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Article

Water Footprint and Impact of Water Consumption for Food, Feed, Fuel Crops Production in Thailand

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Abstract: The proliferation of food, feed and biofuels demands promises to increase pressure on water competition and stress, particularly for Thailand, which has a large agricultural base. This study assesses the water footprint of ten staple crops grown in different regions across the country and evaluates the impact of crop water use in different regions/watersheds by the water stress index and the indication of water deprivation potential. The ten crops include major rice, second rice, maize, soybean, mungbean, peanut, cassava, sugarcane, pineapple and oil palm. The water stress index of the 25 major watersheds in Thailand has been evaluated. The results show that there are high variations of crop water requirements grown in different regions due to many factors. However, based on the current cropping systems, the Northeastern region has the highest water requirement for both green water (or rain water) and blue water (or irrigation water). Rice (paddy) farming requires the highest amount of irrigation water, *i.e.*, around 10,489 million m^3/year followed by the maize, sugarcane, oil palm and cassava. Major rice cultivation induces the highest water deprivation, *i.e.*, 1862 million m^3H_2Oeq/year; followed by sugarcane, second rice and cassava. The watersheds that have high risk on water competition due to increase in production of the ten crops considered are the Mun, Chi and Chao Phraya watersheds. The main contribution is from the second rice cultivation. Recommendations have been proposed for sustainable crops production in the future.

Keywords: water footprint; water stress; crops; Thailand

1. Introduction

The agricultural sector is a major freshwater consumer and around 70% of the world's freshwater withdrawal is for irrigation [1–3]. Although irrigated agriculture constitutes only 20% of the total cultivated land, it contributes around 40% of the total food produced worldwide because irrigation can help increase yields of most crops [4]. Demand for freshwater has been increasing continuously with growing world population and economic development. It is anticipated that water withdrawal, especially for agriculture, will increase by 50% in developing countries by 2025 (base year 2000), and 18% in developed countries [5]. The World Water Development Report (WWDR) has also reported that the global water consumption of agriculture is predicted to increase by 19% or to reach to 8515 km^3 per year by 2025 [3]. Moreover, the water shortage is further exacerbated by the increase in variability of water distribution due to the impacts of climate change. Hence, water resource management is an essential issue for satisfying the increasing demand of agriculture with rising population and consequent increased demand of food. In addition, the proliferation of bioenergy and biofuels derived from crops promises to increase stress on water, an already scarce resource in many countries. This is of particular concern to Thailand, which has a large agricultural base for food for local consumption and export as well as for feed and biofuels.

Thailand is recognized as one of the leading countries in agricultural commodities' exports. Since the country's climate is tropical, *i.e.*, exhibiting hot and humid conditions throughout the year, a variety of crops, fruits as well as perennial trees can be grown nationwide. The agricultural sector shared about 12% of GDP and accounted for 38% of the total employment of the country [6]. Thailand is ranked as the world's 6th largest rice (paddy) producer but the 3rd largest rice exporter. Thailand is also the world's largest cassava producer and exporter contributing about 70% of the world market share. It is the second leading sugar exporter though still relatively small as compared to the outstanding sugarcane producer Brazil. In addition, Thailand is also the key producer of the other agricultural commodities, e.g., palm oil, natural rubber, maize, beans, fruits and vegetables [7]. The promotion of biofuels derived from domestic feedstocks, e.g., cassava, sugarcane and oil palm by the Royal Thai Government over the past decade has spurred the demand for energy crops which in turn could lead to the increased competitive pressure on water resources in some regions since the freshwater resource is unevenly distributed along the country. Thus, the information regarding water resource availability and crop water requirements in each region across the country is essential for water resource planning to satisfy the increased demand for food, feed, and biofuels production in the future.

Water footprint (WF) has been introduced as a method to indicate the water use and impacts of production systems on water resources measured as the total volume of freshwater used to produce products [8,9]. WF divides the water use into three components, *i.e.*, green, blue and grey water which are specified geographically and temporally [10]. The green water footprint refers to the volume of rainwater consumed during the production process of a product. This is particularly important for agricultural and forestry products, where it refers to the total rainwater evapotranspiration plus the water incorporated into the harvested crops and wood. Blue water footprint refers to the volume of surface and groundwater consumed (evaporated and incorporated) into the production of a product. Grey water footprint refers to the volume of freshwater required to assimilate the load of pollutants based on existing ambient water quality to comply with the defined water quality standards [11]. The concept of green and blue WF assessment has been widely applied in many studies concerning water use, especially for food and agricultural products [12–15]. WF analysis has led to a better understanding of the virtual water requirement of agricultural products which can in turn be used to evaluate the implication of agricultural trade. In addition, green/blue and direct/indirect WF distinctions can help the identification of "hotspots" linking the water use and the source of water.

Nevertheless, focusing only the volumetric WF indicator does not directly provide information on the actual impacts of water use [16]. This is because the impacts of water use in regions of water abundance cannot be directly compared to water use in regions of scarcity. It is necessary to consider the water scarcity or water stress issues at the point of water use which will generally vary based on a number of factors, e.g., geographical and climate conditions, environmental, social, economic and political factors [17]. To date, a number of metrics have been proposed to assess and map the geography of water scarcity globally. These include, for example, indicators based on human water requirements, the ratio of population to the renewable water supply, and the most common one, the ratio of total annual freshwater withdrawal to hydrological availability or namely "Withdrawal-to-Availability" (WTA) [18]. Water scarcity assessment methodologies have been further developed for more accurate assessment of global water scarcity and for the assessment of water use impacts especially those combining WF and hydrological water availability, e.g., blue water footprint scarcity [19], water stress index [20] as well as some others proposed in the life cycle assessment (LCA) community [21–24].

For Thailand, the studies on WF and the impact assessment of water use by combining WF and the water stress index are still in the preliminary stage. There have been some studies in the recent past evaluating the volumetric water consumption of field crops, e.g., sugarcane, cassava and maize [25–28]. However, those studies are site specific and lack consideration of the impacts of water use due to the different water scarcity situation in each region. This study therefore aims to (1) assess the water footprint of ten staple crops for food, feed and fuel production in Thailand by considering the country-wide scale; and (2) evaluating the water stress situation in different regions and watersheds of Thailand and the water deprivation from those ten crops in Thailand. The results from the combination of water footprint and water stress assessment are used to recommend the appropriate measures for enhancing water resource use and efficiency for future food, feed, and fuel crops production in Thailand.

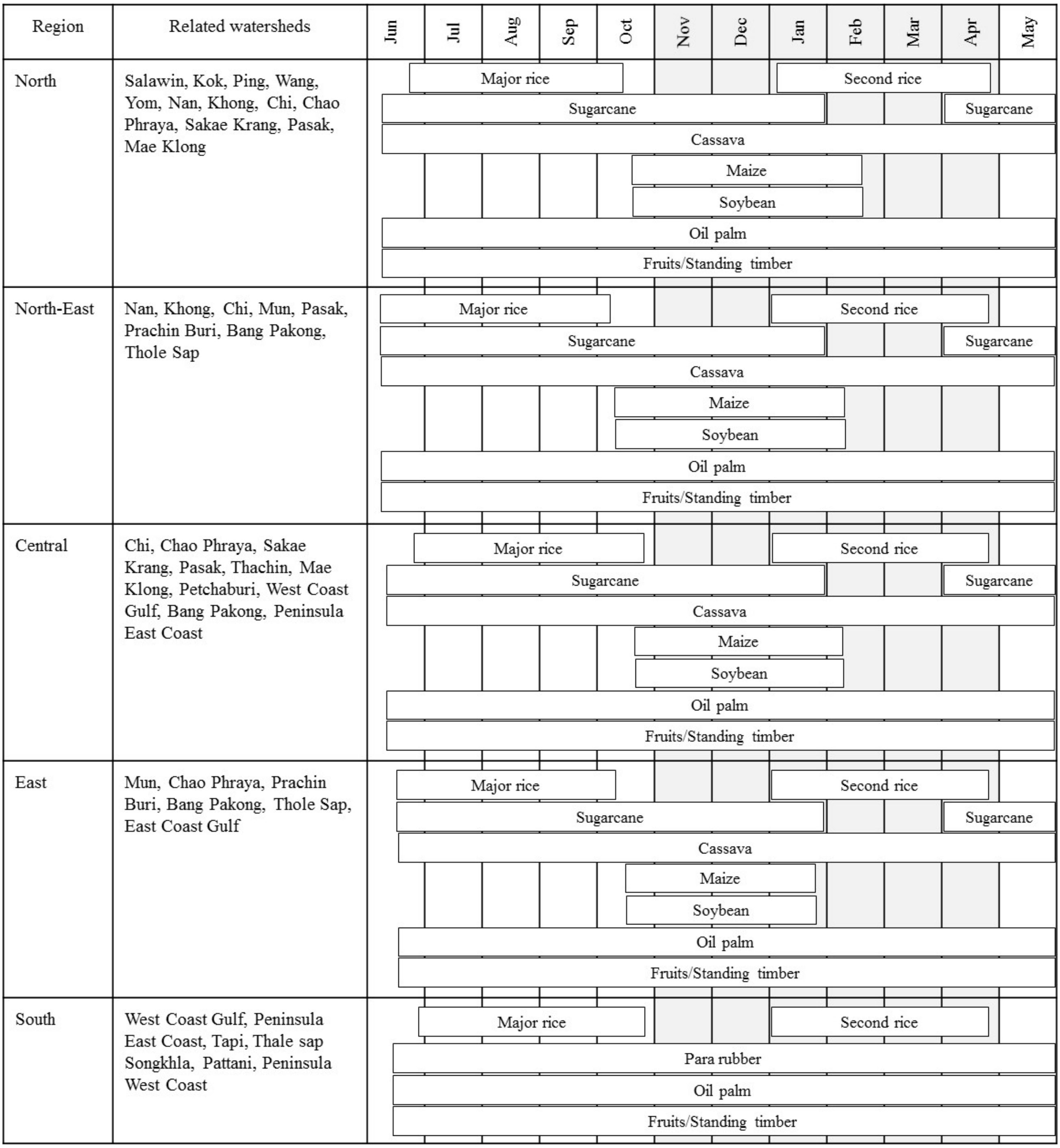
2. Staple Crops Cultivation in Thailand

Agricultural land accounts for around 41% of the total land area of Thailand or about 21 million hectares [7]. Thailand is divided into five regions including North, Northeast, Central, East, and South covering all 76 provinces. The cultivation patterns and water use by the staple crops in different regions will be different depending on their respective geographical and climate conditions. Table 1 shows the planted areas of the ten studied crops classified by regions. Rice is grown nationwide and has the largest plantation area covering around 70% of the plantation areas of the total ten studied crops. Rice can be classified into two types, *i.e.*, major and second rice. Major rice refers to the rice grown during the wet season (*i.e.*, May–October), while, the second rice refers to the rice grown in the dry season (November–April). The largest major rice plantation areas are in the Northeastern region. However, they do not have second rice due to the lack of irrigation system. Second rice is mainly grown in the North and Central regions which are well irrigated. In addition, the Northeastern region is also the main region for cultivation of field crops like cassava and sugarcane. Oil palm is widely grown in the Southern region where the climate is rainy and humid. This region has about 86% of the total oil palm plantation areas of the country. Figure 1 shows the actual cropping calendars for the various crops in different regions of Thailand. This will be used for the calculation of crop water requirement. The dry and wet seasons have been defined by the Royal Irrigation Department (RID) as running from November through April and May through October, respectively.

Table 1. Plantation areas of the 10 studied crops classified by region.

Studied crops	Plantation areas in 2011 (hectare)				
	North	**Northeast**	**Central**	**East**	**South**
Major rice	2,081,888	5,631,790	867,531	360,430	187,646
Second rice	945,906	457,533	728,241	110,071	59,367
Maize	695,333	302,346	76,066	32,802	–
Soybean	66,574	15,471	278	373	–
Mungbean	141,930	3,333	1,757	490	234
Peanut	16,711	10,106	1,282	118	634
Cassava	203,009	614,102	96,536	228,712	–
Sugarcane	294,267	507,617	314,411	81,226	–
Pineapple	14,790	3,375	62,303	19,525	1,073
Oil palm	3,185	9,109	39,559	35,698	552,072
Coconut	2,485	1,731	73,769	14,982	113,141
Total	4,466,078	7,556,513	2,261,733	884,427	914,167

Figure 1. Cropping calendar.



3. Methodology

3.1. Quantification of Crop Water Requirement

The WF assessment concept was used to assess the total water requirements of ten staple crops grown in different regions of Thailand. The assessment has been conducted to evaluate the amount of consumptive water use of those crops classified by each province and respective cropping calendars. The total water footprint of the cultivation process (WF_{crop}) is adapted from the general formula of Hoekstra *et al.* [10] (2011), *i.e.*, $WF_{crop} = WF_{crop,green} + WF_{crop,blue}$ [m^3/ton]; where $WF_{crop,green}$ refers to the green water used for growing a crop (in other words, it implies to the total rainwater evaporated from the field during the growing period) [m^3/ha], $WF_{crop,blue}$ refers to the consumption of blue water resources, *i.e.*, water from rivers, lakes or extracted from underground (or the total irrigation water evaporated from the field during the growing period) [m^3/ha]. The grey water which was introduced in the general *WF* formula of Mekonnen and Hoekstra [12] (2011) is not taken into consideration because it is not a physical quantity of water use, but associated to water pollution**.**

To determine WF_{green} and WF_{blue} of crops or the related agricultural products, the "Crop evapotranspiration (*ET*)" are calculated from the crop coefficient (K_c) and the reference crop evapotranspiration (ET_0) by the Equations (1) and (2) [10]:

$$ET_{crop} = K_c \times ET_0 \text{ (mm/day)} \tag{1}$$

$$WF_{crop} = 10 \times \sum_{d=1}^{lgp} ET_{crop} \text{ (m}^3\text{/ha)} \tag{2}$$

Evapotranspiration is the combination of two processes whereby water is lost, *i.e.*, from soil surface by evaporation and from the crop by transpiration [29]. ET_{crop} represents crop evapotranspiration [mm/day], K_c represents crop coefficient [dimensionless], and ET_0 represents the reference Penman-Monteith crop evapotranspiration [mm/day]. ET_0 for each province has been taken from the Irrigation Water Management Division (IWM), RID of Thailand [30]. The Irrigation Water Management Division of Thailand has calculated ET_0 based on the monthly climatic data of 30 years (1981–2010) including Minimum Temperature, Maximum Temperature, Humidity (%), Wind (km/day), Sun hours, and Radiation (MJ/m^2/day) reported by the Meteorological Department of Thailand. For the crop coefficient (K_c) of the ten studied crops, values have also been taken from IWM [31] (2008) and relevant literature [32,33]. The values of crop coefficient (K_c) have been calculated from the relationship between the ET_0 calculated from climatic data and the actual water consumption from experiments using the Lysimeter tank.

Equation (2) shows the general formula to calculate WF_{crop}. The factor 10 is used to convert water depth in millimeters into water volume per land surface in m^3/ha. The summation will be done over the period from the day of planting (day 1) to the day of harvest (lgp stands for length of growing period in days). The step-by-step method to classify the crop evapotranspiration (ET_{crop}) obtained from Equation (1) into $WF_{crop,green}$ and $WF_{crop,blue}$ is as follows:

- Calculating the evapotranspiration (ET_{crop}) for each crop grown in each region;
- Calculating the effective rainfall in each region during the crop growing period;
- $WF_{crop,green}$ is evaluated by comparing the monthly evapotranspiration (*ET*) of crops during the growing period (in each region) with the effective rainfall during the crop growing period. Then, if ET > effective rainfall, $WF_{crop,green}$ will be equal to the effective rainfall; however, if *ET* < effective rainfall, $WF_{crop,green}$ will be equal to *ET*;
- $WF_{crop,blue}$ is evaluated as the "irrigation water" that is required to achieve the crop evapotranspiration if the effective rainfall is not enough, *i.e.*, if *ET* > effective rainfall, $WF_{crop,blue}$ = *ET*—effective rainfall; however, if *ET* < effective rainfall, $WF_{crop,blue}$ = 0.

Effective rainfall data are taken from the RID [34]. The crop growing periods in each province as well as the cultivated areas and productivity are referred from the Office of Agricultural Economics (OAE) [7]. It must be noted that the ET of crops obtained is the theoretical water requirement. The real

ET might be lower especially in the locations where water stress has occurred. Detailed information about ET_0, K_c and effective rainfall calculations has also been provided in the Tables S1–S4 of supporting information (SI), respectively.

3.2. Water Stress Index (WSI) and Water Use Impact Assessment

A unit of water consumed for growing crops in a region where water stress exists would have more impacts than the same amount of water used in a region of water abundance. To evaluate the impact of water use for crops grown in the different regions and watersheds of Thailand, the "water stress index (WSI)" of Pfister *et al.* [20] (2009) was used as the tool to indicate the extent of water scarcity in the various watersheds. Thailand is located in the south eastern region of Asia, between 5°–20° N and 97°–105° E. The country's climate is therefore mainly tropical, *i.e.*, exhibiting hot and humid conditions throughout the year. For hydrological purposes, the Office of the National Water Resources Committee has divided Thailand into 25 major river basins. We evaluated the water stress index (WSI) of watersheds by using the method developed by Pfister *et al.* [20] (2009) and Ridoutt and Pfister [35] (2010) as shown in Equation (3):

$$WSI = \frac{1}{1 + \mathrm{e}^{-6.4WTA^{*}\left(\frac{1}{0.01}-1\right)}} \tag{3}$$

Regarding the logistic function for WSI presented in Equation (3), the lower and upper limits of water stress index (WSI) values are set at 0.01 and 1, respectively. The levels of water stress are classified into five categories including extreme ($WSI > 0.9$), severe ($WSI \leq 0.9$), stress ($WSI = 0.5$), moderate ($0.1 \leq WSI < 0.5$) and low ($WSI < 0.1$). To estimate the WSI for the 25 watersheds of Thailand, the "weighted withdrawal-to-availability" or "WTA *" of each watershed is calculated from Equation (4). The WTA^* is the ratio of total water withdrawals to hydrological availability of a basin or "WTA" after adjusting with the variation factor (VF) of water flows due to the monthly and annual variations of rainfall as shown in Equation (5). S^{*}_{month} and S^{*}_{year} represent the standard deviations of monthly and annual rainfall over the past ten years of each watershed.

$$WTA^{*}{}_{i} = \sqrt{VF} \times WTA_{i} \tag{4}$$

$$VF = \mathrm{e}^{\sqrt{\ln{(S^{*}_{\text{month}})^2} + \ln{(S^{*}_{\text{year}})^2}}} \tag{5}$$

The WTA of a basin (i) shown in the Equation (4) is the ratio of total water withdrawals to hydrological availability of a basin calculated from the Equation (6):

$$WTA_i = \sum_{\text{j}} \times WU_{ij}/WA_i \tag{6}$$

where WTA_i represents the withdrawal to availability ratio for each watershed i; WU_{ij} refers to the water withdrawal from watershed/basin i by each sector j (or commonly referred as the sum of estimated water use for industrial, agricultural, and domestic sectors); WA_i represents the water availability of the watershed/basin i (and it is estimated as the sum of the precipitation and the stored water in the reservoir from the end of previous year). The published data on WU_j from the RID have been referred in the assessment [36,37]. Detailed information about water use coefficients for various sectors including industrial, agricultural and domestic sectors and the water availability (WA_i) of each watershed have been shown in Tables S5–S9 of the supporting information.

The obtained WSI for the 25 watersheds of Thailand derived from Equation (3) have been applied to evaluate and compare the impact of water use for crop cultivation in different regions by quantifying the "WSI-weighted water volume consumed" or so called "water deprivation" [38]. This water deprivation quantifies the amount of water deficient to downstream human users and ecosystems. It can be calculated by multiplying the blue WF of crops with the water stress index (WSI) in the specific location *i* as shown in the Equation (7):

$$\text{Water deprivation}_{\text{crop},i} = WF_{\text{crop,blue},i} \times WSI_i \quad (7)$$

The unit of water deprivation is m^3 water-equivalents (m^3H_2Oeq) [38]. The advantage of calculating the water deprivation values is that policy makers can compare the impact of water consumed for growing crops in various regions of Thailand where the water stress levels are different. Lower water deprivation indicates lower impacts on water consumed due to the lesser water competition with other users, e.g., downstream human users and ecosystems.

4. Results and Discussion

4.1. Potential Water Requirements of Staple Crops in Thailand

Table 2 shows the comparison of water requirements of the ten studied crops grown in Thailand. The results indicate that per hectare of planted area, oil palm, pineapple and coconut require the highest amount of water since they are perennial trees and hence need water all year round. For the field crops, cassava has the highest crop water requirement per hectare at around 7827 m^3, followed by rice (5354 m^3) and maize (3756 m^3), respectively. For rice, it is clear that the high water requirement is because the paddy field cultivation is under flooded conditions. However, the high water requirement for cassava is because its cropping period is over the whole year unlike rice which has a short cropping cycle. Based on a ton of crop produced, mungbean has the highest water requirement followed by oil palm, coconut, peanut and rice, respectively. Sugarcane and cassava have the two lowest water requirements per ton of crop produced, *i.e.*, around 159 and 395 m^3/ton. Furthermore, the crops grown in different regions would have high variations of water requirements resulting from the difference of weather, and especially crop productivity. For example, the total water footprint of major rice and oil palm can range between 1224–2581 m^3/ton of paddy rice and 1072–5508 m^3/ton of fresh fruit bunches, respectively. Nevertheless, it must be noted that the crop water requirement results shown in Table 2 are the theoretical values of consumptive water use for crops; in actual practice the water use might be lower as some crops are cultivated in non-irrigated areas.

Table 2. Water footprint of the studied crops grown in Thailand.

Staple Crops	Water Footprint (m^3/ha) *				Water Footprint (m^3/ton **)	
	Green WF	Blue WF	Total WF	Range (m^3/ha)	Average (m^3/ton **)	Range (m^3/ton **)
Major rice	4,079	1,275	5,354	4,876–5,570	2,005	1,224–2,581
Second rice	1,179	3,948	5,127	3,306–5,823	1,487	1,147–1,806
Maize	1,014	2,741	3,756	3,292–4,163	982	837–1,084
Soybean	811	2,276	3,087	2,758–3,431	1,851	1,676–2,344
Mungbean	565	1,488	2,053	1,428–4,017	2,980	1,549–6,445
Peanut	863	2,278	3,141	2,804–3,475	2,236	1,800–2,580
Cassava	6,529	1,297	7,827	7,712–7,891	399	394–413
Sugarcane	7,920	2,442	10,362	10,037–10,587	160	150–174
Pineapple	8,323	5,402	13,725	13,376–13,935	611	472–747
Oil palm	8,323	5,405	13,728	13,376–13,935	2,941	1,072–5,508
Coconut	8,245	5,402	13,647	13,376–13,921	2,474	2,028–2,856

Notes: * The values of water footprint are per crop cycle for annual crops and per year for perennial crops (pineapple, oil palm and coconut); ** Average yield 2009–2011.

4.2. Irrigation Water Requirements of Staple Crops Production in Thailand

Blue water has been attached more significance from the policy makers' point of view than green water because it has more economic value especially for agriculture in dry season. The irrigation water demand varies based on two key factors, *i.e.*, effective rainfall and yield. Table 3 shows the average irrigation water requirement of crops. The results indicate that cultivation of mungbean requires the highest amount of irrigation water, *i.e.*, 2994 m^3/ton followed by soybean, peanut, oil palm and second rice, respectively. Most of the irrigation water would be required for the cultivation of crops during the dry season. Based on the ranges of irrigation water required per ton of product in the dry season, water resource management is essential for growing second rice, maize, soybean, mungbean, and oil palm in the Northeastern region which significantly has the lowest precipitation during dry season as compared to other regions. The precipitation maps for wet and dry seasons of Thailand derived from ten-year average data have been shown in Figure 2. The suitable planning of crop cultivation period is also necessary to match which the irrigation water availability in each year.

Based on the total planted areas of Thailand and average crop yields during year 2010/2011 [7], the total water requirement (blue + green WF) and total irrigation water requirement (blue WF) for cultivating the ten studied crops are shown in Figure 3. The Northeastern region has the highest water requirement sharing about 45% of the total water requirement of about 102,390 million m^3/year, followed by the North and Central which share about 24% and 15%, respectively. However, the irrigation water requirement for growing those ten staple crops is only about 35,889 million m^3/year (or equivalent to 63% of the active water stock in 2011). The Northeastern region needs the highest amount of irrigation water. However, the percentage shares of the Central and Northern regions are higher as compared to the total water requirement. For the current cropping profile of Thailand, rice farming requires the highest amount of irrigation water, *i.e.*, around 11,290 million m^3/year followed by sugarcane, maize, oil palm, cassava, coconut, pineapple, mungbean, soybean, and peanut, respectively. The key provinces that require a high amount of water for staple crops cultivation are

Nakhon Ratchasima and Khon Kaen (in the Northeastern region), and Nakhonsawan, Suphanburi and Prachuapkhirikhan (in the Central region).

Table 3. Irrigation water requirement for staple crops production in Thailand.

Staple Crops	Irrigation Water Requirement (m^3/ton)		Range (m^3 of Irrigation Water Required/ton)	
	Dry season	Wet season	Dry season	Wet season
Major rice	–	520	–	296 (N)–771 (S)
Second rice	1139	–	597 (S)–1710 (NE)	–
Maize	850	–	680 (N)–953 (NE)	–
Soybean	1628	–	1347 (N)–2038 (NE)	–
Mungbean	2998	–	1698 (C)–5693 (NE)	–
Peanut	1559	–	384 (S)–2158 (E)	–
Cassava	65	21	52 (N)–80 (NE)	4 (N)–39 (C)
Sugarcane	28	17	24 (N)–29 (C)	5 (N)–34 (C)
Pineapple	226	26	135 (S)–326 (C)	6 (N)–67 (C)
Oil palm *	1174	90	173 (S)–2516 (NE)	32 (E)–181 (NE)
Coconut	870	104	450 (S)–1210 (NE)	32 (N)–179 (C)

Remarks: N: Northern region; NE: Northeastern region; S: Southern region; C: Central region; E: Eastern region; * For oil palm, fresh fruit bunch yield were the average of all regions.

Figure 2. Precipitation maps for wet and dry seasons of Thailand. (**a**) Dry season; (**b**) Wet season.

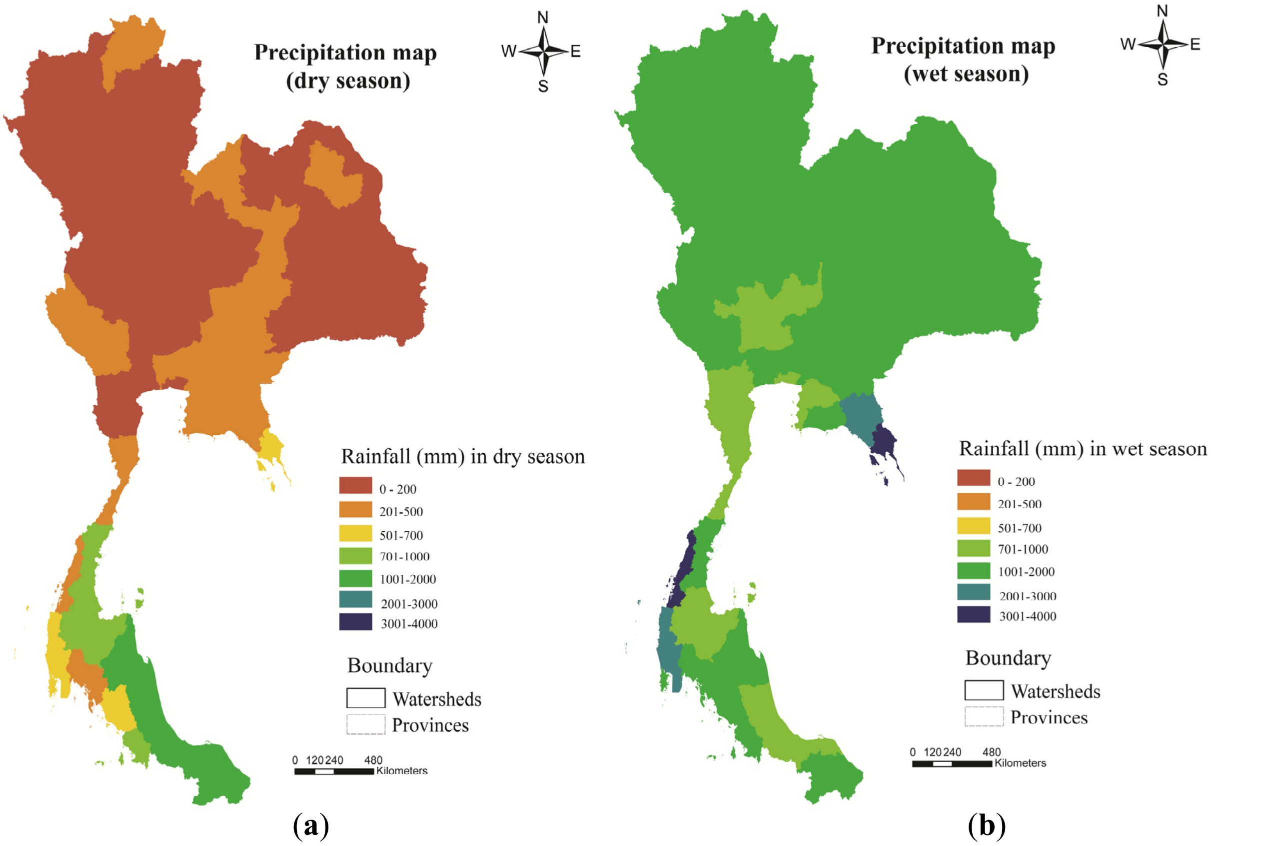
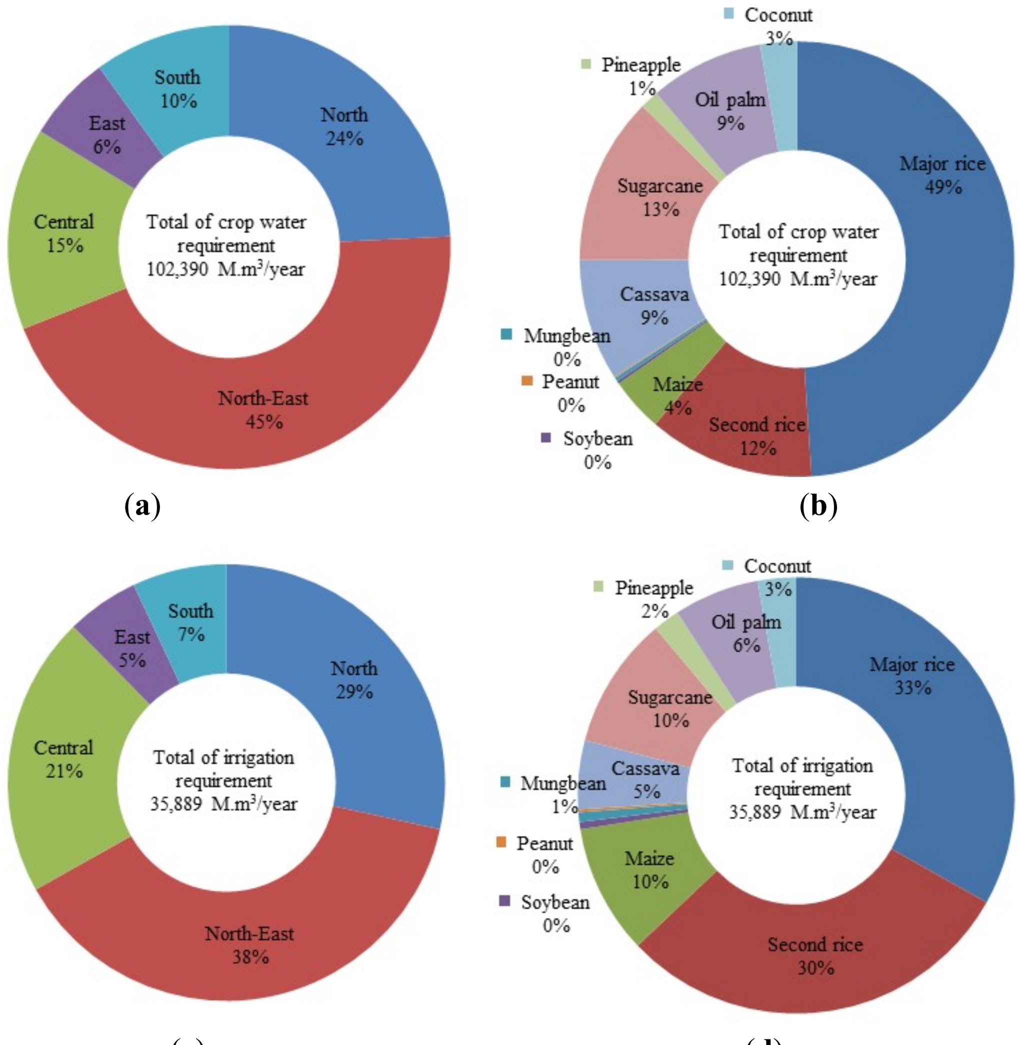


Figure 3. Total and Irrigation water requirements for crops cultivation classified by regions and products. (**a**) Total water requirements for crops cultivation classified by regions; (**b**) Total water requirements for crops cultivation classified by products; (**c**) Total irrigation water requirements for crops cultivation classified by regions; (**d**) Total irrigation water requirements for crops cultivation classified by products.

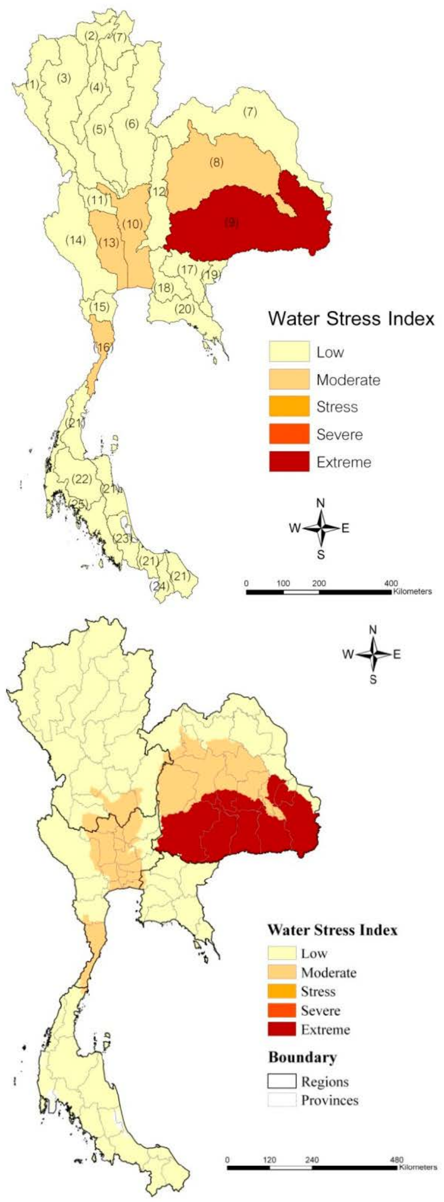


4.3. Impact of Water Use from Agriculture in Thailand

Figure 4 shows the WSI of the 25 watersheds of Thailand obtained from the WSI assessment. They are used as the factors to calculate the impact of water use for crops cultivation in terms of water deprivation potential. The regions having lower water deprivation values have potentially lower impacts from water consumed if the crops were grown there. The policy makers should therefore promote crop cultivation or make the agricultural zoning areas by taking into account such information. Table 4 shows the total water deprivation ($m^3 H_2Oeq$/year) for the ten staple crops plantation in each watershed of Thailand based on plantation areas of year 2012. The results indicate that, for Thailand, major rice has the highest water deprivation, *i.e.*, 1862 million $m^3 H_2Oeq$/year; followed by sugarcane, second rice and cassava cultivation which have the water deprivation about 944, 925 and 598 million $m^3 H_2Oeq$/year, respectively.

Major rice induced high water deprivation in Mun, Chi and Chao Phraya watersheds. Second rice plantation potentially causes high water deprivation in Mun, Sakaekrung, Chi and Chao Phraya watersheds. Sugarcane caused the high water deprivation in Mun, Chi and Thachin. Meanwhile, cassava causes high water deprivation in Mun, Chi and East Coast Gulf watersheds. For oil palm, although the largest plantation areas are found in the Southern regions of Thailand, the highest total amount of water deprivation for oil palm plantations is at the West Coast Gulf watershed (located in the central region). This is because of the high rainfall in the south and the climate which is more suited for oil palm as compared to the other regions of Thailand which would require the higher amount of irrigation water to satisfy the crop water requirement. Mungbean and soybean have relatively high irrigation water requirements per ton product, but their plantation areas and hence overall contributions to the creation of water competition is much lower than the key economic crops like rice, cassava and sugarcane.

Figure 4. Water stress index based on average annual rainfall classified by (**a**) watersheds; and (**b**) provinces.



(**a**) (**b**)

Watersheds	WSI
(1) Salawin	0.017
(2) Kok	0.018
(3) Ping	0.023
(4) Wang	0.021
(5) Yom	0.044
(6) Nan	0.015
(7) Khong	0.014
(8) Chi	0.471
(9) Mun	0.927
(10) Chao Phraya	0.339
(11) Sakae Krang	0.031
(12) Pasak	0.050
(13) Thachin	0.287
(14) Mae Klong	0.018
(15) Petchaburi	0.022
(16) West Coast Gulf	0.158
(17) Prachin Buri	0.016
(18) Bang Pakong	0.026
(19) Thole Sap	0.019
(20) East-Coast Gulf	0.015
(21) Peninsula-East coast	0.067
(22) Tapi	0.060
(23) Thale sap Songkhla	0.014
(24) Pattani	0.025
(25) Peninsula-West coast	0.012

Table 4. Water deprivation of major food, feed, and fuel crops in Thailand.

Region	Related Watershed	Water Deprivation ($M \cdot m^3 H_2Oeq$)										
		Major Rice	**Second Rice**	**Maize**	**Soybean**	**Mungbean**	**Peanut**	**Cassava**	**Sugarcane**	**Pineapple**	**Oil Palm**	**Coconut**
North	Salawin	2.02	1.75	13.14	1.01	0.67	0.23	0.26	0.11	–	0.002	0.20
	Kok	12.19	20.24	11.02	1.49	0.04	0.24	0.11	0.51	0.71	0.19	–
	Ping	21.23	52.04	16.00	2.19	1.94	0.42	7.36	9.55	1.5×10^{-4}	0.43	0.15
	Wang	8.58	3.29	7.74	1.26	0.18	1.17	0.12	1.14	1.79	0.01	0.05
	Yom	25.19	71.31	9.18	1.00	2.09	0.23	5.96	8.72	0.36	0.36	0.03
	Nan	29.90	55.00	36.91	0.51	7.69	0.23	2.29	10.04	0.93	0.13	0.33
	Khong	2.51	3.27	2.92	0.08	0.25	0.03	0.05	0.24	0.12	0.03	0.01
	Chi	2.10	1.22	7.31	0.01	1.97	0.01	0.24	1.34	–	–	0.07
	Chao Phraya	110.27	146.50	35.95	0.05	9.15	0.40	9.46	43.61	–	0.14	0.66
	Sakae Krang	178.04	250.78	36.73	0.09	9.14	0.61	17.81	70.46	–	0.41	0.85
	Pasak	63.35	36.99	221.04	0.38	59.57	0.42	7.19	40.39	–	1.66×10^{-7}	2.11
	Mae Klong	0.77	0.67	7.27	0.19	0.38	0.09	0.15	0.06	–	1.22×10^{-4}	0.11
North-east	Nan	0.02	9.08×10^{-4}	0.13	0.004	–	3.59×10^{-5}	0.01	0.01	2.6×10^{-4}	0.002	1.40×10^{-4}
	Khong	78.20	22.17	38.49	1.26	0.01	0.73	14.51	19.79	0.10	2.39	0.12
	Chi	469.90	230.80	51.87	8.44	1.90	1.58	86.30	181.65	2.11	0.81	0.26
	Mun	1194.18	288.65	199.41	0.24	2.77	3.62	248.47	188.83	6.5×10^{-4}	5.30	1.21
	Pasak	120.36	36.48	44.89	0.47	0.58	0.11	41.96	33.44	0.12	0.21	0.09
	Prachin Buri	16.37	4.73	5.20	–	0.07	0.01	5.69	4.21	–	0.009	0.01
	Bang Pakong	0.02	0.006	0.007	–	9.71×10^{-5}	1.97×10^{-5}	0.008	0.006	–	1.22×10^{-5}	1.57×10^{-5}
	Thole Sap	0.17	0.02	7.79×10^{-5}	–	–	8.49×10^{-4}	0.01	0.01	–	2.25×10^{-4}	2.62×10^{-5}

Table 4. *Cont.*

Region	Related Watershed	Water Deprivation ($M \cdot m^3 H_2Oeq$)										
		Major Rice	Second Rice	Maize	Soybean	Mungbean	Peanut	Cassava	Sugarcane	Pineapple	Oil Palm	Coconut
Central	Chi	0.005	0.02	0.008	–	8.20×10^{-5}	8.19×10^{-5}	0.003	0.01	–	–	–
	Chao Phraya	38.92	116.37	23.57	–	0.26	0.25	8.40	31.03	0.02	0.40	0.17
	Sakae Krang	1.24×10^{-5}	2.57×10^{-5}	1.40×10^{-7}	–	2.52×10^{-8}	1.43×10^{-8}	1.04×10^{-6}	2.48×10^{-6}	–	–	5.96×10^{-8}
	Pasak	22.32	70.36	30.99	–	0.33	0.33	10.47	38.16	–	–	0.01
	Thachin	94.88	239.79	9.29	0.04	0.03	0.04	5.62	91.60	2.92	0.56	0.54
	Mae Klong	20.02	45.24	9.84	0.14	–	0.11	10.22	53.68	7.76	2.34	0.87
	Petchaburi	24.17	18.17	0.96	–	–	0.13	1.05	10.78	10.91	2.61	4.17
	West Coast Gulf	7.72	2.75	0.36	–	–	0.03	0.01	6.84	75.78	58.68	119.22
	Bang Pakong	0.11	0.33	–	–	–	–	–	–	–	0.02	0.001
	Peninsula-East coast	0.07	0.02	0.004	–	–	2.21E-4	–	0.08	0.97	0.76	1.54
East	Mun	0.006	0.002	0.003	1.88×10^{-5}	3.59×10^{-7}	7.48×10^{-6}	0.003	0.002	–	3.59×10^{-4}	1.30×10^{-5}
	Chao Phraya	2.01	3.44	0.04	0.005	–	-	0.57	0.22	0.07	0.14	0.10
	Prachin Buri	104.22	59.65	39.65	0.33	0.01	0.11	48.22	35.82	0.09	5.42	0.51
	Bang Pakong	33.04	56.51	0.74	0.08	2.88×10^{-4}	8.04×10^{-6}	10.37	4.58	1.46	3.34	2.32
	Thole Sap	136.32	17.28	63.57	0.36	–	0.18	53.67	56.24	0.05	8.51	0.04
	East-Coast Gulf	0.28	0.30	0.46	6.62×10^{-5}	–	2.45E-3	1.32	0.97	0.59	1.33	0.65
South	West Coast Gulf	0.03	0.01	–	–	–	1.39×10^{-4}	–	–	0.04	4.31	1.14
	Peninsula-East coast	7.41	2.21	–	–	–	8.02×10^{-4}	–	–	0.17	32.18	8.74
	Tapi	4.18	1.49	–	–	–	6.72×10^{-4}	–	–	–	48.59	9.16
	Thale sap Songkhla	10.36	2.12	–	–	–	–	–	–	–	1.49	0.48
	Pattani	1.91	0.10	–	–	–	–	–	–	–	0.42	0.57
	Peninsula-West coast	1.33	0.43	–	–	–	9.13×10^{-6}	–	–	0.001	9.98	0.54
	Total	2844.7	1862.5	924.7	19.6	99.0	11.3	597.9	944.2	107.1	191.5	157.0

Figure 5 shows the contribution of total irrigation water requirements for growing all ten crops classified by watersheds. The largest irrigation water requirement was found for the Mun watershed, followed by Chi and Chao Phraya. After including the WSI indicator of each watershed into the assessment to calculate the total amount of water deprivation (Figure 6), the Mun watershed (located in the Northeastern region) is still the most important hotspot for water use impact due to crops production, *i.e.*, the Mun watershed potentially faces the highest competitive pressure on water use for food, feed, fuel crops production; followed by Chi, Pasak and Chao Phraya watersheds, respectively. This is due to two reasons, *i.e.*, the Mun watershed has the highest WSI as well as has the largest crop plantation areas.

Figure 5. Share of irrigation water requirements for staple crops production in 2012 classified by watersheds.

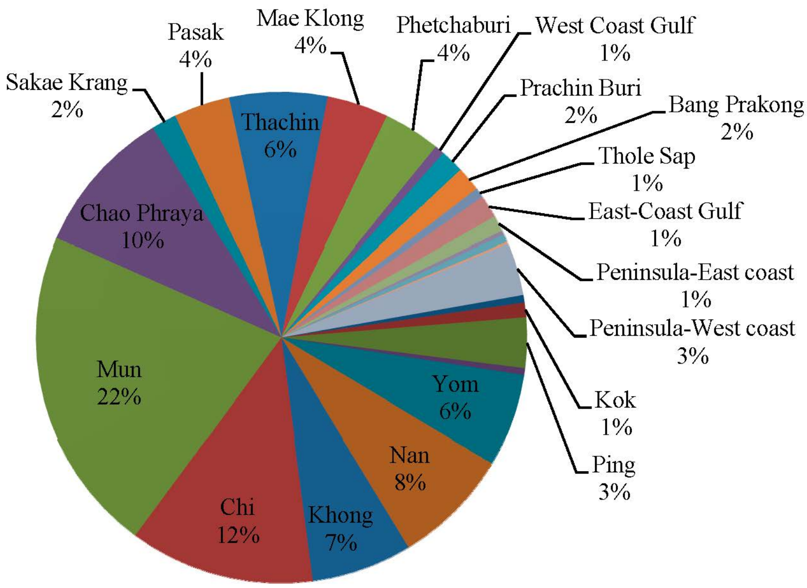
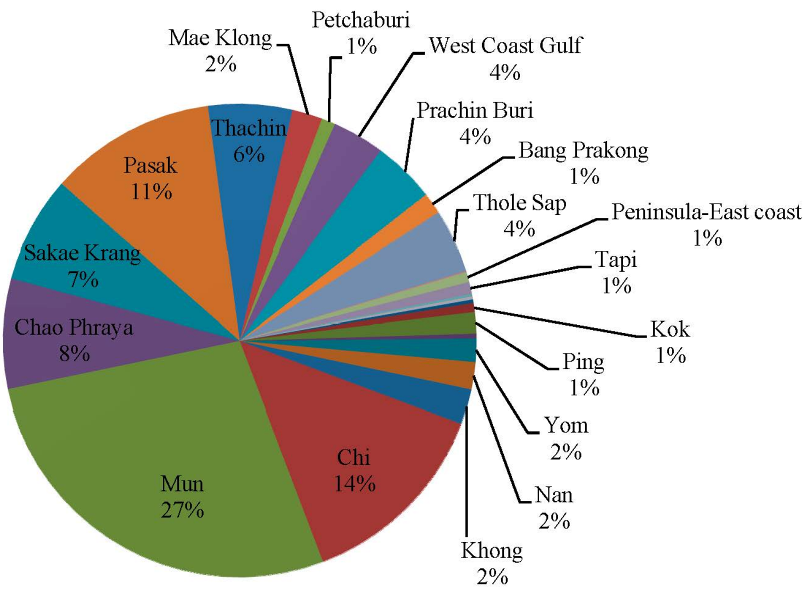


Figure 6. Share of water deprivation from staple crops production in 2011 classified by watersheds.



4.4. Recommendations for Further Water Resource Management for Crops Production in Thailand

The study reveals that there is a necessity for the government to have an appropriate plan for sustainable water resource management to avoid and/or mitigate the water stress arising from the increase of agricultural water requirement in the future. The increased demands for water are not only for food and feed crops but also for fuel crops according to the energy policy. Therefore, the following measures are recommended to reduce water footprint of crops and to enhance the water resource management efficiency for the agricultural sector in Thailand.

4.4.1. Crop WF Reduction

Water footprint of crops depends on many factors, the most important being the crop yield. To reduce the water footprint, crop productivity needs to be improved. The average staple crop yields nowadays, e.g., for cassava and sugarcane (19 and 76 tons/ha respectively) are still lower than their genetic potentials (31–50 and 94–112 ton/ha, respectively). To achieve the high genetic potential yields, good agricultural practices especially for the small scale farmers in rural areas are imperative, e.g., improving soil quality by using organic fertilizers and good practices in land preparation, plantation, harvesting and regular weed control. The areas focused by the government agencies should be the cassava and sugarcane plantations in the Mun and Chi watersheds where the large scale bio-ethanol plants are being established due to the bio-ethanol promotion policy of the government [39].

For paddy, which needs relatively high water inputs especially irrigation water in dry season, the efficient use of irrigation water use during growing rice is therefore essential for the areas with limited water resources [40]. Rice water productivity can be improved by developing high yield varieties and improving agronomic management, *i.e.*, improving pest control, straw mulching, and nutrient management to enhance yields [41]. Furthermore, water use for land preparation can be reduced through land leveling, reducing the land preparation period or even the dry tillage technique. Rice planting practices such as wet or even dry seeding of rice will also consume less water than the traditional rice transplantation method. Moreover, as the water management practices during the first two weeks from planting are essential to enhance weed suppression, the early flooding of wet seeded rice and the intermittent flooding during crop growing can help reduce water use.

Policy on research and development for improving crop varieties, especially those suitable for energy production needs to be adopted. For example, ideal fuel crops in the water supply perspective to minimize the WF of biofuels should be drought-tolerant, high-yield crops grown on little irrigation water or non-irrigated areas. The Cane and Sugar Research and Development Center, Kasetsart University has, for example, introduced a high yield, drought resistant sugarcane variety [42]. In addition, shortening of the crop cycle is also a possible method to reduce the crop evapotranspiration. However, this must be traded off with lower biomass accumulation which in turn will decrease the final yields.

4.4.2. Irrigation Development in the High Potential Water Stress Areas

The *WF* and *WSI* assessment in the paper reveal that the development and improvement of irrigation system should be promoted in the areas that potentially have high water stress due to the expansion of biofuels industry, e.g., Mun and Chi watersheds. The promotion should not include only large scale water storage implementation, but small scale irrigation systems using local water reservoirs in the plantation areas are also possible, e.g., surface irrigation, sprinkler irrigation, micro-irrigation, and sub-surface irrigation and water storage system. The technique such as drip irrigation system in which the water is directly input into the soil or onto the soil surface to reduce the risk of run-off and to reduce evaporation loss can also be applied for some crops/vegetables cultivation. However, the government policy to support investment in irrigation systems to conserve water is necessary.

4.4.3. Promoting Expansion of Energy Crop Cultivation in the Suitable Areas

Government policy has emphasized the promotion of crop productivity improvement instead of expanding the cultivation areas. This is in order to avoid the other consequent impacts, *i.e.*, not only competition for water but also for land. However, in reality, there are still instances of continued expansions of cultivation areas for energy crops by farmers through the displacement of other low productivity crops. Thus, the policy on crops zoning for supporting the energy policy of the government, such as bioethanol and biodiesel policy, needs to be considered. The suitable areas should be identified and set by taking water resource availability and water stress into consideration. For example, the expansion of new oil palm plantations should be considered in the areas that have enough water resources, e.g., the southern or the eastern region.

5. Conclusions

The proliferation of food, feed, and biofuels derived from crops promises to increase stress on water in Thailand which has a large agricultural base for food for local consumption and export as well as for feed and biofuels. The study combined the water footprint and water stress index of different regions and watersheds of Thailand to determine the crop water requirement, irrigation water requirement and water deprivation in different regions and watersheds of the country. The water requirements for growing the ten staple crops in different provinces, regions and watersheds across the country have been evaluated. The results indicated that per hectare, the perennial trees like oil palm, pineapple and coconut have higher water footprint as compared to the field crops like rice, maize, cassava and sugarcane. However, per ton of crop, mungbean has the highest water footprint, followed by the oil palm, coconut, peanut and rice, respectively. Nevertheless, there are huge variations of the water footprint or crop water requirement from crops grown in different regions due to climate and geographical conditions. Cultivation of mungbean requires the highest amount of irrigation water followed by soybean, peanut, oil palm and second rice, respectively.

Based on the current cropping system of Thailand, the Northeastern region needs the highest amount of irrigation water. Rice (paddy) farming requires the highest amount of irrigation water, *i.e.*, around 10,489 million m^3/year followed by maize, sugarcane, oil palm and cassava. The key provinces that require a high amount of water for staple crops cultivation are Nakhon Ratchasima, Khon Kaen, Nakhonsawan, Suphanburi and Prachuapkhirikhan. The results from impact assessment of water use for crops cultivation indicated that major rice cultivation bring about the highest water deprivation, *i.e.*, 1862 million m^3H_2Oeq/year; followed by sugarcane, second rice and cassava cultivation with about 944, 925 and 598 million m^3H_2Oeq/year, respectively. The watersheds that have the highest risks on water competition due to the crops production are the Mun, Chi and Chao Phraya watersheds. The high risks come from the second rice cultivation. For biofuel crops, sugarcane cultivation is the major source of water stress in Mun, Chi and Thachin whereas cassava causes high water stress in Mun, Chi and East Coast Gulf watersheds. Recommendations have been proposed for reducing crop water demand and for sustainable crops production in the future of Thailand.

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Author Contribution

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Conflicts of Interest

The authors declare no conflict of interest.

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