Development of Water Stress Indices for the Watersheds of Thailand to Support Water Footprint Calculations

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Abstract: When demands for water cannot be met sufficiently due to lack of available water, the excess demand will possibly cause impacts on freshwater resources. Thus, water footprint (WF) and water stress index (WSI) are gaining recognition as important tools for assessing water use impact leading to support policy makers on development of water resource management policy. The WSI has been widely applied as a characterization factor of water scarcity footprint; a first attempt was made some years ago by determining the WSI for 25 watersheds of Thailand based on a top-down approach. Subsequently, in this study, a bottom-up approach with more refined data was used to determine the annual and monthly WSIs for the 25 watersheds. The most critical watersheds were found to be located in the Central region of Thailand. Cultivating in irrigated or non-irrigated areas and shifting crop calendar can affect the WSI values. Accordingly, the annual and monthly WSI would be recommended as one of the criteria or tools to support the future agricultural policy decision making in various applications, particularly agricultural zoning. The annual WSI may be useful for the top-down vision for a quick assessment and the monthly WSI for a comprehensive assessment.

1. Introduction

Water footprint (WF) and Water stress index (WSI) are gaining recognition as important tools to support policy makers in their development of water resource management policy, especially for Thailand where agriculture which accounts for about 65-70% of the water consumption. To this end, a research project was conducted in the years 2012-2013 to assess the water footprint of key agricultural food, feed, and fuel crops and to evaluate the situation and potential to affect the water stress in different regions of Thailand. The results showed that WF and WSI can provide useful information for identification of the potential areas of water stress due to the expansion of agricultural activities and for determining the measures for improving water resource planning and management for sustainable food, feed, and fuel crops production in the future (Gheewala et al., 2013; 2014) [1-2]. The outcome of this first project was the annual WSI for the 25 watersheds in Thailand which has been widely useful and referred for water scarcity footprint assessment of various agricultural products in the country. However, due to the time limitation of that study, some factors that are able to influence to the WSI results were excluded from the investigation. For example, the earlier study was based on a top-down approach using generic data that were available from related agencies and theoretical crop water requirement values for agriculture. The use of the theoretical crop water requirement for water demand resulted in an overestimation because there are many crops/regions in Thailand which are mainly rainfed; irrigation is not provided. The development of the water-use impact assessment method for Thailand has been continued by doing a more detailed analysis of the temporal aspects of the WSI by using data from "bottom-up approach" to obtain the monthly and seasonal WSI of Thailand (Gheewala et al., 2018) [3]. As the annual and monthly WSI are estimated based on different equations (Pfister et al., 2009; Pfister and Bayer, 2013) [4-5], the updated study aims to uses the detailed data from Gheewala et al. (2018) [3] for calculating the annual WSI values of the 25 watersheds as well as providing all the detailed monthly WSI values for the 25 watersheds. As these values should preferably be used for water footprint-related research, including for the newly developed water scarcity footprint label of Thailand, it is imperative to present the methods and values for information and reference.

2. Methods

2.1 Bottom up approach framework

Improvement of the WSI by using "bottom-up approach" refers to the method where data is collected a more detailed level in the identified critical zones. The data collection efforts focused on collating information from local sources e.g. local governments, local irrigation department and other related organizations in the studied provinces/watersheds.

2.2 Withdrawal-to-Availability (WTA) and Water Stress Index (WSI)

The WTA term was estimated from the ratio of total water withdrawals to water availability for each watershed/basin as expressed in Equation (1). The difference between annual and monthly WSI calculation is that the WTA and W_{ij} data used in the calculation were yearly and monthly based, respectively.

$$WTA_i = \frac{\sum_j W_{ij}}{WA_i} \quad (1)$$

WTA_i : water withdrawal to availability ratio for each watershed i;
W_{ij} : water withdrawal from watershed/basin i by each sector j;
WA_i : water availability of the watershed/basin

Equation (2) is a general formula used to calculate the annual WSI of Pfister et al. (2009) for each watershed. The advantage of using the proposed water index by Pfister et al. (2009) is that the variation of rainfall is included in the WTA as well as the factors regarding the strongly regulated flow (SRF) and non-strongly regulated flow (non-SRF) of the basins/water storages [4].

$$WSI = \frac{1}{1+e^{-6.4WTA^*(\frac{1}{0.01}-1)}} \quad (2)$$

The factor regarding seasonal variations to the flows and availability of water is applied as the weighting factor for WTA.

Hence the weighted WTA is then expressed as WTA^*. Annual WTA^* can be calculated by Equations (3) and (4), respectively. Equation (3) shows the simple formula to determine the WTA^* i.e. the WTA in Equation (2) has been adjusted by the variation factor (VF) which was introduced to account for seasonal variations in water availability in relation to regulation effects of water reservoir on flow regime. Thus the effect of VF will reduce if river flows are regulated by water reservoir. This criterion is defined as an SRF. In contrast, a non-SRF is classified if the river flows naturally; then the effect of VF is fully taken into account in the ratio of WTA. Equation (4) shows the formula to calculate the VF by using the standard deviations of monthly average (S^*_{month}) and annual rainfall(S^*_{year}).

$$WTA^* = \begin{cases} \sqrt{VF} \times WTA \ \text{ for SRF} \\ VF \times WTA \ \text{ for non} - \text{SRF} \end{cases} \quad (3)$$

$$VF = e^{\sqrt{\ln(S^*_{month})^2 + \ln(S^*_{year})^2}} \quad (4)$$

Although the monthly WSI of 25 watersheds were determined by Gheewala et al. (2018), the monthly results of this study were presented as monthly maps, and the monthly WSI values were revealed only for some watersheds. Thus the monthly WSI values for all 25 watersheds are provided in this updated study [3].

Data requirements for WSI calculation are presented in Table 1. Data, criteria and standards obtained from different sources were analyzed and compared with statistical records in order to obtain the most reasonable and consistent data. In addition, discussion with experts from related organizations were arranged for clarification and confirmation of the obtained results. After that, consultation meetings were performed for validating the obtained results and receiving comments and suggestions from stakeholder, local governments, and related organizations. The calculation of annual WSI with more refined data is illustrated in Figure 1.

Details of estimating each parameter in Table 1 are described below. Water withdrawal is commonly referred as the sum of estimated water used for industrial, agricultural, domestic, and livestock sectors.

- Water availability: the total of rainwater and stored water in water reservoirs is taken into account in order to cover all sources of available water. The total rainwater is calculated based on the 10-year of rainfall data. Referring to the 25 watersheds, annual rainfall based on statistical data during 1973-2008 is approximately 1,450 mm covering 5-6 months in the wet season; May to October. Besides, the 10-year of rainfall data during 2002-2011 is about 1,600 mm.
- Water withdrawal for household sector: the water withdrawn by the household sector is estimated based on the number of people in the province multiplied with the basic minimum water requirement for humans, based on literature. The amounts of basic minimum water requirement for people who live in and outside the municipal area are 200 and 100 liters/person/day. The population classified into living in municipal and non-municipal areas is available at the National Statistical Office of Thailand.
- Water withdrawal for industrial sector: water demand for industry is assessed based on the types of industries and their areas. Data obtained based on a watershed boundary refers to 10 major industries classified by the Department of Industrial Works (DIW). Tourism is accounted as one of the industrial sectors in this assessment and the water intensity of tourism sector will be assessed based on number of tourists and excursionists (RID, 2011) [6].
- Water withdrawal for livestock sector: the amount of water withdrawal for this sector is estimated from the number of heads of livestock multiplied with a coefficient (an average water use per animal) (RID, 2010; RID, 2011) [6-7]. Livestock refers to dairy cow, beef cattle, buffalo, pig, goat and poultry. Thus the number of heads of livestock is classified by province.
- Water withdrawal for agriculture: water required by crops or so called “crop water requirement (CWR)” refers to the volume of water lost via evapotranspiration process including evaporative water from soil and crop surfaces and transpired water from crop to atmosphere. In other words, CWR is denoted as crop evapotranspiration (ET_c). This term can be quantified either by empirical measurement at a field or theoretical estimation via a formula or model. Results obtained from a field experiment are specific and cannot be applied to another area because of differing weather conditions, soil characteristics, and crop variety affecting the volume of water used by crops. Therefore ET_c or CWR is practically computed by theoretical estimation formula or model simulation. The theoretical approach is developed based on two significant factors affecting crop water use which are weather conditions and crop coefficient. The general formula (Eq. 5) used for estimating crop water use is expressed as follows (Allen et al., 1998; FAO, 2010) [8-9].

$$ET_c = K_c \times ET_0 \quad (5)$$

Variations of weather and crop species are taken into account through a reference crop evapotranspiration (ET_0) and crop coefficient (K_c). The Penman Monteith method is applied with particular meteorological data for calculating the ET_0 and K_c values of each crop are referred from RID. As the ET_0 is calculated based on location of crop cultivation and the K_c is computed specifically for each crop, the theoretical equation can be applied for any crop cultivated in any area. Accordingly, CWR of 10 staple crops (rice (major and second), maize, cassava, sugarcane, oil palm, mungbean, soybean, peanut, coconut, para rubber and pineapple) is estimated in this study based on crop calendar. Water deficit condition for assessing the amount of agricultural water is taken into consideration by estimating the water used for crops based on existing irrigated and rain-fed (non-irrigated) areas. Water required for growing crops in non-irrigated areas is supposed to be equal to the amount of rainfall used by crop, so-called effective rainfall. If CWR is higher than effective rainfall, water withdrawal for field crops in non-irrigated areas is equivalent to the amount of effective rainfall. On the other hand, if effective rainfall is higher than CWR, water withdrawal for field crops in non-irrigated areas is equivalent to the amount of CWR. Water required for growing crops cultivated in irrigated areas are expected to meet total amount of crop water requirement. Thus, a sum of effective rainfall and irrigation water is accounted as the total water withdrawal for crops cultivated in irrigated areas.

2.3 Crop water requirement (CWR) and deficit irrigation means the total irrigation over the period of crops cultivation in both the designated irrigated as well as non-irrigated areas as mentioned earlier. This is considered in the study because, in practice, there are many crops e.g. cassava and sugarcane, that grown in the designated non-irrigated areas which therefore generally consume lesser amount of water as compared to the theoretical water requirement. The theoretical water requirement and freshwater use from field data (deficit condition) for major crops cultivation is evaluated and compared. The water use assessment is estimated based on the crop evapotranspiration calculation complementing with the rainfed and/or irrigated conditions of the planted areas.

Table 1. Data requirements and sources for WSI calculation.

Parameters	Terms	Data Source
Water availability:		
Rainfall	Monthly rainfall (10 years monthly average data during 2002-2011) by station	Thai Meteorological Department (TMD)
Stored water	Monthly stored water in reservoirs by watershed	Royal Irrigation Department (RID)
Water withdrawal:		
$W_{Household}$	Water withdrawal for household sector by province is estimated from the number of persons in the province multiplied with water consumption rate per person	RID; Provincial Waterworks Authority (PWA); National Statistical Office Thailand (NSO)
$W_{Industry}$	Water withdrawal for industrial sector by watershed is assessed based on types of industries and their areas	Royal Irrigation Department (RID); Department of Industrial Works (DIW)
$W_{Agriculture}$	Water withdrawal for agricultural sector by province is estimated from crop water requirements and cultivated areas	RID; Office of Agricultural Economics (OAE)
$W_{Livestock}$	Water withdrawal for livestock sector by province is estimated from the number of each livestock multiplied with water consumption rate per head of each livestock	RID; Department of Livestock Development (DLD)

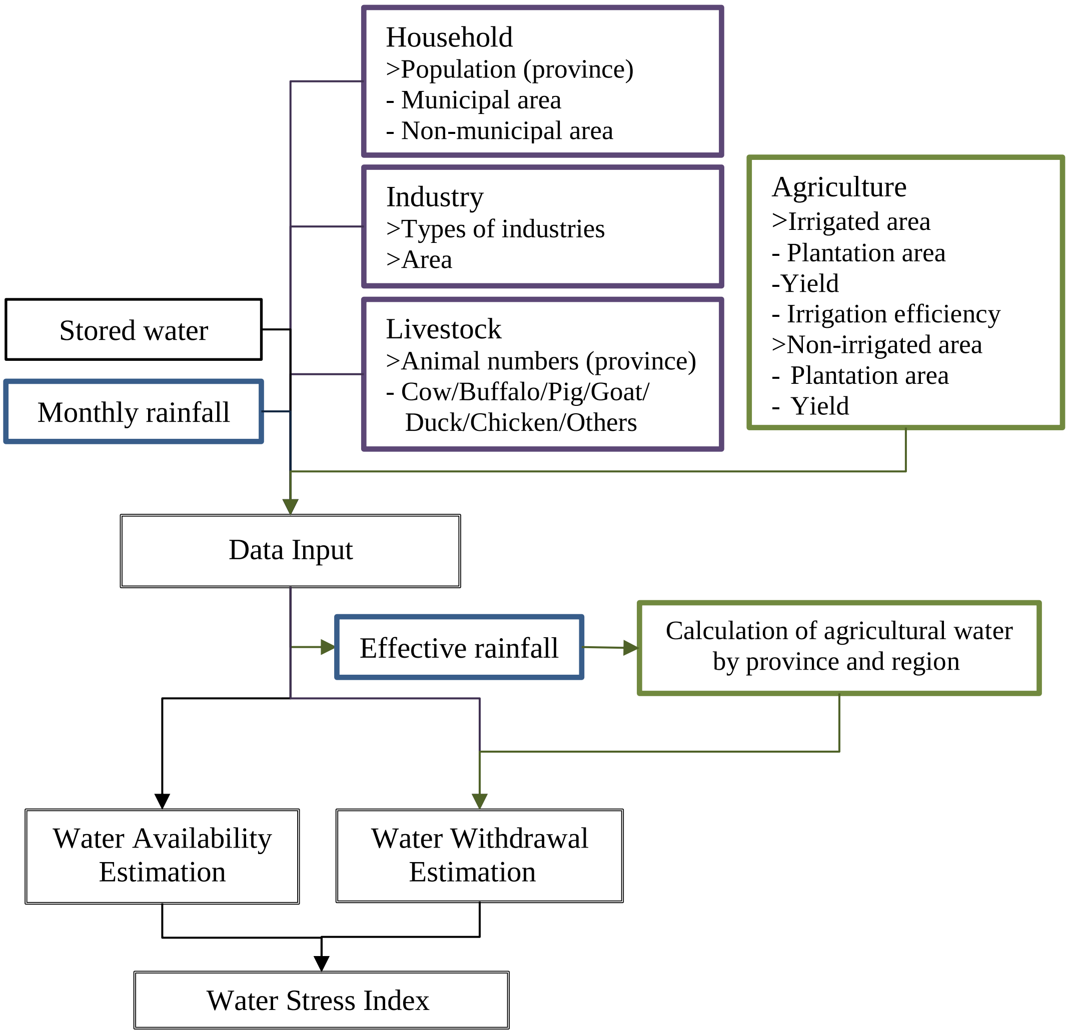

Figure 1. Calculation flow of annual WSI.

3. Results and Discussion

Figure 2 shows the annual water stress map and the water stress index (WSI) for the 25 watersheds of Thailand. The levels of water stress are still classified into five categories including extreme condition (WSI >0.9), Severe (0.5 < WSI ≤ 0.9), Stress (WSI = 0.5), Moderate (0.1 ≤ WSI < 0.5) and Low (WSI < 0.1).

The Central region, especially the Chao Phraya, Tha Chin, and Bang Pakong watersheds, is clearly noticed to the most critical area from the WSI results revealed in Figure 2. Extreme water stress is revealed in the area of the Chao Phraya watershed and severe water stress is seen in the areas of the Tha Chin and Bang Pakong watersheds. In addition, moderate water stress is observed in the Northeastern watersheds. These obtained results are caused by the agricultural sector. The amount of agricultural water requirement depends on crop and plantations, whether in irrigated or non-irrigated areas. Rice cultivation is the most significant factor affecting the water stress situation in these critical watersheds. Rice is the major economic crop of the country and mainly cultivated in the wet season known as a major rice. Rice cultivation in the dry season is called second rice; however, rice cultivation more than twice a year is also possible for some regions, particularly the Central region. As the wet season in the Central region is affected by two monsoons in two periods, the Southwest monsoon starts since mid-May to mid-August and the Northwest monsoon begins in mid-October to end of November. Thus, rice is generally grown more than one crop per year if farmers have enough water supply for land preparation. Moreover, large plantations of the second rice are found in both irrigated and non-irrigated areas. However, this is different for the Northeastern region especially the Mun and Chi watersheds, where the wet season generally comes a bit later than the Central region and most of the agricultural plantations are not in irrigated areas. Rice is largely cultivated in both irrigated and non-irrigated areas when the wet season begins. In the dry season, the amount of rainfall in the Northeastern region is lower than other regions and water storage is limited due to geographical conditions. Avoiding the second rice cultivation by cultivating legume crops is highly recommended in this region by the Department of Agriculture (DOA). Accordingly, there is very less or no rice production takes place when entering into the dry season. As a result, the water stress situation in the Northeastern region is better than in the Central region. As the extreme water stress in the Central region is due to intensive rice plantations, water taken from upper watersheds is considered as other sources for the Central region to satisfy not only the agricultural demand but also other demands for water. Therefore, this possibly leads to increase the water stress level of some watersheds in the Northern region which are connected to the Central part. Hence to manage the upper watersheds for providing additional water will help in minimizing water stress for the Central region. This however will lead to increasing potential water competition among other users and agriculture if water is not enough to satisfy all demands.

The obtained results reveal that determining crop water use by accounting for irrigated and non-irrigated crops significantly affects the WSI results because currently the non-irrigated agricultural areas are higher than the irrigated areas. In reality, the amount of crop water use depends on cultivated areas. If crops are cultivated in irrigated area, it is possible to provide enough water to fully meet the theoretical CWR. This event hardly takes place in non-irrigated areas. However, it is generally impossible to determine the exact worst-case scenario or existing situation because there are several factors related to the amount of water required by crops such as soil quality, crop species, weather conditions, farming practices and so on.

Although the annual and monthly WSI are estimated based on different equations, the updated annual WSI results in Figure 2 are determined based on the same dataset used in the monthly WSI of Gheewala et al. (2018) [3]. As only the map of monthly WSI is presented in Gheewala et al. (2018), the monthly WSI values are provided in Table 2 [3].

The results of the annual WSI revealed that Chao Phraya, Tha Chin, Bang Pakong, Mun, and Chi are still in crisis as indicated in the results of monthly WSI as well. The more variation of WSI results among the different month can also be seen in the monthly results rather than the annual results. The results of monthly WSI indicated a serious concern for the Chao Phraya and Tha Chin watersheds in the two periods between December to March and July to August. This is because of the large second rice plantations in both irrigated and non-irrigated areas of the Central region similar to the results of annual WSI. However, the situation becomes better when entering into the wet season as found in the monthly results. On the other hand, the situation is different for the Northeastern part. A low level of

Watershed	WSI
(1) Salawin	0.014
(2) Kok	0.044
(3) Ping	0.026
(4) Wang	0.021
(5) Yom	0.181
(6) Nan	0.070
(7) Khong	0.162
(8) Chi	0.302
(9) Mun	0.439
(10) Chao Phraya	0.922
(11) Sakae Krang	0.287
(12) Pasak	0.212
(13) Thachin	0.779
(14) Mae Klong	0.027
(15) Petchaburi	0.055
(16) West Coast Gulf	0.159
(17) Prachin Buri	0.079
(18) Bang Pakong	0.612
(19) Thole Sap	0.053
(20) East-Coast Gulf	0.044
(21) Peninsula-East coast	0.051
(22) Tapi	0.026
(23) Thale sap Songkhla	0.030
(24) Pattani	0.015
(25) Peninsula-West coast	0.046

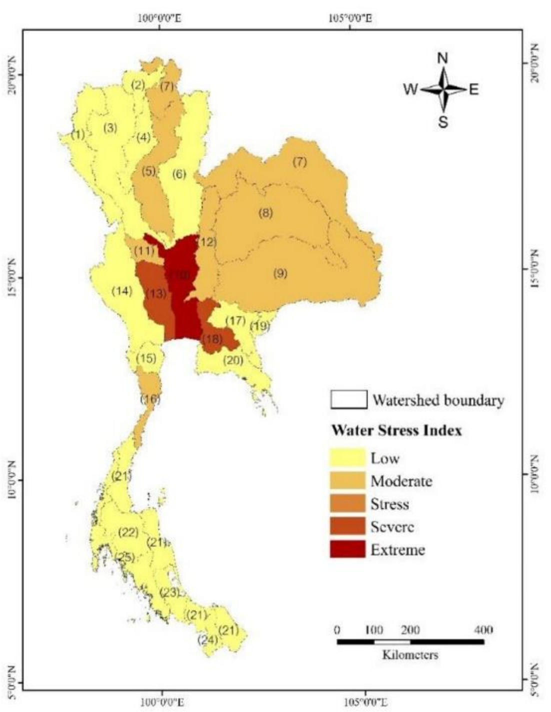

Figure 2. Annual WSI for the 25 major watersheds of Thailand.

Table 2. Monthly WSI values for the 25 major watersheds of Thailand

	Monthly WSI											
Watershed	**JAN**	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
Salawin	0.02	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Kok	0.17	0.11	0.09	0.01	0.01	0.04	0.03	0.03	0.04	0.02	0.01	0.02
Ping	0.04	0.04	0.03	0.01	0.01	0.02	0.03	0.02	0.02	0.02	0.01	0.01
Wang	0.06	0.04	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.02
Yom	0.98	0.99	0.60	0.02	0.01	0.10	0.17	0.10	0.07	0.02	0.02	0.05
Nan	0.11	0.12	0.14	0.01	0.01	0.04	0.06	0.05	0.05	0.02	0.02	0.02
Khong	0.06	0.07	0.04	0.03	0.02	0.10	0.09	0.07	0.08	0.04	0.02	0.03
Chi	0.10	0.07	0.03	0.02	0.02	0.21	0.34	0.18	0.20	0.03	0.02	0.03
Mun	0.08	0.07	0.02	0.02	0.02	0.37	0.36	0.34	0.25	0.03	0.01	0.04
Chao Phraya	1.00	1.00	0.99	0.08	0.04	0.52	0.90	0.86	0.28	0.05	0.35	0.98
Sakae Krang	0.38	0.05	0.09	0.04	0.03	0.13	0.43	0.70	0.33	0.05	0.06	0.04
Pasak	0.83	0.37	0.08	0.03	0.02	0.06	0.21	0.14	0.13	0.05	0.06	0.08
Tha Chin	1.00	1.00	0.94	0.04	0.03	0.42	0.76	0.82	0.28	0.04	0.06	0.69
Mae Klong	0.03	0.03	0.02	0.02	0.01	0.02	0.02	0.03	0.02	0.02	0.01	0.01
Phetchaburi	0.16	0.97	0.11	0.02	0.01	0.04	0.07	0.10	0.03	0.01	0.02	0.04
West Coast Gulf	0.38	0.65	0.30	0.06	0.05	0.13	0.17	0.12	0.04	0.03	0.03	0.26
Prachin Buri	0.77	0.19	0.06	0.02	0.02	0.06	0.05	0.06	0.04	0.03	0.02	0.13
Bang Pakong	1.00	0.79	0.28	0.06	0.05	0.23	0.51	0.67	0.16	0.09	0.51	0.98
Thole Sap	0.03	0.04	0.04	0.03	0.02	0.04	0.04	0.05	0.04	0.03	0.02	0.02
East-Coast Gulf	0.05	0.19	0.15	0.10	0.02	0.02	0.02	0.03	0.02	0.03	0.07	0.07
Peninsula-East coast	0.06	0.06	0.04	0.22	0.07	0.13	0.09	0.15	0.09	0.03	0.02	0.02
Tapi	0.01	0.01	0.01	0.03	0.04	0.04	0.05	0.07	0.04	0.02	0.01	0.01
Thale sap Songkhla	0.02	0.02	0.01	0.08	0.06	0.06	0.04	0.11	0.05	0.02	0.01	0.01
Pattani	0.01	0.01	0.02	0.03	0.02	0.03	0.02	0.02	0.02	0.01	0.01	0.01
Peninsula-West coast	0.03	0.04	0.01	0.11	0.05	0.04	0.05	0.04	0.03	0.02	0.02	0.02

water stress is revealed in the dry season but the situation becomes worse in the wet season as noticed in the monthly results of Mun and Chi watersheds. The moderate level is spotted in Mun and Chi during June to September. When the wet season starts, the agricultural demand for water also increases because of the intensive major rice cultivated in both irrigated and non-irrigated areas. Furthermore less rainfall and lack of water storage are limitations of this region. Overall, the monthly WSI shows that the situation of water stress in the dry season particularly during January to February becomes worse than the situation in the wet season. Gheewala et al. (2018) also presented the implications of land use change policy on converting 0.37 million ha low-productivity rice fields to sugarcane in the Northeastern and Central regions [3]. This policy potentially reduces the amount of water requirement for agriculture in the two regions and which in turn will lead to the reduction of the monthly WSI of Mun, Chao Phraya, Bang Pakong, Tha Chin, Mae Klong, Sakae Krang, etc. especially the WSI values of June to September.

The annual WSI may be useful for the top-down vision for quickly determining the potential impact from agricultural policy on water scarcity in different region. However, the monthly WSI may be useful for comprehensive assessment in order to see the potential stress and how they are affected if the shifting crop calendar policy is implemented. This is because the variation of WSI in each month has been considered. As seen from the monthly WSI values of the Chao Phraya watershed, the extreme water stress will not be found over the entire year. The high WSI values are found in two periods i.e. December to March and May to July due to high water demands for second rice and major rice, respectively. This is consistent to the cropping calendar of rice in Chao Phraya watershed as well. Accordingly, an appropriate plan for water resource management focusing on cropping system and crop calendar of each watershed is much required especially for the dry season for preventing the water problems. Changing the cropping practice can shift irrigation water consumption within a year, which in turn can increase or decrease the related water stress. Additionally, the plan for lower watershed such as Chao Phraya should be correlated with the plan of the upper watersheds such as Yom and Nan.

4. Conclusion

The annual WSI results obtained in this study are updated from a previous study, based on the more refined datasets used in developing the monthly WSI. Thus, the annual and monthly WSI of 25 watersheds are determined from the same dataset. The annual results also provide a better estimation for the 25 watersheds. The critical watersheds are found in the Central and Northeastern regions. Rice cultivated in both irrigated and non-irrigated areas as well as cropping calendar are two important factors affecting the WSI results. To support the future agricultural policy decision making in various applications, the annual and monthly WSI as well as crop water use information are essential and would be recommended as one of the criteria for further agricultural zoning.

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