams using a reservoir module, and hence water can be stored for later use. Thus the model has been successfully implemented to reproduce irrigation effects on surface water fluxes at the continental and global scales (Haddeland et al., 2006a, 2006b, 2013). The irrigation scheme of the model was further improved to represent water supply efficiency and successfully applied to assess the irrigation impact on surface water fluxes in the TRB (Hao et al., 2015).

In this study, we develop a new agricultural drought index. Compared to other agricultural drought indices, the major difference is that we take into account the effects of the irrigation process and reservoir operations, as both of them are important components of the surface water balance and can dominate drought evolution in the TRB. The evaluation and analysis are based on the soil moisture derived from a long-term retrospective simulation of a physically-based land surface hydrologic model. In addition, we use the above new method to quantitatively assess drought conditions over space and time for the study area. Section 2 describes our study area and Section 3 describes the methods we used. The results for this study are presented in Section 4 and the corresponding discussion is in Section 5. The conclusions are summarized in Section 6.

2. Study area

The 1321-km-long Tarim River is the longest inland river in China and the main water source for the Tarim River Basin (TRB). The TRB comprises the entire southern part of the Xinjiang Uyghur Autonomous Region and is bordered by the Tianshan, Pamir and Kunlun mountain ranges. As the surrounding mountains cut off all humid air currents from the Indian and Atlantic Oceans, the climate in the TRB is extremely arid. The long-term mean annual precipitation is less than 100 mm (Tao et al., 2011; Hao et al., 2015). In addition to the alpine rainfall, snow and glacier melt largely contribute to the runoff of the Tarim River (Yang and Zeng, 2001). Irrigation agriculture has been concentrated in the oasis along the foothills of the mountains. The oases were steadily enlarged and opened to agriculture along the upper and lower reaches of the Tarim River from the 1950s until the 1990s. Cotton became the major crop and resulted in increasing water demands in Xinjiang (Thevs, 2011). Due to the extremely arid climate, the agriculture in the TRB highly depends on irrigation facilities (e.g., dams), which were constructed to store and provide water flowing from the mountains (Zhou et al., 2000).

The TRB with an area over 1 million km^2 is the largest continental river basin in China (Fig. 1). The headwater streams within the TRB are supplied by snowmelt, glacier melt and summer rainfall in the Kunlun, Pamir and Tianshan Mountains (Yang and Zeng, 2001). Snowmelt largely contributes to the spring-time runoff of the Tarim River (Song et al., 2000). During the late summer, when the temperature in the high mountains rises, glacier melt water and alpine rainfall become the major sources of runoff (Yang and Zeng, 2001). Three-quarters of the annual runoff are concentrated in the summer season in the TRB (Song et al., 2000).

In the past, there were nine water systems flowing into the main stem of the Tarim River. With intensifying human activities, especially the exploitation of water resources, great changes have taken place in recent decades. Only three water systems still have the natural hydraulic relationship with the main stem, including the Aksu River, Hotan River and Yarkant River. The Hotan River usually dries up during most of the year as indicated in Fig. 1. The Kaidu River transports water to irrigation areas in the lower reaches of the Tarim River from Bosten Lake when necessary. These four rivers form the headwater streams that feed the Tarim River and play an important role in agricultural production, socio-economic development and ecological conservation in the TRB (Chen et al., 2009). To satisfy the increasing requirements for irrigation, a series of storage projects were constructed in past years. Most of them were built in the depression and the lower part of the alluvial plains (Hao et al., 2015). Meanwhile, cultivated lands were also reclaimed or expanded rapidly during the period (Fan et al., 1998).

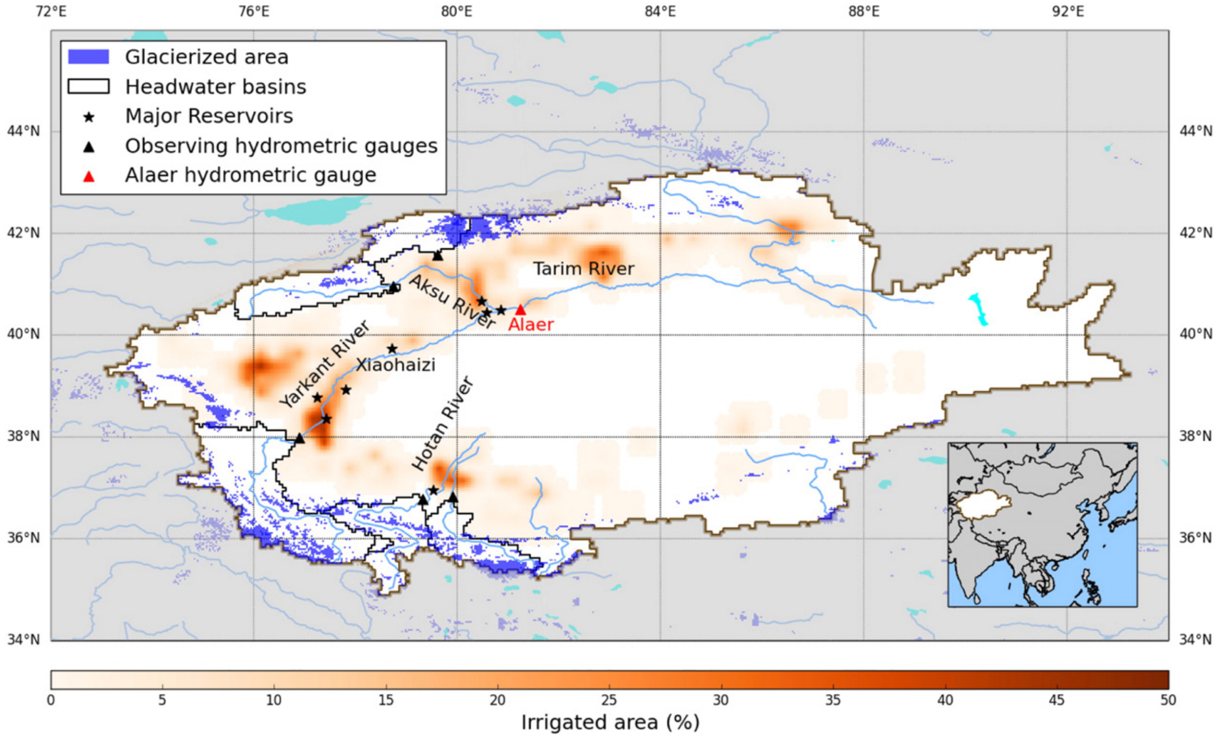

Fig. 1. Tarim River Basin with the location of hydrometric gauges and major reservoirs. The colorbar shows the percentage of the irrigated area.