Ecological Indicators 86 (2018) 58–66

Contents lists available at ScienceDirect

Ecological Indicators

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

Effective use rate of generalized water resources assessment and to improve agricultural water use efficiency evaluation index system

Xinchun Cao[a,b,c], Jie Ren[b], Mengyang Wu[b], Xiangping Guo[b,c], Zhenchang Wang[b,c], Weiguang Wang[a,b,*]

[a] *State Key Laboratory of Hydrology Water Resources and Hydraulic Engineering, Hohai University, Nanjing, Jiangsu 210098, China*
[b] *College of Water Conservancy and Hydropower, Hohai University, Nanjing, Jiangsu 210098, China*
[c] *Key Laboratory of Efficient Irrigation-Drainage and Agricultural Soil-Water Environment in Southern China of Ministry of Education, Hohai University, Nanjing, Jiangsu 210098, China*

ARTICLE INFO

Keywords:
Indicator
Water use efficiency
Blue-green water
Evapotranspiration
China

ABSTRACT

Efficient utilization of water resources contributes to regional food, water and ecological security. An indicator, generalized efficiency (GE), was established based on a blue-green water framework for evaluating regional effective use of water resources. GE is defined as the ratio of total water consumption (TWC) to total water inflow (TWI) into an agricultural production system over a single year. Then, the spatial pattern of GE in the irrigated, rain-fed and total cropland of China in 2010 was analysed based on the quantification of provincial TWI and TWC, taking grain production as a case study. The results show that TWI in China was approximately 978.6 Gm^3, of which rain water was close to 70.0%; national TWC was approximately 577.5 Gm^3 in the study year, including 72.0% green and 28.0% blue water; and rain-fed cropland made up approximately 33.0% of the TWI and TWC. The spatial distributions of TWI and TWC per unit arable land differs greatly; national GE in irrigated, rain-fed and total cropland were 0.584, 0.603 and 0.590, respectively; and regional rain-fed GE was larger than that in irrigated farmland due to the uneven distribution of precipitation. This work expanded the applicability of evaluation of effective use rate of water resources from blue water and irrigated cropland, to generalized water resources and any designated region. GE cannot be replaced by other exciting indicators in either scientific connotation or spatial distribution. Hence, the establishment of GE is a more advanced agricultural water use efficiency evaluation indicator system.

1. Introduction

The issue of water shortage has been increasingly perceived as a global systemic risk (Bakker, 2012; Sun et al., 2016). Accounting for approximately 80% of the total water withdrawal, agriculture is the sector with the largest utilization of water resources worldwide. Meanwhile, more than 9000 G m^3 of water is directly and indirectly consumed by humans each year, of which agricultural production contributes approximately 92% (Hoekstra and Mekonnen, 2012). The improvement of agricultural water use efficiency has contributed to regional water, food and ecological security (Piao et al., 2010; Falkenmark, 2013). The water resources demand of all of society will increase with population growth, urbanization and changes in the structure of consumption (Cao et al., 2017a). However, the supply of water resources is unlikely to increase, subject to the shortage of water resources. Therefore, improving water use efficiency, especially in the agricultural production, is the only way to ensure the sustainable use of water resources, with the establishment of a complete water resources efficiency evaluation indicator system as the basic premise.

Theories and methodologies to evaluate agricultural water use performance have become a focus of water resources and environmental management research (Rodrigues et al., 2010; Wang et al., 2015a,b). Two categories of parameters, irrigation efficiency (IE) and water productivity (WP), are currently used to evaluate water use efficiency in agricultural production systems (Table 1). Taking blue water and irrigated cropland\system as research objects, IE was used for the effective ratio of irrigation water withdrawal evaluation. It can be expressed by various indicators, such as classical irrigation efficiency (IE_c) and net or effective irrigation efficiency (IE_n and IE_e) (Jensen, 2007; Scott et al., 2013). Classical irrigation efficiency was defined as the ratio of irrigation water consumed by the crops of an irrigated farm or project to the water diverted from a river or other natural water source into the farm project canal or canals (Israelsen, 1932; Bruce, 2012). Classical efficiency concepts have ignored the irrigation water return

* Corresponding author at: State Key Laboratory of Hydrology Water Resources and Hydraulic Engineering, Hohai University, Nanjing, Jiangsu, 210098, China.
E-mail addresses: caoxinchun@hhu.edu.cn, wangweiguang@hhu.edu.cn (W. Wang).

https://doi.org/10.1016/j.ecolind.2017.12.016
Received 1 August 2017; Received in revised form 4 December 2017; Accepted 5 December 2017
Available online 11 December 2017
1470-160X/

Table 1
Documented water use efficiency evaluation indicators in crop production systems.

Parameter	Indicator	Object	Calculation approach	Main references
Irrigation efficiency	Classical irrigation efficiency (IE)	Blue water and irrigated cropland/system	ET_b/IWW; IWW: irrigation water withdrawal ET_b: irrigation (blue) water evapotranspiration	Israelsen (1932); Bos (1980); Yilmaz et al. (2009); Bruce (2012)
	Net or effective irrigation efficiency (IE_n, IE_c)	Blue water and irrigated system	IWU_e/IWW IWU_e : effective use of irrigation water	Solomon and Davidoff (1999); Wallender and Grimmer (2002)
Water productivity	Crop water productivity (CWP)	Generalized water and any designated cropland	Y/ET or Y/CWR; Y: harvestable crop yield ET: field evapotranspiration; CWR: crop water requirement	Molden (1997); Abdullaev and Molden (2004); Zwart and Bastiaanssen (2004); Yang et al. (2015)
	Water use efficiency (WUE)	Generalized water and any designated cropland	Similar to CWP	Mishra et al. (2001); Aujla et al. (2005); Karaba et al. (2007); Singh et al. (2014)
	Generalized water productivity (GWP)	Generalized water, any designated cropland or region	Y/(IWW + P_e); P_e: efficiency precipitation	Playán and Mateos, (2006); Mainuddin and Kirby (2009); Cao et al. (2015a)
	Gross inflow water productivity (GIWP)	Generalized water, any designated region	Y/(IWW + P_e) P: precipitation	Dong et al. (2004); Hafeez et al. (2007); Cao et al. (2015a);
	Irrigation water productivity (IWP)	Blue water and irrigated land	Y_I/IWU or Y_I/IWC Y_I: harvestable yield in irrigated cropland	Wokker et al. (2014); Cao et al. (2015a)
	Rain-fed water productivity (RWP)	Green water rain-fed cropland	Y_R/P_e; Y_R : harvestable yield in rain-fed cropland	Oweis and Hachum (2006); Cooper et al. (2008); Cao et al. (2015b)
	Consumptive crop water footprint (CWF)	generalized water and any designated region	(P_e + ET_b + DWR)/Y DWR: dilution water requirement	Mekonnen and Hoekstra (2014); Cao et al. (2014), (2017b); Marano and Filippi (2015); Zhuo et al. (2014) 2016; Wang et al. (2015a,b)

flows that re-enter the water supply, and effective irrigation efficiency refers to the crop consumptive use of applied irrigation water divided by the effective use (Keller and Keller, 1995; Qureshi et al., 2011). Irrigation water withdrawal, water application efficiency, evapotranspiration (ET), water consumption, return flow and net depletion (Jensen, 2007; Bruce, 2012) are closely related to IE assessments. Water productivity, which was originally defined by Molden (1997), is used to measure the relationship between crop yield and the amount of water involved in the process of crop production and is expressed as crop production per unit volume of water resources (Kijne et al., 2003; Xiao et al., 2013; Ali and Klein, 2014; Azad et al., 2015). The objective of water use efficiency evaluation has shifted from blue water and irrigated farmland to generalized water resources, including blue and green water and regional total cropland. The numerator is defined as the crop production gained per volume of water resources input. According to the water input options, the water productivity (WP) can be expressed as crop water productivity (CWP), water use efficiency (WUE), generalized water productivity (GWP), gross inflow water productivity (GIWP), irrigation water productivity (IWP) and rain-fed water productivity (RWP) (Table 1) (Playán and Mateos, 2006; Pereira et al., 2012; Cao et al., 2015a,b; Jägermeyr et al., 2015). CWP, WUE, GWP and GIWP take the use of both blue and rain water in agricultural production processes into account for water production capacity evaluation. The study area for these indicators is not limited, and could be irrigated farmland, rain farmland or arbitrarily designated. IWP and RWP simply select irrigation and rain water as inputs and applied them alone for irrigated and rain-fed farmland.

The indicator, the crop water footprint, for crop production and water resources relationship description is also listed in Table 1. The water footprint of a crop product is defined as the volume of fresh water that is consumed during the crop production process (Hoekstra and Chapagain, 2011; Wang et al., 2015b). Normally, the crop water footprint has three components: blue, green and grey water footprints (Hoekstra et al., 2011; Cao et al., 2017b; Zhuo et al., 2016). The sum of blue and green water footprints, which is called the consumptive water footprint, is closely related to irrigation, precipitation, crop water requirement and water use efficiency (Wang et al., 2015a; Cao et al., 2018). From the calculation method, there is no difference between the reciprocal of the crop consumptive water footprint and the WP when it is used for agricultural water resources use efficiency evaluation (Wang et al., 2015a).

Water use efficiency can be assessed comprehensively by allying IE and WP, while the current indicators are limited to irrigated farmland. In reality, an observed region (administrative unit or river basin) includes irrigated area and the farmland without irrigation, frequently. In addition, rain water is the main source of water resources for crop field evapotranspiration. It is of great importance to improve the sustainable utilization of regional water resources by increasing the effective utilization of water resources in the total farmland, including both irrigated and rain-fed cropland. However, we cannot simultaneously reveal the utilization coefficient and production capacity of water input by using the existing indicator when the observation object contains both irrigation and rain farmland. How to measure the effective use of water in any given area is the current gap in the knowledge. Based on the framework of blue-green water, the objectives of this paper are to: 1) establish a new index, generalized efficiency (GE), for the utilization coefficient of generalized water resources evaluation; 2) quantify the provincial GE value for China, taking the grain production in 2010 as a case study; and 3) explore the spatial pattern of GE and its discrepancy with existing indicators. These objectives provide the structural subheadings used in the following Methods, Results and Discussions sections.