Ecological Indicators 69 (2016) 422–433

Contents lists available at ScienceDirect

Ecological Indicators

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

Development and implementation of a spatial unit non-overlapping water stress index for water scarcity evaluation with a moderate spatial resolution

Qiuwen Zhou[a,b], Shengtian Yang[a,*], Changsen Zhao[a], Mingyong Cai[a,c], Hezheng Lou[a], Ya Luo[a,b], Lipeng Hou[a]

[a] School of Geography, Beijing Normal University, State Key Laboratory of Remote Sensing, Beijing Key Laboratory for Remote Sensing of Environment and Digital Cities, 100875 Beijing, People's Republic of China
[b] School of Geography and Environment Science, Guizhou Normal University, 550001 Guiyang, People's Republic of China
[c] Satellite Environment Center of MEP, 100094 Beijing, People's Republic of China

ARTICLE INFO

Article history:
Received 10 July 2015
Received in revised form 29 April 2016
Accepted 4 May 2016
Available online 22 May 2016

Keywords:
Water scarcity
Spatial unit non-overlapping
Hyper-resolution
Yarlung Tsangpo-Brahmaputra River

ABSTRACT

Water scarcity is a serious global problem, and accurate estimations are urgently needed. The Water stress index (WSI) is one of the most commonly used methods for global or large scale water scarcity evaluation, but this method lacks of consideration of water demand and water supply positions non-overlapped spatial distribution, tends to overestimate water stress when applied to a moderate resolution grid (e.g., 1 km). In this study, we used a non-overlapping water supply-and-demand unit approach to improve the calculation scheme and constructed a spatial unit non-overlapping WSI model (Sun-WSI model). We then applied the new model to the Yarlung Tsangpo-Brahmaputra River (TBR) and estimated monthly water stress from 2006 to 2012 with a 1 km spatial resolution. The results showed that the determination coefficient (R^2) between the normalized Drought Index (DI) and water stress was mainly in the range of 0.2–0.7, accounting for 77.4% of the study area. The spatial pattern of water stress estimated by the Sun-WSI model was consistent with the DI. Further analysis showed that both overall and grid water stress estimated by the Sun-WSI model were close to the results from existing studies; however the Sun-WSI model had a higher spatial resolution. With a 1 km resolution, the Sun-WSI model performed better than the conventional WSI with respect to both overall results and spatial details. This suggests that the Sun-WSI model is suitable for evaluating regional or moderate-resolution grid water scarcity.

1. Introduction

Freshwater resources are a major requirement for food security, public health, ecosystem protection, and human well-being (Setegn et al., 2014). In 1900, the global population was less than 1.7 billion, but it has grown by more than four times in the 20th century, and currently exceeds 7 billion (WadaWisser and Bierkens, 2014). To sustain growing food demands and increasing standards of living, global water withdrawal increased at a rate of 17% per decade between 1960 and 2000 (Vörösmarty et al., 2005). As a result, meeting the consumptive and non-consumptive water needs with available freshwater resources is now a global challenge (Setegn et al., 2014).

Hydrology as a scientific discipline traces its roots to the service of society (Wood et al., 2011). Most studies have dedicated hydrological models (including other water resources related models) to support water resources management and planning as well as operational forecasting (Chau and Wu, 2010; Gholami et al., 2015; Taormina and Chau, 2015). But most models can only be applied at rather coarse spatial resolutions regardless of their global, continental, or basin domains (~10–100 km over continental to global domains). The hydrology field thus faces an important challenge in developing hyper-resolution hydrological prediction capabilities. These efforts are rendered more difficult by the daunting modeling, computational, and data requirements (Wood et al., 2011; Bierkens et al., 2015). As a result of scientific and technological development, it has been increasingly possible to "spur the development of next-generation models that can readily exploit recent advances in computing power and structure, the Internet, and access to very high-resolution data" (Famiglietti et al., 2009). Water scarcity assessment is a tool for water resources management, and

---

* Corresponding author. Tel.: +86 13910109986.
E-mail address: yangshengtian@bnu.edu.cn (S. Yang).

http://dx.doi.org/10.1016/j.ecolind.2016.05.006
1470-160X/

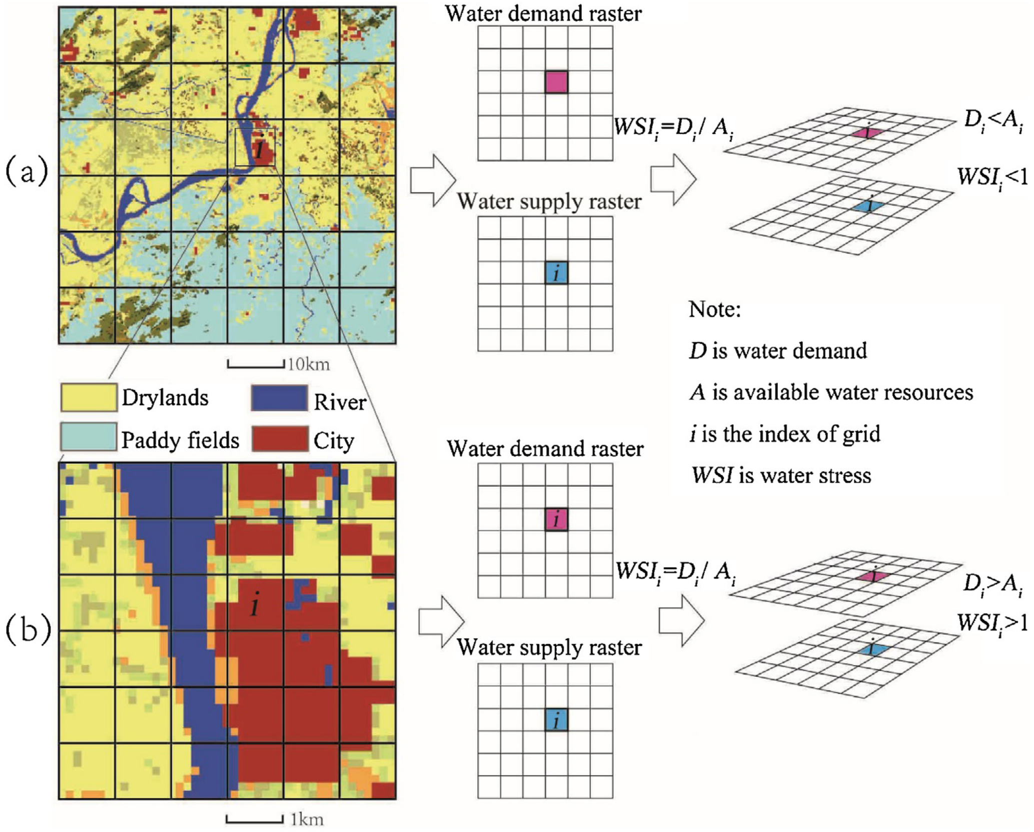

Fig. 1. Schematic of WSI calculation using an overlapping water supply and demand units scheme and the results of a large grid (a) and a small grid (b).

it is also important as an application for hydrological models. Thus, finer resolution in water scarcity assessment modeling is a critical component of hyper-resolution hydrological modeling.

In several studies, a typical, direct WSI was adapted to evaluate water scarcity, in which simulated available water resources were compared with estimated water demand. An early form of the WSI is the Falkenmark index. This index measures water scarcity through per capita water resources, and it determines their critical value according to the demand for water resources in medium developed countries in arid areas (Falkenmark, 1989). Although per capita water resources are a rough estimate of water scarcity, the measure does not take into account the differences in demand across a range of areas. In order to solve this problem, Raskin et al. (1997) proposed a criterion using the ratio of water demand to available water resources (water stress) to measure water scarcity, with water stress being divided into four levels: no stress (0–0.1), low stress (0.1–0.2), moderate stress (0.2–0.4), and high stress (>0.4) (Raskin et al., 1997).

WSI has been widely applied in both global and regional water scarcity evaluations (Oki et al., 2001; Vörösmarty et al., 2005; Collet et al., 2013; Vandecasteele et al., 2014; Boithias et al., 2014). Early on, WSI was applied over a long time period, which could be one year or the average of many years, in a lumped spatial unit, such as an administrative region or basin (Alcamo et al., 2003; Kummu et al., 2014). In recent years, the time scale has been refined to a month or less (Hoekstra et al., 2012; Voisin et al., 2013). The spatial scale, mainly grid cells used for spatially distributed WSI computing, typically covers a large area (Hoekstra et al., 2012; Vandecasteele et al., 2014; Schlosser et al., 2014). Furthermore, the WSI also has been recently coupled to some hydrological models (Gosling and Arnell, 2013; Menzel and Matovelle, 2010; Hejazi et al., 2013; Hanasaki et al., 2013; Wada et al., 2014a,b; Vörösmarty et al., 2010).

Currently, WSI is for the most part applied in large-scale water stress calculations (e.g., 0.5° or 1° grid) and has achieved good results (Islam et al., 2007; Hanasaki et al., 2008; Van Beek et al., 2011). However, when WSI is applied at a higher spatial resolution (e.g., 1 km grid), the results may not be as reliable and tend to reflect a significantly higher degree of water stress. This is because distributed (grid) water stress still adopts the conventional WSI calculation method (hereafter called WSI model). In the conventional WSI model, the water stress of grid *i* is equal to the water demand of grid *i* divided by its available water resources. This approach is characterized by overlapping water supply-and-demand units (Fig. 1a). The available water resources of grid *i* equal the grid's discharge, lacking of the consideration of water demand and water supply positions non-overlapped spatial distribution. When this scheme is applied to medium-resolution (e.g., 1 km) or high-resolution grids, the available water resources of the grid may be confined to a small area. This means that a grid can be extremely limited in water resources even though neighboring grids have plenty of water that in reality is often easy to access (by pipes, channel, etc.). In the real world, people usually obtain water several kilometers from their house, city, or farmland. However, the WSI model uses overlapping water supply-and-demand units and cannot simulate the allocation of water to grid *i* from an adjacent grid when applied to medium or high-resolution grids, and this can greatly underestimate water stress.

Accordingly, we constructed a spatial unit non-overlapping WSI model (Sun-WSI model) using non-overlapping water supply-and-demand units in which available water resources of grid *i* are not confined to discharge in grid *i* but also include neighboring water supplies while taking into account current levels of economic and technological development that may affect how water is used and transported. This new model allows the calculation of water stress within a medium-resolution grid cell, and may not