Water Resour Manage (2018) 32:1585–1598
https://doi.org/10.1007/s11269-017-1892-2

Method Development for Including Environmental Water Requirement in the Water Stress Index

Pariyapat Nilsalab[1,2] • **Shabbir H. Gheewala**[1,2] • **Stephan Pfister**[3]

Received: 20 June 2017 / Accepted: 27 December 2017 /
Published online: 13 January 2018

Abstract The overuse of human demand for water threatens the capacity of rivers or watersheds to retain their ecosystem services. Environmental water requirement (EWR) needs to be taken explicitly into account when assessing the impact from freshwater use on freshwater resources. Thus, we propose two perspectives for incorporating EWR into the Demand to availability (DTA) ratio of the water stress index (WSI); including it as a separate demand along with anthropogenic demands (Index 1) or reserving it from the available water (Index 2). It is expected that the more demand increases, the more pressure is put on the lowest priority sector. Index 2, by definition, gives the first priority to EWR whereas this is not so for Index 1. Thus Index 2 provides a more conservative approach in terms of the environmental protection and Index 1 allows a more flexible prioritization approach. Both these indices, however, allow flexibility of changing the EWR based on specific circumstances and context, thus making the evaluation more appropriate for water resource planning at both policy and implementation levels.

Keywords Water stress · Environmental water requirement · Freshwater · Screening indicator · Decision support

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11269-017-1892-2) contains supplementary material, which is available to authorized users.

✉ Shabbir H. Gheewala
shabbir_g@jgsee.kmutt.ac.th

[1] The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, 126 Prachauthit Rd, Bangmod, Thungkru, Bangkok 10140, Thailand

[2] Center of Excellence on Energy Technology and Environment, PERDO, Bangkok, Thailand

[3] Ecological Systems Design, Institute for Environmental Engineering, Swiss Federal Institute of Technology Zurich, John-von-Neumann-Weg 9 Rd, 8093 Zurich, Switzerland

1 Introduction

The increase of human demands for water and the issue of water scarcity inducing pressure or stress on freshwater resources is currently a serious cause of concern. In countries where freshwater resources are insufficient to meet existing demands, this situation will force the country to make a trade-off between water withdrawn for human activities and water reserved for a river or watershed system. Thus overuse or unbalance of available freshwater not only leads to water scarcity but also threatens the capacity of rivers or watersheds to provide their ecosystem services (Börkey et al. 2005; Pastor et al. 2014; Popan 2011; Smakhtin et al. 2004; Wei et al. 2008). To assess this impact on freshwater resources, the widely accepted index known as water stress index (WSI) proposed by Pfister and colleagues in 2009 has been applied in several study (Nilsalab et al. 2017). Additionally, the WSI is also accounted as a water scarcity index in the ISO 14046:2014-water footprint (Boulay et al. 2014). This is because the impact of freshwater use on freshwater resources has also been placed in the context of life cycle assessment (LCA) (Boulay 2012; Boulay et al. 2014; ISO 2014). LCA is a valuable decision-support tool in assessing potential environmental impacts of products, processes, or service throughout their life cycle. The WSI is developed based on the hydrological perspective and reflects the magnitude of water stress in different watersheds. Thus, this index is used for assessing the impact on freshwater use on freshwater resources in LCA.

The water stress depends mainly on changes in human demands for water and water availability with reference to the defined thresholds of water stress. A concern of water reserved for a watershed system called as environmental water requirement (EWR) in the WSI is implicitly accommodated in the values of water stress thresholds. The situation of water stress will be severe if human demands for water exceed 40% of the available water in a watershed. As a result, it seems like the EWR can be implicitly interpreted from the water stress levels but this term is unable to be considered in terms of different quantitative aspects as well as temporal and local context. To account for EWR in the characterization factor of freshwater resource impact is also strongly recommended in the study of Fingerman et al. (2011) and has been integrated in the models of Hoekstra et al. (2012) and Boulay et al. (2017), but in both cases not compatible with the WSI approach. Since, EWR varies based on environmental conditions and period of time for maintaining river functions and its ecological services. Policies, management plans or standards at a national level to protect EWR for maintaining a river system and ecological services have been implemented in many countries such as some states of the United States, New Zealand, Australia, European countries, South Africa. However, practices in water resource and demand management are found as a limitation of EWR implementation in some developing countries (Amarasinghe et al. 2005). If available water is not enough to satisfy all demands for water, it will become increasingly difficult to maintain EWR as well as it may not guarantee delivery of water to downstream users. Thus excluding a concern of EWR can lead to a cause of river desiccation found in many areas such as Yellow river, Colorado river, Egypt's Nile (Penning de Vries et al. 2003).

Thus the WSI will be allowed to modify different amount of EWR when the term of EWR is explicitly integrated. Therefore this study challenges to highlight the importance of EWR as a significant sector in the WSI modifying Pfister et al.'s (2009) equation. Accordingly, the objective of this study is to present modification and findings from accounting EWR in the WSI based on a local context. This is to strengthen the environmental water aspect in the WSI and to provide more relevant and useful results of the potential impact on freshwater resources by means of LCA perspective. Therefore, the proposed indices might be useful and enable application in other countries as one of the criteria at a policy level, especially during a decision-making process for supporting sustainable management of freshwater resource regarding EWR.

2 Methodology

The newly updated consensus on a water scarcity indicator for LCA-based water footprint from the Water Use in LCA Working Group (WULCA) is that a scarcity indicator is recommended to consider demand to be equal to human water consumption and EWR (Boulay et al. 2017). To align with this recommendation, the water withdrawal term in the ratio of water withdrawal to availability (WTA) is redefined in this study as the amount of water withdrawn to meet all demands for water and is thus renamed as DTA. We stick with withdrawals, since often they are relevant for environmental degradation in rivers. In addition, to distinguish between the Pfister's method (Pfister et al. 2009; Pfister and Bayer 2013) and the method proposed in this study, the WSI of Pfister's methods is called as $WSI_{Pfister}$ and the proposed method incorporating EWR in the WSI is named as WSI_e for both annual and monthly index. The WSI based on annual and monthly basis is taken into consideration because it will cover all contexts of decision support.

Theoretical background of WSI developed by Pfister et al. (2009) and Pfister and Bayer (2013) is provided in the supplementary material (S1).

To address the importance of EWR in the $WSI_{Pfister}$, the DTA ratio includes the EWR explicitly. Thus, the value of EWR can be changed as a function of environmental circumstances in order to maintain a river or watershed system and its ecosystem in a fair state.

Explicit incorporation of EWR in the DTA ratio is proposed by considering the EWR either as a part of water demand or water availability (Boulay et al. 2014; Hoekstra et al. 2012). The EWR included in the demand part of the DTA ratio refers as Index 1 (termed as the $DTA_{e,1}$) and Index 2 means the EWR accounted in the availability part of the DTA ratio (termed as the $DTA_{e,2}$).

Index 1 considers the environmental water as a demand of environment and gives the identical importance to this water as to the human demand for water. Thus, the EWR is defined in Index 1 as one "sector" of demanding sectors. All demands for water both human and environment are taken into account. Accordingly incorporation of EWR in Index 1 is proposed in terms of a human perspective. Index 2 considers the environmental water as the reserved water for the environment, which implicitly gives higher importance to this water compared to the water demanded by human. Hence, the EWR is defined in Index 2 as part of the availability. The environmental water is not available for human use and needed to remain in a river system for its safeguard. Accordingly incorporation of EWR in Index 2 is proposed an environment-priority perspective. Moreover, Index 1 is similar to a scarcity hydro-centric indicator and Index 2 is closed to a scarcity eco-centric indicator in the study of Boulay et al. (2014). Index 2 also corresponds to the studies of Smakhtin et al. (2004) and Hoekstra et al. (2012).

To further observe the difference of EWR incorporation in the DTA, the proposed two indices are expressed in forms of Eq. 1 and Eq. 2.

Index 1:

$$DTA_{e,1} = \frac{WD + EWR}{WA} = \frac{WD}{WA} + \frac{EWR}{WA} = \mathrm{DTA} + \frac{EWR}{WA} \tag{1}$$

Index 2:

$$DTA_{e,2} = \frac{WD}{WA - EWR} = \frac{WD}{WA}\left(\frac{WA}{WA - EWR}\right) = \mathrm{DTA}\left(\frac{WA}{WA - EWR}\right) \tag{2}$$

Where; $DTA_{e,1}$ means the demand to availability where demand includes EWR.

$DTA_{e,2}$ means the demand to availability where availability excludes EWR.

WD is water demands for agriculture, industry, household, and livestock.

WA is total water availability.

Then these two proposed indices have been further accounted in the WSI; as a result, the WSI equation is needed to be modified for accommodating the incorporation of EWR.

3 Results and Discussion

The results and discussion of applying the two proposed indices are divided into four parts. Explicit incorporation of EWR in the DTA is firstly interpreted and discussed. Then, the DTAe relating to the WSI is analyzed in terms of the threshold adjustment for the WSI function. Furthermore, interpretation and discussion of the obtained results from the adjustment are presented. Finally, implications of an existing concern on environmental water are added to highlight the importance of EWR.

3.1 Incorporation of Environmental Water Requirement (EWR)

The difference of EWR incorporation in the DTA is investigated by plotting water demand, EWR and the DTA_e value of the two indices in Fig. 1. Two patterns of the $DTA_{e,1}$ and $DTA_{e,2}$ results are reflected due to different equations expressed in Eq. 1 and Eq. 2.

The difference of the two indices is noticed at high values of water demand and EWR. The sharp increase in the results of $DTA_{e,2}$ is obviously distinguished when the values of EWR and water demand increases especially more than 50%. The results of $DTA_{e,1}$ and $DTA_{e,2}$ are quite similar at the small values of EWR and water demand.

Total water demand based on Index 1 is limited by the total of available water; therefore, the $DTA_{e,1}$ results are not larger than 2. Higher values would result in case of water resource depletion. The available water of Index 2 is associated with the EWR leading to unbounded results of $DTA_{e,2}$. The higher the EWR, the larger the difference, since the remaining available water can get a much lower denominator (Fig. 1).

To further clarify the difference of EWR incorporation in the DTA_e, the relation between the values of $DTA_{e,1}$ and $DTA_{e,2}$ and the values of EWR is assessed. The values of DTA_e for both indices are quantified by varying the EWR at the same value of water demand (see Fig. S1 in the supplementary material). The results of $DTA_{e,1}$ clearly show a linear relationship

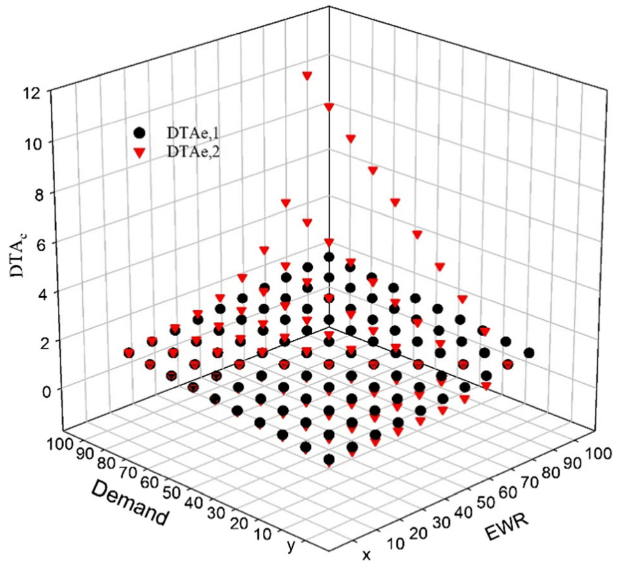

Fig. 1 Different amounts of EWR and water demand in relation to the ratio of DTA_e when considering EWR in terms of water demand ($DTA_{e,1}$) and water availability ($DTA_{e,2}$)

while a polynomial relationship fits the results of $DTA_{e,2}$. For the same value of water demand, DTA_e equal to 1 appears where $DTA_{e,1}$ and $DTA_{e,2}$ intersect. The $DTA_{e,1}$ results show a higher value than the $DTA_{e,2}$ results before reaching the intersection point. After crossing the intersection point, the $DTA_{e,2}$ results show a higher value than the $DTA_{e,1}$ results.

In addition, Index 1 consists of a sum of two ratios; the WD/WA (or DTA) and the EWR/WA (see Eq. 1). A non-zero value of the EWR/WA or the WD/WA will lead to a $DTA_{e,1}$ result larger than zero. Index 2 is a product of the two ratios; the DTA of (WD/WA) and the WA/(WA-EWR) (see Eq. 2). The $DTA_{e,2}$ will be a value of zero if either the water demanded for human or EWR is equal to zero. Furthermore, the value of EWR plays an important role in decreasing the value of water availability in case of Index 2 or increasing the value of water demand in case of Index 1. Accordingly, a large value of EWR will not only increase the $DTA_{e,2}$ results but also the difference between the $DTA_{e,1}$ and $DTA_{e,2}$. Hence, the EWR term is a key factor influencing the results of DTA_e. This is the same for the relation between the DTA_e and the DTA as the DTA_e result will get closer to the value of DTA for smaller EWR values.

The two indices are introduced as alternative ways of accounting for EWR. Preference between these two indices depends on the context of the situation and how important ecological services EWR provides. More details are provided under a discussion of implications from an existing concern on environmental water.

3.2 Adjusting the Thresholds for the WSI Function

Taking EWR explicitly into account in the DTA by the two indices entails the need to re-define the thresholds of the WSI function by keeping the same equations and index classification of Pfister's method, such as done for adjusting WSI to consumption and different water sources by Scherer and Pfister (2016). Accordingly, the critical threshold of water stress for the two indices is defined in order to reflect changes in accounting EWR explicitly in the DTA ratio. This will lead to indicate the range of threshold values for the ratio of DTA_e.

The critical threshold of $WSI_{Pfister}$, where a severe water stress situation is supposed to take place, reflects the value of WTA of 0.4. If we account for EWR explicitly, this value needs to be adjusted. Whether incorporation of EWR in water demand (Index 1) or water availability (Index 2), a balance should be maintained between demand and availability to avoid physical water scarcity. Hence, this balance can be converted into the term of DTA_e equal to 1.

At the $DTA_{e,1} = 1$ where demand including EWR equal availability can imply that the total water available is used for both human and environment (a river or watershed system). Hence, the $DTA_{e,1}$ results depend on the demand for both human use and environment. Therefore, a small value of EWR will lead to a large value of water demand for human use, and vice versa. Accordingly, the critical threshold at the $DTA_{e,1} = 1$ is considered as the starting point of the stress situation corresponding to the $WSI_{e,1} = 1$ (see Fig. 2).

Before reaching the critical threshold ($DTA_{e,1} < 1$ corresponding to $WSI_{e,1} < 1$), the severe stress situation has not yet occurred because water demand for human and environment does not exceed availability. After crossing the critical threshold, the stress situation exists leading to the $WSI_{e,1}$ value greater than 1. The demand exceeds the availability and there is no water available for the excess or additional demand. This excess can be a human or environmental demand corresponding to the $DTA_{e,1}$ ranging from 1 to 2. The severity of the situation is measured as a percentage of excess demand for water equivalent to the $WSI_{e,1}$ value ranging from 1 to 2. Thus this indicator has a larger range as it includes EWR in the demand, but demand can exceed availability without depleting water (by tapping into EWR).

The severity of the stress situation is classified into different levels increasing with the distance from the starting point to the maximum point (Fig. 2). The maximum point at the $DTA_{e,1} = 2$ is supposed to be equivalent to the sum of two fractions in Eq. 1 leading to limit the $WSI_{e,1}$ value equal to 2.

Consequently the $WSI_{e,1}$ function and classification are revised based on a consistency with the original structure and curve pattern of $WSI_{Pfister}$. The annual and monthly $WSI_{e,1}$ equations are revised based on the maximum value of $WSI_{e,1}$ at 2 as expressed in Eq. 3 and Eq. 4. These equations are similar to the $WSI_{Pfister}$ equations; therefore, the calculations of the terms $DTA^*_{e,1}$ and $DTA^*_{e,1\ month}$ are the same as the original equation detailed in S1 and S2 in the supplementary material.

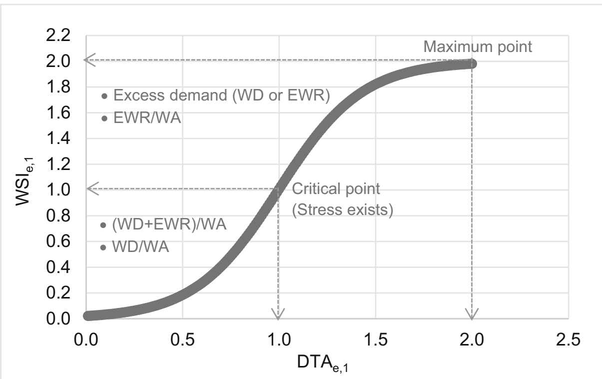

Fig. 2 Logistic curve of the water stress index with reference to environmental water ($WSI_{e,1}$) and the demand to availability where demand includes EWR ($DTA_{e,1}$)

The proposed water pressure ranges of Frischknecht et al. (2006) is applied for categorizing the levels of the stress situation. Accordingly the classification in Table 1 is established. In addition, a water stress watch and warning are defined as water stress action levels before approaching the critical threshold. The minimum and maximum of EWR in Pastor et al. (2014) are applied to design the two additional levels. This is to raise awareness and help communicate the severity of the stress situation as Iglesias et al. (2007) suggests about managing the risk of water scarcity based on preparedness rather than a crisis approach.

$$annual\ WSI_{e,1} = \frac{2}{1 + e^{-2.56\left(DTA^*_{e,1}\right)}\left(\frac{1}{0.01} - 1\right)} \quad (3)$$

$$monthly\ WSI_{e,1} = \frac{2}{1 + e^{-3.93\left(DTA^*_{e,1\ month}\right)}\left(\frac{1}{0.01} - 1\right)} \quad (4)$$

The water availability of Index 2 at the $DTA_{e,2} = 1$ can be inferred that the availability is already allocated for human and environment. The environmental water is firstly conserved and the remaining water can be withdrawn for human demand. Then a large value of EWR results in a small value of water availability for human use, and vice versa. Accordingly, the critical threshold at the $DTA_{e,2} = 1$ is considered as the starting point of the stress situation corresponding to the $WSI_{e,2} = 0.5$ (see Fig. 3).

Before reaching the critical threshold ($DTA_{e,2} \leq 1$ corresponding to $WSI_{e,2} \leq 0.5$), there is only a limited possibility of stress and environmental threat because the total water availability is already allocated for human and environment. Also the demand for human demand does not exceed allocated water for human. After crossing the critical threshold implies that the human demand for water exceeds the available water for human. The stress situation has not yet existed because there is the environmental water possibly available for the excess demand of human. Thus this situation is imminent. As a result, the values of $DTA_{e,2}$ from 1 to 2 are considered corresponding to the $WSI_{e,2}$ values ranging from 0.5 to 1. Accordingly the imminent stress situation is considered by means of possibility and measured in terms of the excess demand of human equivalent to the environmental water to be withdrawn.

The DTA ratio is the key factor approaching water stress and is influenced by the ratio of WA/(WA-EWR). The water availability excluding environmental water is determined through the WA/(WA-EWR) term. EWR values close to zero lead to the value of WA/(WA-EWR) term equal to 1. However, the value of WA/(WA-EWR) is undefined if the maximum of EWR equal

Table 1 Classifications of the water stress index with reference to environmental water ($WSI_{e,1}$)

$DTA_{e,1}$	$WSI_{e,1}$	Level of stress situation
$0 < DTA_{e,1} \leq 0.4$	$0 < WSI_{e,1} \leq 0.12$	No stress
$0.4 < DTA_{e,1} \leq 0.7$	$0.12 < WSI_{e,1} \leq 0.40$	Watch
$0.7 < DTA_{e,1} \leq 1$	$0.40 < WSI_{e,1} \leq 1$	Warning
$1 < DTA_{e,1} \leq 1.4$	$1 < WSI_{e,1} \leq 1.72$	Moderate
$1.4 < DTA_{e,1} \leq 1.6$	$1.72 < WSI_{e,1} \leq 1.88$	Severe
$1.6 < DTA_{e,1} \leq 2$	$1.88 < WSI_{e,1} \leq 2$	Extreme

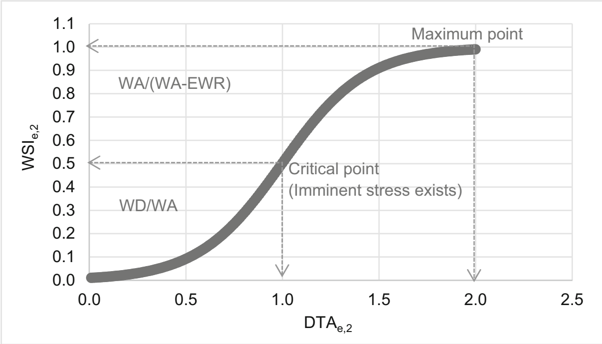

Fig. 3 Logistic curve of the water stress index with reference to environmental water ($WSI_{e,2}$) and the demand to availability where availability excludes EWR ($DTA_{e,2}$)

to the water availability (EWR = WA). Thus the $WSI_{e,2}$ equal to 1 is defined as the maximum point of Index 2. Accordingly the 0.5 of $WSI_{e,2}$ corresponding to the $DTA_{e,2}$ at 1 is indicated as the critical threshold.

Based on the same process as establishing the $WSI_{e,1}$ function, the annual and monthly $WSI_{e,2}$ equations are revised based on the maximum value of $WSI_{e,2}$ at 1 as expressed in Eq. 5 and Eq. 6. Also, the same concept as classifying the severity of stress for Index 1 is applied to the classification of Index 2 as shown in Table 2.

$$annual\ WSI_{e,2} = \frac{1}{1 + e^{-2.56\left(DTA^{*}_{e,2}\right)}\left(\frac{1}{0.01} - 1\right)} \tag{5}$$

$$monthly\ WSI_{e,2} = \frac{1}{1 + e^{-3.93\left(DTA^{*}_{e,2\ month}\right)}\left(\frac{1}{0.01} - 1\right)} \tag{6}$$

In conclusion, the same critical threshold (the $DTA_e = 1$) is applied for both Index, but it corresponds to different the WSI_e-equivalent values due to different interpretation of the stress situation (see Fig. S2 in the supplementary material).

The WSI_e ranges of Index 1 and Index 2 are not the same, as the perception of the situation of Index 1 is more stressful than Index 2. There is no water available for any excess demand in case of Index 1; therefore the stress situation occurs at the $WSI_{e,1} > 1$. To address this interpretation when the DTA_e greater than 1, the WSI_e-equivalent values indicating the severity of the stress situation in case of Index 1 (the $WSI_{e,1} = 1$ to 2) are greater than that of Index 2 (the $WSI_{e,2} = 0.5$ to 1).

Table 2 Classifications of the water stress index with reference to environmental water ($WSI_{e,2}$)

$DTA_{e,2}$	$WSI_{e,2}$	Level of approaching stress
$0 < DTA_{e,2} \leq 0.4$	$0 < WSI_{e,2} \leq 0.06$	No stress
$0.4 < DTA_{e,2} \leq 0.7$	$0.06 < WSI_{e,2} \leq 0.20$	Watch
$0.7 < DTA_{e,2} \leq 1$	$0.20 < WSI_{e,2} \leq 0.5$	Warning
$1.2 < DTA_{e,2} \leq 1.4$	$0.72 < WSI_{e,2} \leq 0.86$	Moderate
$1.4 < DTA_{e,2} \leq 1.6$	$0.86 < WSI_{e,2} \leq 0.94$	Severe
$1.6 < DTA_{e,2} \leq 2$	$0.94 < WSI_{e,2} \leq 1$	Extreme

3.3 Interpretation of WSI with Reference to EWR

3.3.1 Considering EWR in Terms of Water Withdrawal (Index 1)

The ratio of DTA in Eq. 1 is redefined as the demand to availability where demand includes EWR. Thus water demands based on this index ($DTA_{e,1}$) refer to water demanded for agriculture, industry, household, livestock, and ecosystem.

Consideration of EWR in this index means that environmental water is defined as a human interest; therefore, it can be accounted as one sector of demands for water similar to household, agriculture, industry and livestock. Hence water allocation and prioritization play a significant role in this index and these two factors are also considered in developing water resource management plan. As a result, all sectoral water demand is managed and controlled based on allocation and prioritization as well. Hence this index reflects a view of human demand management with priority setting, and focuses on sectors that water demand facing water stress. In principal, weighting for prioritization among the sectors and EWR could be introduced.

Extreme stress situation occurs when all demand exceeds the availability. Thus to satisfy the excess demand, it has to be taken from other sectors. Typically, available water is allocated based on priority, the lowest priority sector will possibly face a higher level of water stress situation than other sectors. If the lowest priority is not given to the environment (EWR), the stress or conflict will not be put directly on freshwater resources and ecosystems but on the lowest-priority sector (Asian Development Bank 2009; Speed et al. 2013). Therefore this lowest-priority sector is the focus of this index because the stress occurs in this sector. As this index is established based on all demand for water and available water, this index is a non-conservative approach to assess the stress situation.

3.3.2 Considering EWR Incorporated in Water Availability (Index 2)

The ratio of DTA in Eq. 2 is redefined as the demand to availability where availability excludes EWR. Thus water availability based on this index refer to the difference between total water availability and EWR. Accordingly, EWR is considered as a part of available water reserved in a river channel or a watershed system that corresponds to the definition of EWR (Smakhtin et al. 2004; Poff et al. 2009).

This index put an emphasis on EWR as it is firstly subtracted from water availability. This can be implied that EWR is not available for other human uses. This interpretation also corresponds to the study of Speed et al. (2013) which highlighted that allocating available water to meet EWR before other demands is recognized in the sense of environmental protection. Therefore the ecosystem of freshwater resource is the focus of this index as the first priority is given to this sector. Accordingly, a fair condition of a river and its ecosystem is still maintained by the environmental water, and the remaining available water is totally allowed for satisfying human demand.

When human demand exceeds the available water allocated for human and the environmental water is strictly reserved, the excess demand would be satisfied by allocated water from other sectoral water users. This excess demand will put pressure on the lowest priority of sectoral water users without touching the environmental water. Consequently Index 2 is a rather strict and conservative approach to assess the stress situation.

Other than this, incorporation of EWR in water availability is also taken into account in the studies of Smakhtin et al. (2004) and Hoekstra et al. (2012). The EWR in Smakhtin et al.

(2004) is based on an annual basis using flow-quartile analysis (Arthington et al. 2006; Pastor et al. 2014). The study of Hoekstra et al. (2012) employs the 20% rule as an indicative safeguard of EWR based on Richter et al. (2012). The environmental water included in their studies is defined as a fixed. On the other hand, Index 2 makes the EWR to be more flexible allowing the possibility to change depending on the purpose the EWR provides.

3.3.3 Comparison of Index 1 and Index 2

Incorporation of EWR in the WSI by the two indices proposed is not apparently displayed in Eq. 3 to Eq. 6, since the EWR term is part of DTA_e. The value of EWR has significant effect on the DTA_e and WSI_e of both indices as it will increase the total of demand ($DTA_{e,1}$) or decrease the total of availability ($DTA_{e,2}$). The EWR term has a greater influence on the $DTA_{e,2}$ than the $DTA_{e,1}$. A rapid increase in the values of $DTA_{e,2}$ is seen at the value of EWR equivalent to 50% of water availability. The DTA_e and WSI_e of both indices are investigated based on the different shares of environmental water in relation to the human demand for water.

When $DTA_{e,1}$ and $DTA_{e,2}$ are less than 1, two indices indicate 'no stress' since there is no excess demand over available water as both human and environmental demands for water are satisfied. Higher EWR could occasionally happen in sensitive areas in order to protect, restore, or manage environmental water system particularly when a river or watershed is sensitive to environmental impact. To mitigate or avoid the extreme situation during the period of higher EWR, a water management plan on reducing human demand for water would be recommended. Although there is no excess demand over available water ($DTA_{e,1}$ and $DTA_{e,2} < 1$), the water stress action levels would help to avoid or mitigate the stress situation.

When $DTA_{e,1}$ and $DTA_{e,2}$ are greater than 1, both indices reveal the same level of the stress situation. This occurs when sum of the EWR and the human demand for water is equal to the total available water. Index 2 shows a higher level of stress than Index 1 when the demands for both human and environment are larger than 50% of water availability. For instance if EWR is 50% and human demand for water up to 80%, a 'medium' level is obtained from Index 1 and Index 2 indicates an 'extreme' level. Based on Index 1, the total water demand is 130% while there is only 100% of water availability. Thus the excess equal to 30% refers as the severity of the stress situation that exists. If the 30% of excess needs to be satisfied, it will be taken from water use sectors of human activities or the environment (EWR). As a result, this excess will become a pressure put on the lowest priority sector. The same excess at 30% is assessed by Index 2 and implied as human demand. This is because the EWR at 50% of available water is firstly allocated; therefore, the remaining water at 50% of available water is reserved for human demand. If the 30% excess needs to be fulfilled, two situations could happen. The first situation is in case the 50% of available water for environment is not allowed to use. The excess will be taken from water use sectors of human activities and the stress situation will occur in the lowest priority sector. The second situation is a river and its ecosystem will be affected through the excess demand. If the EWR is not strongly secured, the excess will be taken from the 50% of available water for environment. Hence this excess is considered as a possibility of the stress situation that could occur on a river system and its ecosystem.

Although both indices assess the stress situation based on the same value of excess demand, the assessment of Index 2 provides more conservative results than the assessment of Index 1. This is because the water availability of Index 2 is lower than that of Index 1. Index 2 would be appropriate to create management plans at policy level in terms of regulatory or advisory policy providing committed efforts to safeguard freshwater resources. On the other side, Index

1 might better reflect management options at practical level, where water needs to be allocated to minimum flows in a river (RID 2015). This index would be suggested for high demand areas having non-sensitive ecological systems.

3.4 Implications from an Existing Concern on Environmental Water

Sustaining a safe and healthy environment for a river and its ecosystem depends on perceived value and services provided to upstream and downstream water-use sectors. Many countries take this concern into account by means of standard setting. The hydrological approach has been applied for developing several methods to assess EWR. This approach can fulfill a concern of EWR with a quick assessment; therefore, it is internationally accepted practices for establishing standards or initiatives of EWR. More complex approaches will be required for comprehensive assessment of a particular watershed (Tharme 2003; King et al. 2003). Over 40 countries and around 200 methods are reported in King et al. (2003).

EWR based on a fixed minimum flow, a fixed-percentage of mean annual flow, or annual flow quantiles will be applicable to define as a standard precaution for rivers containing constant flows and less monthly variation in flows. These rivers can be found in temperate areas (Chebaane et al. 1993; Pastor et al. 2014). In addition, if areas where demands for water are also stable and always lower than available water, as well as the aquatic ecosystem is less sensitive, EWR based on the fixed flow will be sufficient to maintain a river system. However since rivers have different natural patterns of flow, a method developed from different percentages related to monthly flow variability will be more appropriate because it can deal with different flow patterns. Thus this method will provide EWR corresponding to the existing natural flows. Furthermore habitat conditions and ecological services are different depending on patterns of river flows. It will require further studies to determine specific flows for specific purposes such as for quality control, natural protection, ecological monitoring. For instance, estuarine watersheds will require more environmental water for some periods of time to control or mitigate a problem of seawater intrusion such as shown for cases in Thailand, India, Egypt, China, Turkey (RID 2015; Gonzalez et al. 2005; de Vries FWT et al. 2003.

Explicit incorporation of EWR for a case of Thailand is considered as a part of water withdrawal according to the definition and regulation of the Royal Irrigation Department (RID). EWR is classified as one of water demand sectors having the second-highest priority of water allocation after the requirement for domestic purposes and regulated at a fixed minimum flow (RID 2014). The proposed annual $WSI_{e,1}$ (Eq. 3) is further developed for the case of Thailand by recalculating the constant (the exponent of "e") based on the precipitation data of the country. The results showed a no stressful situation for all the watersheds; however, Mun watershed showing the highest value (indicating as a 'watch area') could potentially face the stress situation in the future. Mun, located in the eastern part of Thailand, is revealed as the most critical watershed determined by Gheewala et al. (2013, 2014). In fact, a fixed minimum flow defined as a standard by RID may underestimate the reality of an actual EWR. Environmental water is significantly required especially during the dry season for preventing seawater intrusion and/or improving river quality. For instance, the EWR standard of Chao Phraya watershed is regulated at 40 m^3/s, this rate was increased to 70–75 m^3/s for mitigating the sea water intrusion in 2015 (RID 2015). Thus explicit incorporation of EWR in the WSI function allows flexibility of varying EWR based on the local context. This helps not only to conserve the health of water resource but also to enhance robustness of WSI results. In addition, a large volume of EWR needed for some areas particularly in the dry season can lead to increased water stress situation, which may be more important in the monthly than annual WSI. Furthermore improving the standard of EWR based on seasonal variation in water availability is recommended for Thailand.

Although in principle all water should be remained in freshwater systems, government regulation or standard for EWR could help ensure that the EWR meets some baseline standards. If the regulation or standard for EWR has not yet been established, a focus area to initiate action on EWR would be suggested in areas where freshwater resources are being demanded continuously and those demands sometimes exceed available water. It can be implied that such areas have a high potential for water stress and it would be possible to allocate all available water for human uses without considering the importance of EWR (Speed et al. 2013).

4 Conclusion

The concern on environmental water is implicitly associated in the WSI of Pfister et al. (2009) by mean of the defined thresholds. However, the threshold from moderate to severe water scarcity defined at 40% of available water does not imply that the remaining water is reserved for the environment. To allow flexibility in changing the amount of EWR based on the local environmental context, the term of EWR is explicitly considered within the WTA ratio. Demand including EWR (Index 1) and availability excluding EWR (Index 2) are proposed as two possible ways to include EWR in the DTA, with different interpretation. The starting point of the stress situation can be defined where demand equals availability. Thus, the impact on freshwater resources is measured from the excess demand instead of the predefined threshold.

The two indices help not only to safeguard freshwater resources by means of explicitly accounting for EWR but also to enhance robustness of water stress assessment using the WSI with reference to EWR.

This study highlights that EWR is not only important for sustaining a river system and ecological services but also relevant to the water scarcity issue. Priority setting and water allocation significantly influence decisions making on limits of EWR. Thus including EWR in the WTA as a part of Demand or availability will depend on the country or local context, while it is still consistent with the original WSI.

Acknowledgements Financial support by the Joint Graduate School of Energy and Environment (JGSEE) and the Thailand Research Fund under the Royal Golden Jubilee Ph.D. program (Grant PHD/0028/2555) is gratefully acknowledged. This research has been carried out under the project “Research Network for LCA and Policy on Food, Fuel and Climate Change” supported by the National Science and Technology Development Agency, Thailand.

References

Amarasinghe UA, Sharma BR, Aloysius N, Scott C, Smakhtin V, de Fraiture C (2005) Spatial variation in water supply and demand across river basins of India. IWMI research report, 83. IWMI

Arthington A, Bunn SE, Poff NL, Naiman RJ (2006) The challenge of providing environmental flow rules to sustain river ecosystems. Ecol Appl 16(4):1311–1318

Börkey P, Cassar A, Meadors L, Saade L, Siebentritt M, Stein R, Tognetti S, Tortajada C (2005) Chapter 7 freshwater ecosystem services. In: Chopra K, Leemans R, Kumar P, Simons H (eds) Ecosystems and human well-being: policy responses, volume 3 The Millennium Ecosystem Assessment Series

Boulay A-M (2012) WATER footprinting: where are we now? WATER in LCA: which assessment techniques are emerging or ready? Including lots of challenging aspects. 50th LCA discussion forum, ETH Zurich, Switzerland

Boulay A-M, Bare J, Benini L, Berger M, Klemmayer I, Lathuilliere M, Loubet P, Manzardo A, Margni M, Nunez M, Ridoutt B, Worbe S, Pfister S (2014) Building consensus on a generic water scarcity indicator for LCA-based water footprint: preliminary results from WULCA. 9th international conference LCA of food San Francisco, USA, October, 8-10

Boulay A-M, Bare J, Benini L, Berger M, Lathuilliere M, Manzardo A, Margni M, Motoshita M, Nunez M, Pastor AV, Ridoutt B, Oki T, Worbe S, Pfister S (2017) The WULCA consensus characterization model for water scarcity footprint: assessing impacts of water consumption based on available water remaining (AWARE). Int J Life Cycle Assess. https://doi.org/10.1007/s11367-017-1333-8

Chebaane M, Salas JD, Boes DC (1993) Modeling of monthly intermittent streamflow processes. DIANE Publishing Company

Penning de Vries FWT, Acquay H, Molden D, Scherr SJ, Valentin C, Cofie O (2003) Integrated land and water management for food and environmental security. Comprehensive Assessment of Water Management in Agriculture Research Report 1. Colombo, Sri Lanka: Comprehensive Assessment Secretariat

Fingerman KR, Berndes G, Orr S, Richter BD, Vugteveen P (2011) Impact assessment at the bioenergy-water nexus. Biofuels Bioprod Biorefin 5(4):375–386. https://doi.org/10.1002/bbb.294

Frischknecht R, Steiner R, Arthur B, Norbert E, Gabi H (2006) Swiss Ecological Scarcity Method: The New Version 2006. ESU-Services, Switzerland. http://www.esuservices.ch/fileadmin/download/Frischknecht-2006-EcologicalScarcity-Paper.pdf. Accessed 19 Nov 2014

Gheewala SH, Silalertusksa T, Nilsalab P, Mungkung R, Perret SR, Chaiyawannakarn N (2013) Implications of the biofuels policy mandate in Thailand on water: the case of bioethanol. Bioresour Technol 150:457–465. https://doi.org/10.1016/j.biortech.2013.07.052

Gheewala SH, Silalertusksa T, Nilsalab P, Mungkung R, Perret SR, Chaiyawannakarn N (2014) Water footprint and impact of water consumption for food, feed, fuel crops production in Thailand. Water 6(6):1698–1718. https://doi.org/10.3390/w6061698

Gonzalez FJ, Basson T, Schultz B (2005) Final report of IPOE for review of studies on water Escapages below Kotri barrage. Delft, the Netherlands http://s3.amazonaws.com/zanran_storage/www.pakistan.gov.pk/ContentPages/19050336.pdf. Accessed 30 Jan 2016

Hoekstra AY, Mekonnen MM, Chapagain AK, Mathews RE, Richter BD (2012) Global monthly water scarcity: blue water footprint versus blue water availability. PLoS One 7(2):e32688. https://doi.org/10.1371/journal.pone.0032688

Iglesias A, Garrote L, Flores F, Moneo M (2007) Challenges to manage the risk of water scarcity and climate change in the Mediterranean. Water Resour Manag 21(5):227–288

ISO (2014) ISO 14046:2014-Environmental management -Water footprint-Principles, requirements and guidelines

King J, Brown C, Sabet H (2003) A scenario-based holistic approach to environmental flow assessments for rivers. River Res Appl 19(5-6):619–639. https://doi.org/10.1002/rra.709

Nilsalab P, Gheewala SH, Silalertruksa T (2017) Methodology development for including environmental water requirement in the water stress index considering the case of Thailand. J Clean Prod 167:1002–1008. https://doi.org/10.1016/j.jclepro.2016.11.130

Pastor AV, Ludwig F, Biemans H, Hoff H, Kabat P (2014) Accounting for environmental flow requirements in global water assessment. Hydrol Earth Syst Sci 18(12):5041–5059. https://doi.org/10.5194/hess-18-5041-2014

Pfister S, Bayer P (2013) Monthly water stress: spatially and temporally explicit consumptive water footprint of global crop production. J Clean Prod 73:52–62. https://doi.org/10.1016/j.jclepro.2013.11.031

Pfister S, Koehler A, Hellweg S (2009) Assessing the environmental impacts of freshwater consumption in LCA. Environ Sci Technol 43(11):4098–4104. https://doi.org/10.1021/es802423e

Poff NL, Richter BD, Arthington AH, Bunn SE, Naiman RJ, Kendy E, Acreman M, Apse C, Bledsoe BP, Freeman MC, Henriksen J, Jacobson RB, Kennen JG, Merritt DM, O'Keeffe O, Olden JD, Rogers K, Tharme RE, Warner A (2009) The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. Freshw Biol 55(1):147–170. https://doi.org/10.1111/j.1365-2427.2009.02204.x

Popan A (2011) Impact of sea water intrusion on soil salinity and land used in bang Pakong River basin, Chachoengsao Province. Dissertation, King Mongkut's Institute of Technology Ladkrabang. Doi:https://doi.org/10.14457/KMITL.res.2011.67

Richter BD, Davis MM, Apse C, Konrad C (2012) A presumptive standard for environmental flow protection. River Res Appl 28(8):1312–1321. https://doi.org/10.1002/rra.1511

RID (2014) Annual Report 2014. Royal Irrigation Department. http://www.rid.go.th/2009/_data/docs/AnnualRID57.pdf. Accessed 13 May 2015

RID (2015) RID response plan for tidal bore to prevent seawater intrusion and maintain raw water quality for tap water. Royal Irrigation Department. http://water.rid.go.th/news/news_58_032.htm. Accessed 13 May 2015

Scherer L, Pfister S (2016) Dealing with uncertainty in water scarcity footprints. Environ Res Lett 11(5). https://doi.org/10.1088/1748-9326/11/5/054008

Smakhtin V, Revenga C, Döll P (2004) Taking into account environmental water requirements in global-scale water resources assessments. Comprehensive assessment research report 2. Colombo, Sri Lanka: comprehensive assessment secretariat

Speed R, Li Y, Le Quesne T, Pegram G, Zhiwei Z (2013) Basin water allocation planning. Principles, procedures and approaches for basin allocation planning, UNESCO, Paris

Tharme RE (2003) A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Res Appl 19(5-6):397–441. https://doi.org/10.1002/rra.736

Wei Y, Miao H, Ouyang Z (2008) Environmental water requirements and sustainable water resource management in the Haihe River basin of North China. Int J Sust Dev World 15(2):113–121. https://doi.org/10.1080/13504500809469776