Journal of Cleaner Production xxx (2016) 1–7

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Methodology development for including environmental water requirement in the water stress index considering the case of Thailand

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ARTICLE INFO

Article history:
Received 14 January 2016
Received in revised form
21 November 2016
Accepted 22 November 2016
Available online xxx

Keywords:
Environmental water
Water stress index
Freshwater resources
Thailand

ABSTRACT

Environmental water requirement is important for a river or a watershed to maintain the ecosystem functions and services. Thus, it needs to be an essential component in water demand calculations for maintaining water resources. This study proposes to explicitly account the environmental water as a part of water withdrawal in the withdrawal to availability ratio of the water stress index. A revised equation is formulated and calibrated using Thailand as an example. This incorporation allows flexibility in changing different amounts and setting different priorities of environmental water requirement based on a local context. The results obtained are satisfactory for explaining the actual stress situation incorporating environmental water requirement. The method and approach proposed in this paper can also be applied to other countries based on their priorities for water allocation to various water demand sectors. This paper is proposed as a step towards developing a sustainable tool for assessing the impact on freshwater resources.

1. Introduction

Water scarcity has become an issue of concern in many countries where there are situations of insufficient water to satisfy all demands all the year round or seasonally (IHP, 2011). This crisis affects not only human activities but also environmental functions. More serious is a concern about overuse of freshwater resources that which may result from both from increasing of demands for water or lacking of water supply. Areas where water is insufficient to satisfy all the existing demands tend to be under water stressed conditions. Also, if future demands for water is expected to increase and future water supply may not be able to meet this increasing demand, it will lead to put additional stress or pressure on freshwater resources accordingly. In 2015, Thailand faced the worst drought in 15 years and the farmers cultivating dry season crops especially in Chao Phraya and Mae Klong watersheds were the first group suffering from the direct impacts of drought (Teerawiroon, 2015). In accordance with the statistical data during 1992–2011, 51–60 provinces underwent drought in the dry season, especially in the northeastern region. Some of these drought periods, for example in 2010, were affected by El Niño events (OAE, 2010; TMD, 2010). In particular, agricultural areas in 42 provinces were affected by drought during 2003–2007 (DWR, 2012; LDD, 2013; Mapraneat, 2014; DOAE, 2014). However, more recently, there has been more awareness on this concern and it has been receiving more attention with development of indicators for measuring the stress or impact on freshwater resources from freshwater use. The water stress index (WSI) developed by Pfister et al. (2009) has been used as it is one of the more accepted methods and widely applied in many studies, including Thailand (Gheewala et al., 2013, 2014). Several studies related to individual food product such as milk and dairy farming (De Boer et al., 2013; Zonderland-Thomassen and Ledgrad, 2012), tea and margarine (Jefferies et al., 2012), wine (Quinteiro et al., 2014), tomato (Page et al., 2011, 2012), fruits and vegetables (Stoessel et al., 2012) or an agricultural crop such as cassava, maize, corn (GIZ, 2013; Jeswani and Azapagic, 2011) have used this method. All these case studies revealed that cultivation is the most water intensive process of food and agricultural crop production. As a result, a nexus of food, feed, and fuel crops such as rice, cotton, maize and sugarcane is taken into consideration by studies of Pfister et al. (2011), Nunez et al. (2012) and Gheewala et al. (2013). Other than these applications, the WSI has also been applied for the

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http://dx.doi.org/10.1016/j.jclepro.2016.11.130
0959-6526/

Please cite this article in press as: Nilsalab, P., et al., Methodology development for including environmental water requirement in the water stress index considering the case of Thailand, Journal of Cleaner Production (2016), http://dx.doi.org/10.1016/j.jclepro.2016.11.130

assessing environmental impacts of water supply alternatives and water use of a particular area such as Segura Basin in the southeast of Spain (Uche et al., 2014, 2015). In addition to the studies on the WSI application, studies have also been conducted on the method development (Ridoutt and Pfister, 2013; Hospido et al., 2013). This index is derived from quantitative thresholds with reference to reduced water availability from withdrawal. It is also accounted as a water scarcity index based on the ISO 14046 (Boulay et al., 2014) and can be used as a characterization factor for a water deprivation impact based on life cycle assessment (LCA) methodology, an decision making tool to assess environmental sustainability.

Basically not only humans need water for satisfying their demands, but water is also required by the environment, especially a river or a watershed system, to maintain its functions and ecosystem services. The environmental water has become an important issue at every level: global, regional, national and local, in order to maintain the values and benefits of a river or watershed. This environmental water is affected by overuse of freshwater resources as well as water scarcity (Navarro-Ortega et al., 2015) and it requires a concern at different scale of analysis from large to small (Smakhtin, 2002). The environmental water requirement (EWR) appears to have been concerned at a global scale when the study of Smakhtin et al. (2004) suggested that EWR needs to be addressed seriously in water resources management and development. In addition, in some countries such as the United States (some parts), Australia, South Africa, India, Thailand, etc., a concern of EWR has been taken into consideration in policy and management contexts to protect their natural water resources (Davis et al., 2001; RID, 2011a; Venot et al., 2008). Hence environmental water legislation is regulated to ensure that available freshwater must remain in a river (Pimentel et al., 2004). As a result, the total demands for water, including for humans and the environment, must be accounted in order to ensure that the impact on freshwater resources are equitably and consistently assessed. In the case of Thailand, allocating water to all users and setting priorities for water allocation are under the Royal Irrigation Department (RID) which considers EWR as one of the water demand sectors (RID, 2011a).

The concern of environmental water is implicitly included in the WSI metric of Pfister et al. (2009) as it is accommodated in the values of the water stress thresholds. However the EWR term is not taken into account separately and explicitly in this method. Thus, it is the same for the case of the country WSI for Thailand which followed Pfister's method (Gheewala et al., 2013; 2014). As the regulation of EWR defined by RID varies based on the environmental conditions, using constant threshold values as in Pfister's method may tend to take a conservative approach and sometimes lead to overestimation of water stress. Consequently this study attempts to emphasize the importance of the EWR by explicitly accounting the EWR in the country WSI. This revised approach will help ensure confidence in how much freshwater can be extracted sustainably without causing damage to the ecological system. Accordingly, this approach can be used as decision support in evaluating cleaner production.

2. Methodology

2.1. The water stress index of Pfister et al. (2009)

The WSI of Pfister et al. (2009) is developed based on a logistic function in relation to a ratio of water withdrawal to water availability (WTA) as showed in Equation (1). Four significant sectors of water consumers including household, industry, agriculture, and livestock contribute to water withdrawal, and the available freshwater to supply these demands is considered based on the hydrological boundaries.

$$WSI = \frac{1}{1 + e^{-6.4WTA^*}\left(\frac{1}{0.01} - 1\right)} \quad (1)$$

where; WTA* is defined by flow regulation by dams (strong regulation flow, SRF) and without dams (non-SRF); $\text{WTA}^* = \sqrt{VF} \times \text{WTA}$ (for SRF) and $\text{WTA}^* = \text{VF} \times \text{WTA}$ (for non-SRF).

The WTA* is established in order to address variation of water availability affecting water stress level. Thus precipitation variation (variation factor, VF) and flow regulation are taken into account in Pfister's method. The flow regulated by dam leads to a decrease in the influence of VF while this influence is fully accounted for in the unregulated flow. Monthly average and annual precipitation are assumed to follow a log-normal distribution; therefore, VF is quantified from the arithmetic standard deviations of the log-transformed values of monthly and annual rainfall as expressed in this equation: $VF = e^{\sqrt{\ln(S^*_{month})^2 + \ln(S^*_{year})^2}}$.

Water stress levels of Pfister's method are defined based on threshold values of the WTA ratio ranging from 0.2 to 0.6. This range indicates a level of water stress situation from moderate to severe and the critical threshold is determined at 0.4. Values above this critical value indicate a severe water stress situation and an unhealthy freshwater ecosystem. The range of water stress thresholds is established based on expert judgement and literature with a concern on freshwater ecosystem (Alcamo et al., 2000, 2003; Pfister et al., 2009). Accordingly it can be inferred that lesser than 60% of water availability at the critical threshold cannot meet a good or fair condition of freshwater ecosystem. Although 60% of available water cannot be concluded as the total EWR, it can imply that EWR is implicitly included in the WSI via the thresholds varying from 0.2 to 0.6.

The logistic function is applied to convert the threshold values of WTA ratio into a continuous value of WSI which ranges from 0.09 to 0.91. Thus the inflection point of the logistic curve, which is at 0.5, is equivalent to the critical threshold at 0.4 of WTA ratio. Classification of WSI in relation to WTA is tabulated in Table 1.

In the revised approach, the national standard of EWR is obtained from the RID. The EWR for 25 watersheds of Thailand is assigned based on a minimum flow of a long-term runoff in order to maintain a certain water volume/flow for ecosystem health. According to the priority given by the RID, the EWR is taken into account by incorporating it in water withdrawal. To reflect this incorporation, the thresholds are redefined in relation to the EWR by keeping the same structure of the WSI function.

2.2. Environmental water requirement

The important function and purpose of EWR is to maintain a river system in desired environmental conditions for ecosystem services and human livelihoods. Therefore definition of EWR can be described in terms of a certain quantity and/or quality in relation to a time scale (Forslund et al., 2009; Boelee, 2011). Accordingly EWR can be used as indicators of not only aquatic ecosystem health but also the impact on freshwater resources. However there are various factors influencing functions and ecosystem services of a river or a watershed, stream flow and

Table 1
Water stress index (WSI) classification (Pfister et al., 2009).

WTA	WSI classification	Category
<0.2	$WSI_p < 0.09$	Low water stress
0.2 < WTA < 0.4	$0.09 \leq WSI_p < 0.5$	Moderate
0.4 < WTA < 0.6	$0.5 < WSI_p \leq 0.91$	Severe
>0.6	$WSI_p > 0.91$	Extreme

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