Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2019.23841

149 (2019) 274–287
May

Assessing water scarcity in Malaysia: a case study of rice production

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Received 22 October 2018; Accepted 15 January 2019

ABSTRACT

Recent years have seen a surge of interest in assessing water withdrawal in the agricultural sector which has been experiencing an increasing concern with sustainable environmental requirements. Like other highly water-intensive crops, rice production systems rely on an ample water supply, thus posing a serious threat to water availability. This study estimates the water use of rice cultivated in the off- and main seasons in Malaysia. The water withdrawal of rice was estimated based on the monthly climatic data of 30 y (1983–2013) and a 10-y (2002–2011) average annual crop yield. The water stress index (WSI) of the 16 major watersheds in Malaysia was also derived to assess the water deprivation. We found that the blue water use for rice cultivation in the off- and main seasons ranges between 619 and 1,421 m^3/t and 504 and 1,031 m^3/t, respectively. The results also showed that the average WSI for 11 states in Peninsular Malaysia is 0.08 with a total water deprivation of 97 million m^3H_2O eq/y. This study can serve as baseline information for the government in identifying the areas that need to be conserved and the recommendations that should be drawn toward sustainable management of water resources in Malaysia.

Keywords: Water consumption; Water footprint; Water stress index; Water resources; Water management; Water withdrawal; Malaysia

1. Introduction

Freshwater is a vital element to human and all living organisms; however, it varies based on location and these variations being exacerbated due to the effects of climate change [1,2]. The demand for freshwater is soaring, as supply is becoming less certain. Report from the United Nations Development Programme [3] on world water resources in 2006 indicates that more than 10 billion of the world's population is facing lack of enough safe water to support their basic needs, while about 40% of the population has limited access to basic hygiene infrastructure. An increasing demand for food together with a growing demand for energy crops has resulted in an increasing demand as well as competition over freshwater [4]. This demand has led to an increased concern of water shortages and deterioration of water quality caused by agricultural practices.

It is estimated that within the next 50 y, total water use for each individual in the large cities and developing countries will reach 500–1,000 L/d [5]. In the last few decades, global freshwater demands have increased to meet the growing population of human beings for food and industrial needs. About 70% of global freshwater is consumed by the agricultural

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sector [5,6]. However, irrigation for agriculture is one of the most water-consuming activities and a rapid development in agricultural sectors exacerbating water depletion around the world. In Malaysia, rice is one of the primary crops contributing to the economy as the agricultural sector is the second largest income for Malaysia after the manufacturing industry [7]. Rice is related to high water consumption, and to address this problem, water footprint has been introduced to assess total water withdrawal from various activities including agricultural sector [8]. It can also be used at different levels of consumer activity, i.e., for individuals, households, regions, states, nations, etc. The water footprint concept, first introduced by Hoekstra and Hung [9], is a temporary and spatial explicit indicator considering location and timing of the volumes of water used and polluted [8,10,11]. This implies that the water footprint analysis depends not only on the volume of water use but also on where and when the water is consumed (Hoekstra et al. 2011). Many studies have been carried out to assess the water footprint of crops [4,8–10,12–20]. However, this methodological approach is still new and under development in Malaysia. No study has been done to assess the total amount of water consumed by crop commodities using a water footprint method.

Water management is important in order to sustain regional water resources [21]. For the past 20 y, there are many tools developed to quantitatively assess the productivity of water resources, water scarcity, water vulnerability, water sustainability, water poverty, water deprivation, or water stress [15,22–31]. The initial method developed by Falkenmark [32] serves as a remarkable foundation for water stress in terms of water consumption demands. Water stress index (WSI) is one of the methodologies used to evaluate the ratio of water withdrawal that deprives other water users in the same watershed area. WSI that has been developed by Pfister et al. [28] acts as a screening indicator or characterization factor (CF) for water withdrawal in Life Cycle Impact Assessment to measure potential environmental damages or human health damage caused by excessive water withdrawal. It covers three main protection areas such as human health, ecosystem quality, and natural resources. In this method, Pfister et al. [28] focused on the assessment of consumptive water use where blue virtual water withdrawal was used to generate the WSI. The principle of deriving WSI is based on the actual ratio of water withdrawal to hydrological availability (WTA). The WTA ratio can be used to assess the water deprivation of a watershed [15].

Therefore, the aim of the present study was to assess the water footprint of rice cultivation in Malaysia. Eleven rice cultivating areas in the Peninsular Malaysia were included in the assessment of water footprint. The derivation for WSI includes 16 main watersheds in Peninsular Malaysia, where these values were multiplied with the blue water withdrawal to assess the water deprivation from rice cultivation in Malaysia.

2. Materials and methods

2.1. Conceptual framework

Peninsular Malaysia lies on the southern shores of Asian land with an area of 131,598 km^2. Peninsular Malaysia extends from latitude 01°20′ north to latitude 06°40′ north and from longitude 99°35′ east to longitude 104°20′ east [33]. It has a hot wet equatorial climate characterized by warm temperatures and a seasonal distribution of rainfall with a daily temperature range from 21°C to 32°C in the lowlands throughout the year and a cooler temperature for higher altitude places.

This paper consists of two phases with the first phase focusing on the assessment of water footprint for rice cultivation in the Peninsular Malaysia. The latter phase involves the development of new water stress indices for 16 selected watersheds in the Peninsular Malaysia. The applicability of the newly developed WSI was determined by assessing the water deprivation from rice cultivation. This has been done by multiplying the blue water footprint and the WSI. Fig. 1 shows the conceptual framework of assessing water scarcity in Malaysia using rice cultivation as a case study.

Data inventory formed the basis of this study consisting of foreground and background data collection. In this research, data were compiled from various secondary data sources such as books, publications, reports, and government agencies including the Department of Irrigation and Drainage, Malaysian Meteorological Department, Department of Agriculture for Peninsular Malaysia, and Department of Statistics. Data were also obtained from relevant agencies such as The Malaysian Agricultural Research and Development Institute and the National Water Services Commission. Meanwhile, foreground data were obtained through a series of site visits by communicating with data providers and developing questionnaires.

2.2. Water footprint assessment

The assessment of water footprint was based on the method described by Hoekstra et al. [11]. The blue water footprint is defined as the volume of surface and groundwater consumed during production processes that can be evaporated or incorporated into the product, whereas the green water footprint refers to the volume of rainwater consumed (evaporated or incorporated into the product). In the present study, the water footprint of rice cultivation was assessed for 11 rice-growing states located in the Peninsular Malaysia [34]. The assessment includes both planting seasons at the same areas, i.e., main and off-seasons were taken into account. Main season refers to the period of rice planting without depending on the irrigation system, mainly in August to February, whereas off-season is a period when rice planting is normally dependent on the irrigation system, between May to July.

Fig. 2 illustrates the input and output for rice cultivation by using the water footprint approach. The gray water footprint is defined as the volume of freshwater that is needed to assimilate the load of pollutants into the water body. It can be calculated as the volume of water that is required to maintain the quality of water according to agreed water quality standards. As the gray water is described as virtual water, it was excluded in the assessment of water footprint for growing rice in the present study.

The climatic data used for this study include temperature, humidity, sunshine, and wind speed. In accordance with the agrometeorological standards, CROPWAT 8.0

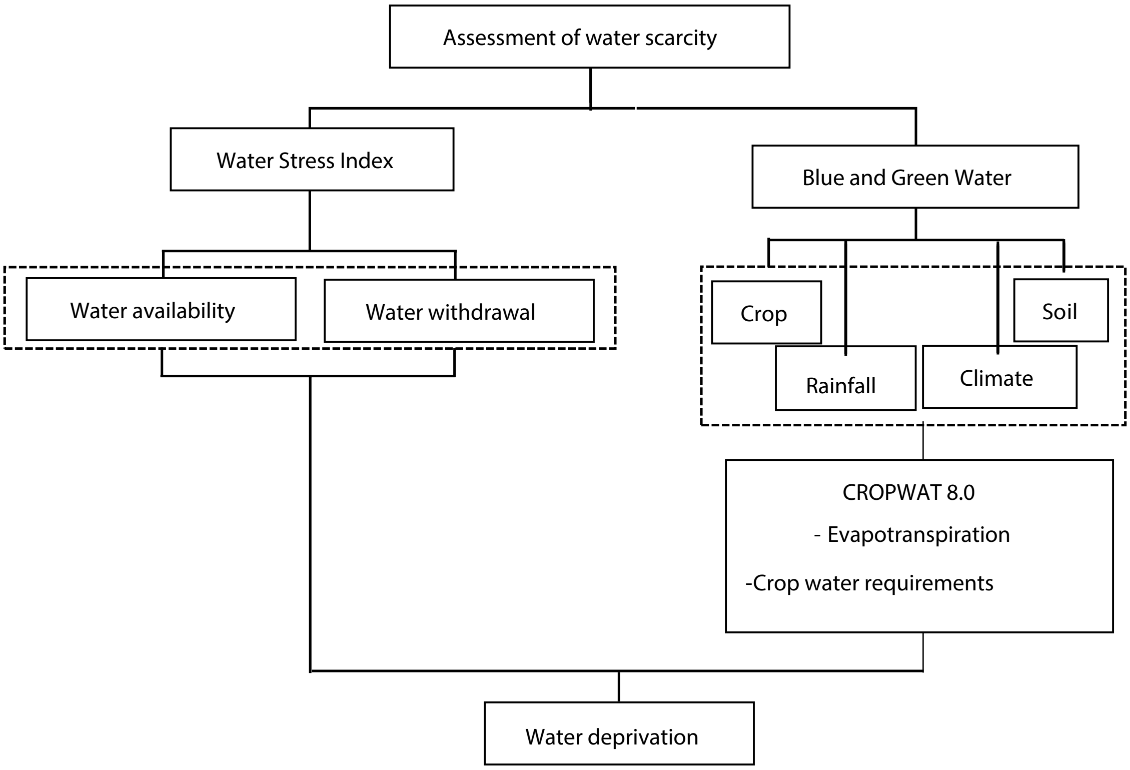
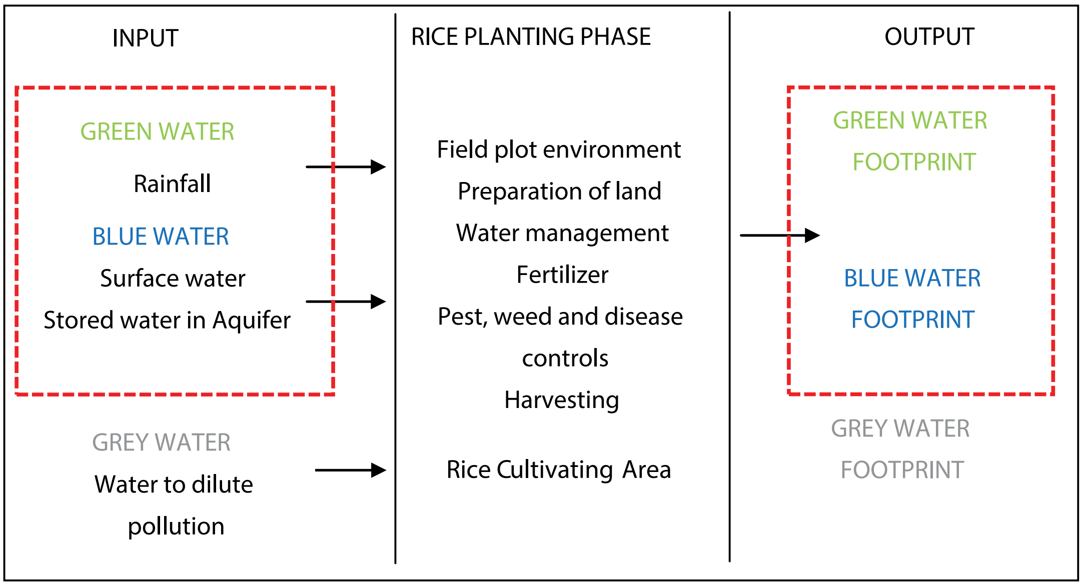


Fig. 1. Conceptual framework of the present study.



* Grey water footprint was excluded from this study.

Fig. 2. The input and output for rice cultivation by using the water footprint approach.

refers temperature as a measurement of air temperature at 2 m above the ground with the temperature unit of degree Celsius (°C). In this system, minimum and maximum temperatures were used to calculate the crop water use (CWU). If the minimum or maximum temperature values are not available, the mean of temperature can be used as representative. For humidity, the CROPWAT 8.0 classified the air humidity into two types: actual vapor pressure or relative humidity. Relative humidity is defined as the degree of saturation of air which means the proportion of the volume of water in the ambient air and the maximum quantity of water it could hold at the same temperature. Meanwhile, sunshine is described as the length of daylight without clouds and shade from the high mountains. In this model, the data rely on the position of the sun without the clouds which shows significance to the latitude and day of the year. As for the wind speed, it varied with the height at the lowest level of the surface. To adjust these data, a logarithmic wind speed profile might be suitable to be used. Parameters and data requirement for the calculation of CWU are shown in Table 1.

CROPWAT 8.0 model, a tool for the calculation of crop water requirement (CWR) developed by the Land and Water Development Division of Food and Agriculture Organization and water footprint framework, was used as a basis for the calculation of water footprint for cultivating rice in Malaysia. CROPWAT 8.0 is a practical tool that was used to carry out standard calculations for evapotranspiration (ET) and CWU based on inputs of climatic and crop databases. CROPWAT 8.0 model is useful to the design and management of irrigation schemes and the standard calculations for reference crop ET (ET_0), the CWRs, and irrigation requirements based on soil. In addition, the model allows the development of irrigation schedules for different management conditions and the calculation of scheme of water supply for varying crop pattern. CROPWAT 8.0 can also be used to evaluate irrigation practices by farmers and to estimate crop performance under both rainfed and irrigation conditions.

Soil is one of the components that is important in the CROPWAT 8.0 system. It illustrates the characteristics of the remaining water moisture and penetrating depth rate. Following parameters were included in the system:

- *Gross available water (GAW)*: GAW illustrates the total volume of water availability to the crop. It relies on the structure and the texture of soil and also organic matter in soil itself and addressed as millimeter per meter of soil depth.
- *High infiltration rate*: High infiltration rate describes the infiltration of water depth that penetrates the soil in 24 h as a result of rain or irrigation intensity, slope class, and soil type. It is expressed as millimeter per day.

Table 1
Parameters and data requirement for the water footprint analysis

Data	Parameter
Climate	Monthly mean of maximum and minimum temperature, °C
	Relative humidity, %
	Sunshine duration, h
	Wind speed, km/d
	Monthly rainfall, mm
Crop	Crop coefficient, K_c
	Maximum rooting depth, cm
	Area planted, %
Soil	Initial soil moisture depletion, mm/m
	Total available soil moisture content, mm/m
	Maximum rain infiltration rate, mm/d
Irrigation	Irrigation scheduling criteria, mm/d

- *Maximum rooting depth*: In most cases, the maximum rooting depth can be determined by the genetic characteristics of the plant. In some cases, the root depth was restricted by limiting layers.
- *Initial depletion of soil moisture*: The depletion of initial soil moisture represents the dryness of the soil in the beginning of the flourishing season.

In this study, the ET rate was determined using the Penman-Monteith method. A statistical analysis was also used to estimate the rainfall deficit for irrigation water requirements based on long-term rainfall records. This analysis was determined as part of the rainfall which effectively contributes to cover CWRs. Information on inventory database was compiled, and all data were used to model a water footprint of rice cultivation. Finally, a set of recommendations and suggestions were given.

The monthly average climatic data of 30 y (1983–2013) were obtained from the Malaysian Meteorological Department to calculate the ET and the ET_0. ET is the combination of two processes, where water is lost due to evaporation from soil and water surface as well as from transpiration process by plant. There are several factors affecting the evaporation rate, including weather parameters, crop characteristics, management, and environmental characteristics. In this study, the ET was determined using the Penman-Monteith method, calculated from the crop coefficient (K_c) and the ET_0 [Eq. (1)]. ET_0 is referred to the reference Penman-Monteith crop ET, expressed in unit of millimeter per day and defined as the rate of ET process with an extended surface of crop from 8 to 15 cm tall that is actively growing with sufficient water to growth and completely shading the ground [34]. Meanwhile, crop coefficient can be calculated based on the relationship between the ET_0 value and the actual water withdrawal.

The crop module required data related to planting date, crop coefficient, rooting depth, critical depletion factor, and response of yield. Planting date is decided by the climatic conditions and also based on local agricultural systems. Meanwhile, the crop coefficient (K_c) is affected by the crop type and to a trivial extent by soil evaporation and climate. In the CROPWAT 8.0, the system required (K_c) values for early stage, mid-season stage, and harvest stage. But for this study, the K_c values during the growth and late season phases were also added in the system, while rooting depth is defined as the capability of crop to gain benefit from the soil water reservoir. Two values are vital to estimate the rooting depth in which during the flourishing season and at the early stage of crop planting taken as 0.25 and 0.30 m. These values are important as it indicates the effectiveness of soil depth. CROPWAT 8.0 refers critical depletion fraction (p) as the level of critical soil moisture at which the initial drought stress can occur and might influence the crop ET and its production. The values are often varied between 0.4 and 0.6 and have been addressed as a fraction of GAW, and these values are also the outcome from the ET weight of the atmosphere.

$$\mathrm{ET_{crop}} = K_c \times \mathrm{ET_0}\left[\mathrm{mm/d}\right] \tag{1}$$

In the water footprint study, water requirement can be defined as the quantity of water needed to normally growth the crop and can produce yield in a period of time, supplied by irrigation, by precipitation, or by both. As water used for metabolic activities of plant covers only 1% of quantity of water used, the ET is directly considered as consumptive use in the calculation. In general, it consists of the contribution from effective rainfall, irrigation requirement, and soil profile (from shallow water tables), where effective rainfall is referred to as part of rainfall which is effectively used by the crop after accounted rainfall losses from surface runoff and deep percolation occurred. Irrigation requirement is referred to as the quantity of water used to the land surface, supplementary to the water supplied by rainfall. Other parameters including crop, soil, and irrigation were obtained as well to calculate the CWU.

Based on a 10 y (2002–2011) average annual crop yields, the blue and green water footprints of rice cultivation were calculated by dividing a total volume of green and blue CWU (m^3/ha) by the yield of the crop production (Y, t/ha). Blue water footprint refers to the volume of surface and groundwater used for cultivating rice, calculated by

$$\mathrm{WF}_{\mathrm{blue,rice}} = \frac{\mathrm{CWU}_{\mathrm{blue}}}{Y}\left[\frac{\mathrm{m}^3/\mathrm{ha}}{\mathrm{ton/ha}}\right] \quad (2)$$

Green water footprint is defined as the volume of rain water used for cultivating rice, calculated by

$$\mathrm{WF}_{\mathrm{green,rice}} = \frac{\mathrm{CWU}_{\mathrm{green}}}{Y}\left[\frac{\mathrm{m}^3/\mathrm{ha}}{\mathrm{ton/ha}}\right] \quad (3)$$

The total water footprint (m^3/t) was calculated by

$$\mathrm{WF}_{\mathrm{total,rice}} = \mathrm{WF}_{\mathrm{green,rice}} + \mathrm{WF}_{\mathrm{blue,rice}} \quad (4)$$

Blue and green CWU expressed in unit of m^3/ha was calculated by summation of daily ET (mm/d) over the complete rice-growing period. The factor 10 was used to convert water depths in millimetres into volumes of water per surface area (m^3/ha). The total length (l gp) of growing period (days) was considered starting from the first day of planting to the harvesting day.

$$\mathrm{CWU}_{\mathrm{blue,green,rice}} = 10 \times \sum_{d=1}^{\mathrm{lgp}} \mathrm{ET}_{\mathrm{green,blue}} \quad (5)$$

2.3. Derivation of WSI

Parameters involved in deriving WSI are shown in Table 2. Data for water availability were collected for 10 y starting from 2005 to 2014, whereas data for water withdrawal were obtained for 7 y starting from 2007 to 2014. There is a slight difference in the period of the time between water withdrawal and water availability due to the availability of data provided by the National Water Services Commission that are not available at the specific period of time. This issue has been taken into account in the derivation of the WSI.

Following the method of Pfister et al. [28], the WSI was derived based on the ratio of total annual freshwater WTA of selected watersheds [see Eq. (6)]. The WSI ranges from 0 to 1, and following life cycle assessment (LCA) approach, the WSI serves as a CF for a midpoint category and can be used to determine the impact of water deprivation at the endpoint level where areas of protection are preferred.

Table 2
Parameters required for deriving water stress index

Data	Input
Water availability	Precipitation Surface water Stored water in aquifer
Water withdrawal	Industry sector Domestic sector Irrigated agricultural sector Non-irrigated agricultural sector Livestock sector

$$\mathrm{WSI} = \frac{1}{1 + e^{-6.4 \times \mathrm{WTA} \times \left(\frac{1}{0.01} - 1\right)}} \quad (6)$$

WTA_i is the ratio between water withdrawal to water availability in watershed i and user groups j (industry, agriculture, livestock, and domestic). The ratio between annual freshwater availability (WA_i) and withdrawal for different user j (WU_{ij}) for each watershed i was calculated by

$$\mathrm{WTA}_i = \sum_j \frac{\mathrm{WU}_{i,j}}{\mathrm{WA}_i} \quad (7)$$

Hydrological water availability is an annual average for 10 y based on data from the so-called climate normal period (1983–2013, 30 y). However, both annual and monthly variation of precipitation may affect the water stress levels during the specific period. Thus, Eqs. (8) and (9) were used to calculate the correction factor for adjusting for the effects of annual and monthly variations.

$$\mathrm{WTA}^* = \sqrt{\mathrm{VF}} \times \mathrm{WTA}_i \quad (8)$$

$$\mathrm{VF} = \mathrm{e}^{\sqrt{\ln\left(s^*_{\mathrm{month}}\right)^2 + \ln\left(s^*_{\mathrm{year}}\right)^2}} \quad (9)$$

where VF = variation factor derived from the standard deviation for the distribution of precipitation; (s^*_{month}) = standard deviation of monthly precipitation; (s^*_{year}) = standard deviation of annual precipitation.

The value of WSI ranges from 0 to 1, and the levels of water stress for a watershed are categorized into five classes as shown in Table 3.

2.4. Evaluation of water deprivation

In this study, the water deprivation was determined by multiplying the blue water footprint ($\mathrm{WF}_{\mathrm{rice,blue},i}$) with the WSI

Table 3
Classification of water stress index proposed by Pfister et al. [28]

WSI	Condition
>0.9–1.00	Extreme
0.51–0.89	Severe
0.5	Stress
0.1–0.49	Moderate
<0.1	Low

Table 4
Water availability for 16 watersheds in Peninsular Malaysia, classified by state [35]

Watershed	Length (km)	Water availability		
		Catchment area (m^2)	Average rainfall (mm)	Groundwater storage (MLD)
Muda	196	4.2E + 09	2.9E + 04	4.8E-01
Kedah	±100	3.0E + 09	2.8E + 04	4.8E-01
Perlis	11.8	7.2E + 08	2.2E + 04	5.6E + 00
Juru	7.95	8.1E + 07	6.9E + 03	4.8E-01
Pahang	449	2.9E + 10	1.3E + 05	1.4E-03
Kuantan	±80	1.7E + 09	2.7E + 04	1.4E-03
Melaka	44	6.8E + 08	1.4E + 04	7.7E-01
Linggi	83.5	1.3E + 09	2.0E + 04	7.2E-01
Bernam	216	2.8E + 09	4.8E + 04	8.4E + 01
Langat	180	2.8E + 09	5.4E + 04	8.4E + 01
Kerian	90	1.4E + 09	2.2E + 04	3.7E + 00
Johor	106.4	2.3E + 09	2.2E + 04	7.8E-01
Muar	288	6.1E + 09	2.6E + 04	7.8E-01
Kelantan	271	1.3E + 10	8.5E + 04	1.8E + 02
Setiu	84	8.8E + 08	1.3E + 04	1.1E + 00
Terengganu	nil	4.6E + 09	5.9E + 04	1.1E + 00

of each watershed as shown in the Eq. (10). This value indicates the impact of water used for rice cultivation compared with other water users, e.g., ecosystems and the downstream human users [15]. The lower the water deprivation value, the lower the impact on water used. Water deprivation is expressed in cubic meter water equivalents (m^3H_2Oeq).

$$\text{Water Deprivation}_{\text{rice},i} = \text{WF}_{\text{rice,blue},i} \times \text{WSI}_i \tag{10}$$

This WSI-weighted water volume consumed can provide useful information for policy makers and government about the levels of water stress in different regions or areas in Malaysia due to crop cultivation.

3. Results and discussion

3.1. Water availability

The new WSI for Malaysian watersheds was derived for the 16 main watersheds, representing 11 states located in the Peninsular Malaysia. Water availability for each watershed is shown in Table 4.

3.2. Water withdrawal

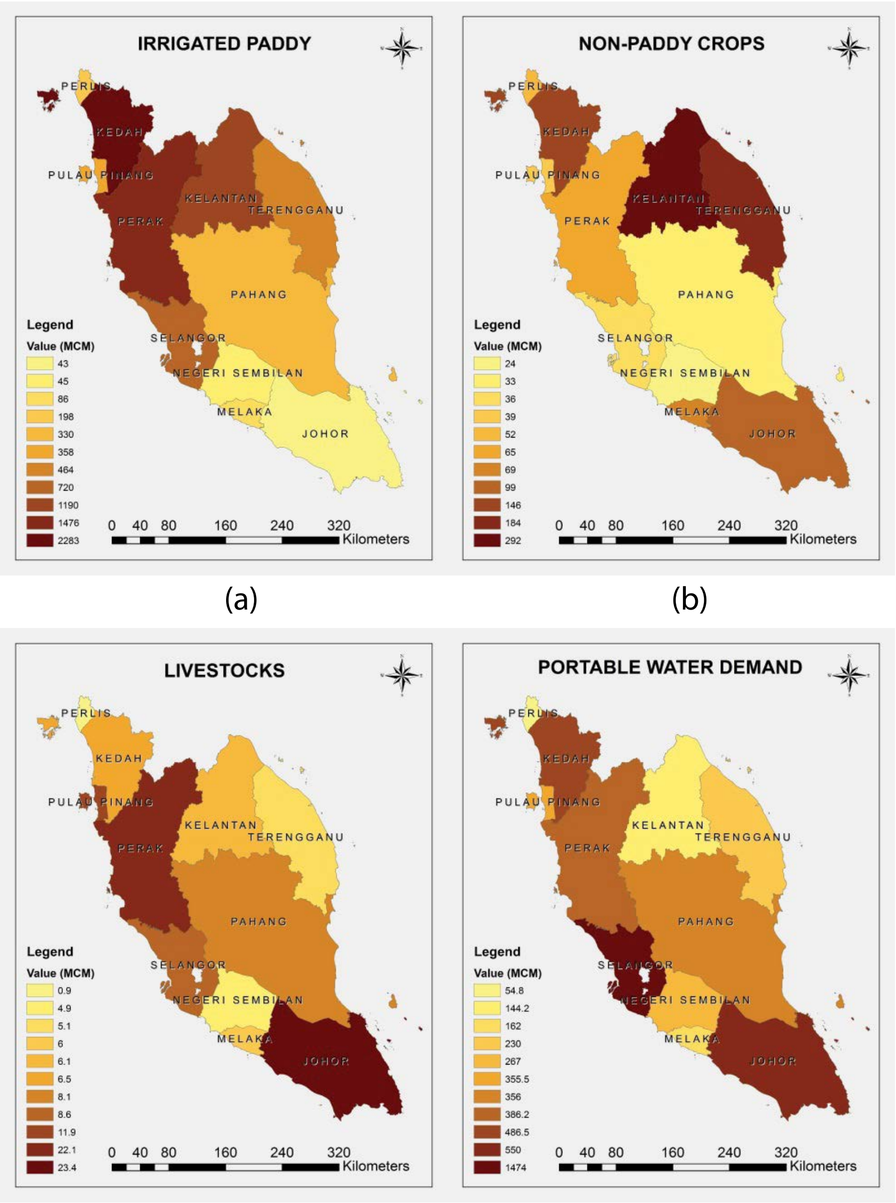
In this study, water withdrawal served as an important element in order to assess WSI of 16 selected watersheds located in Peninsular Malaysia. Data for domestic and non-domestic sectors of water withdrawal were obtained from the National Water Services Commission, Malaysia (SPAN), and relevant agencies from all states. For this study, the potable water demand represents the domestic sector of water withdrawal. This sector covers the activities of the household area, schools, and the industrial areas of the states. Meanwhile, the non-domestic sector has been categorized into three different activities which are irrigated paddy, non-paddy crops, and livestock activities.

As shown in Fig. 4, Kedah state is the major user of freshwater, followed by Selangor, Perak, Perlis, and Kelantan states. The major contribution for the highest total water withdrawal in Kedah State was due to the withdrawal of water to irrigate the paddy fields as the main activity in Kedah is agriculture, specifically rice production. Similar to Kedah, water withdrawal for Perak was also dominated by the agricultural sector, mainly rice production activity. According to the Department of Agriculture, Kedah is the main rice-producing state in Peninsular Malaysia, with planted area of 210,327 ha, followed by Perak, Kelantan, and Perlis, with the planted areas of 81,636, 56,280, and 52,085 ha, respectively. Table S1 in the Supporting Information provides the total water withdrawal per sector in the 11 states in Peninsular Malaysia.

In Selangor, the main water withdrawal was due to the potable water demand to support the domestic sector which covered the household area, industrial area, academic, and government buildings. In Kelantan, the non-paddy crop sector is the major water consumer for the state. Unlike Kedah and Perak, rubber is the main plantation for Kelantan State, covering131,475 ha while herbs and flowers are the least with 13.2 and 34 ha, respectively. Fig. 3 shows the maps of the proportion of domestic and non-domestic sectors of water withdrawal that have been classified by each state.

3.3. Water footprint

The irrigation requirements, yields, cropping pattern, and the environmental impact from water use for rice cultivation can vary greatly from state to state. The water footprint for cultivating rice was estimated for main and off-seasons (Fig. 4). The results of this study show that the total water footprints for cultivating rice for both main and off-seasons range between 1,600 and 2,800 m^3/t and 1,600 and 3,300 m^3/t, respectively. Fig. 4 shows that the green water footprint in the main season ranges between 1,043 and 1,860 m^3/t, whereas the blue water footprint ranges between 504 and 1,031 m^3/t. We found that the green and blue water footprints in off range are between 913 and 1,883 m^3/t and 619 and 1,421 m^3/t, respectively. Table S2 in the Supporting Information provides detailed results of water footprint for the 11 states included in the present study. The variation in the CWRs and water footprints for both seasons across different states depends mostly on the amount of precipitation received and the crop yield.



(a) (b)

(c) (d)

Fig. 3. Water withdrawal of each sector: (a) irrigated paddy, (b) non-paddy crops, (c) livestocks, and (d) portable water demand.

At the state level, the largest total water footprint for cultivating rice during main season was recorded for Pahang with 2,737 m^3/t, while Melaka has the largest total water footprint during off-season with 3,303 m^3/t. The results of the present study showed that the green water footprints for the 11 states in Peninsular Malaysia for both main and off-seasons are a factor of 2 and 1.4 higher than the blue water footprint of rice cultivation. This implies that annual rainfall rate in Malaysia can satisfy the water requirement for rice cultivation and that the irrigation requirement is only needed during the dry season. Malaysian topography and climatic condition ensure that the water availability is sufficient and satisfied the need for crop cultivation, especially rice cultivation. Effective rainfall and yield are two main factors that vary the irrigation water demand. In this study, the amount of blue water footprint is essential as the blue water withdrawal was used to evaluate water deprivation potential of rice cultivation in Peninsular Malaysia.

We found that the average water footprint of cultivating rice differs significantly across production areas. Crops with a high harvested yield have a smaller water footprint per tonne compared with crops with a low harvested yield, implying that the higher the yield, the lower the value of the water footprint. Although this study showed that the average water footprint for rice cultivation in Malaysia may be larger for states with lower yield, however, the results of water footprint may turn out differently for certain areas due to climate variations. Another aspect that is crucial in the water

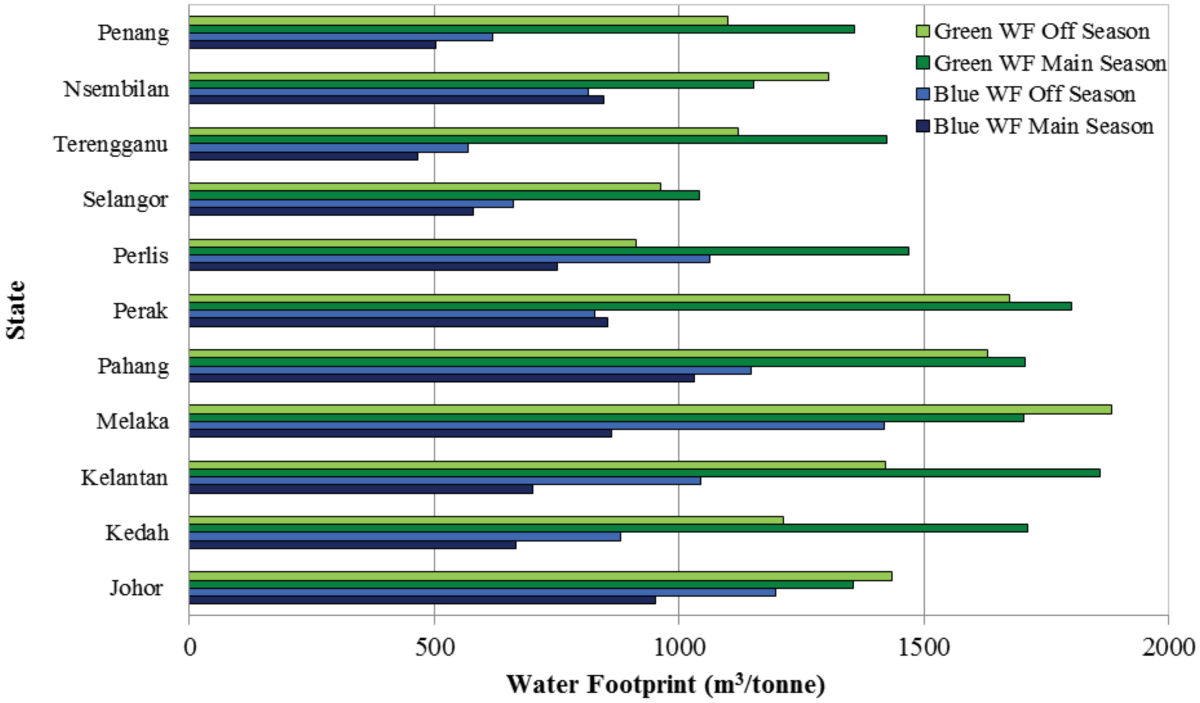


Fig. 4. Water footprint of rice production during main and off-seasons in Peninsular Malaysia (2005–2013).

footprint assessment is the interference by the farming practice on the field such as poor drainage system, conventional or organic farming approaches, etc.

3.4. Water stress index

Fig. 5 shows the WSI for 16 watersheds classified by state located in Peninsular Malaysia. The result of this study shows that Juru watershed in Penang State has an extreme water stress at 0.999 while the other 15 watersheds range below 0.100 indicating low level of water stress. In the present study, the average WSI obtained based on area-based weighting of 16 watersheds in Peninsular Malaysia is 0.08, whereas the average WSI for Malaysia derived by Pfister et al. [28] was 0.0434.

Low level of WSI was obtained for all watersheds, with an exception for Juru watershed that has the highest value of WSI. WSI for Juru watershed was found at 0.999 implying an extreme condition of water availability at Juru watershed. Since the derivation of WSI was obtained based on the ratio between total water withdrawal and water availability, lower water availability recorded for the area resulted in high value of WSI. The major contribution of water withdrawal in Juru watershed is due to vast activities in the industrial, domestic, and agricultural sectors. With an area of 1,046.3 km^2, Penang is a small state compared with the other states in Peninsular Malaysia. Most of the agricultural and livestock activities are operated on the mainland area which is in Seberang Perai. Meanwhile, the Georgetown area comprises mainly the industrial and tourism activities. According to the Department of Agriculture [34], the rice production in Penang has been increasing every year since 2004. In 2013, the average yield of paddy produced in Penang was 5,677 kg/ha, and the production of rice for all seasons (main and off-season) was 94,333 metric tonnes. Compared with Kedah, Penang rice production can be categorized as good and efficient due to its capability to produce rice up to an

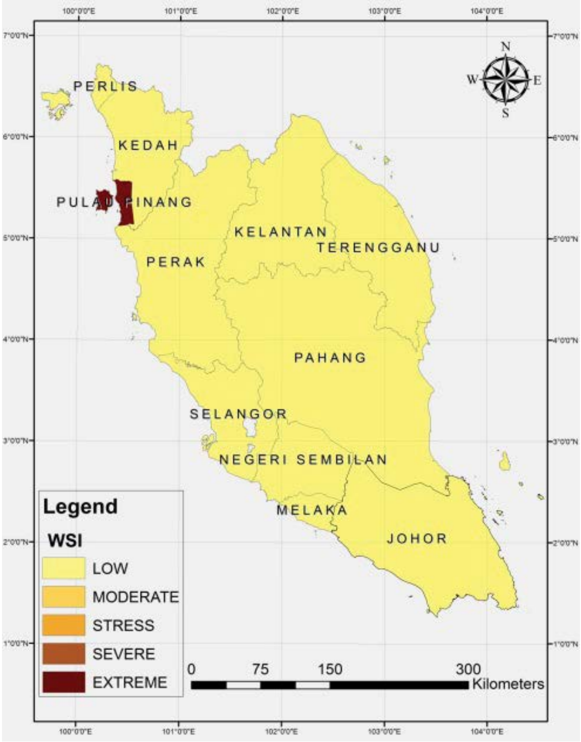


Fig. 5. Water stress index of Peninsular Malaysia.

average yield of 6,000 kg/ha. Unlike Penang and Selangor, other states can produce rice with an average yield of only 2,000–5,000 kg/ha.

Meanwhile, the other 15 watersheds in this study range below 0.100, indicating a low level of water stress. This is due to the fact that the highest rainfall rate and largest catchment area was recorded for Pahang watershed. Furthermore, the highest groundwater storage for Kelantan watershed compared with other watersheds also contributes to the lower water stress in this area. The results from the analysis show that the water withdrawal from domestic and non-domestic sectors in the watershed areas did not surpass the availability of water in those areas. Thus, the potential for water deprivation in those particular watershed areas was low.

3.5. Water deprivation

Based on the total production areas in 2013, the total water deprivation of rice cultivation in 11 states is 97 million m^3H_2Oeq/y (Table 5). This value is considered low compared with water deprivation due to the rice cultivation in Thailand presented by Gheewala et al. [15]. The water deprivation obtained for Thailand is 1,862 million m^3H_2Oeq/y. This is due to the fact that Malaysia produces much less rice than Thailand. Total rice production in Malaysia was 1.5 million metric tonnes in year 2013, whereas Thailand produced 37 million metric tonnes of milled rice in the same year. This result indicates the lower impact on water consumed due to the lesser water competition with other users (downstream human users and ecosystems).

In this study, Penang has the highest water deprivation with 71 million m^3H_2Oeq/y, while the other states have a low water deprivation range between 100,628 and 9.5 million m^3H_2Oeq/y. Penang has the highest water deprivation due to the extreme level of water stress in Juru watershed as well as the highest amount of water withdrawal to irrigate rice field. Compared with other states, lower WSI and lower amount of water withdrawal used in rice sector induce a lower amount of water deprivation potential.

3.6. Comparison with previous studies

For the past few years, several studies have been conducted on water footprint of rice cultivation for many regions (Table 6). Global estimation of the consumptive water use for several crops was first carried out by Hoekstra and Hung [9]. Starting from there, numerous studies have been carried out on a worldwide scale. According to Chapagain and Hoekstra (2004), total volume of global water used for crop production is 6,390 Gm^3/y and rice accounted for about 21% of the total volume of freshwater withdrawal which is the largest share in the total volume of water used for global crop production. Following the study, Chapagain and Hoekstra [8] carried out an assessment on the freshwater withdrawal for 13 major rice-producing countries where detailed information on rainfall and irrigation were included in the assessment. On average, water footprint for rice was recorded at 1,325 m^3/t comprising 48% green water footprint, 44% blue water footprint, and 8% gray water footprint. These values correspond to the global rice water footprint conducted by Chapagain and Hoekstra [36] with 1,391 Gm^3/y. Meanwhile, the study by Mekonnen and Hoekstra [17] also included the same elements of water footprint, where green, blue, and gray water footprints of rice were calculated with a high spatial resolution. In this study, the water footprint of rice was found to be 1,673 m^3/t, almost a similar value recorded for the average water footprint for crops (1,644 m^3/t).

Bulsink et al. [13] calculated water footprint for Indonesian rice and found that the total water footprint was 3,473 m^3/t. Following this, Yoo et al. [20] calculated water footprint of Korean rice, and the total water footprint was obtained at 844.5 m^3/t. Due to the climatic differential data, the results for Korea were nearly half from the study done by Chapagain and Hoekstra [8]. The water footprint for rice cultivation in Nepal and India was conducted by Shrestha et al. [18] with a total water footprint of 3,483 m^3/t.

Most of the previous studies focused on assessing the blue and green water footprints. Gray water footprint has been left out from most studies due to its different focus on the aspect of water quality, instead of the aspect of quantity that is commonly asssessed based on the total water withrawal. Gheewala et al. [15], Wang et al. [19], and Marano and Filippi [16] have quantified the water footprint of rice cultivation for the green and blue water footprints with an exclusion of gray water footprint as their studies focused more onto water balance rather than water footprint. The present study only focused on the green and blue water footprints in order to quantify potential water deprivation in Malaysia.

Compared with other countries, water footprint for rice cultivation in Peninsular Malaysia is slightly lower than the total water footprint obtained in Indonesia (2,305 m^3/t). In Thailand, the water footprint for rice cultivation was estimated for two different seasons, namely, main season and off-season. The recorded water footprint during the wet season (main season) is higher than the water footprint during the dry season (off-season). In the present study, the water footprint for rice cultivation was also conducted for two different seasons. However, we found that the results for Malaysian water footprint are not similar to Thailand. This must be due to the fact that Malaysian rice cultivation used more water for irrigation during off-season to cope with the dry season while high yield in Thailand is the main contributing factor of higher water withdrawal during wet season.

As expected, the green water footprint of rice cultivation in Indonesia and Malaysia is higher during wet season, and the blue water footprint of rice during dry season was slightly high compared with the blue water footprint in wet season. As both regions happen to lie on the same equator lines, both countries are expected to get a similar pattern of precipitation. The only difference that arose between the two regions is due to the productivity of rice production and the irrigation system. Malaysia received sufficient water to supply the rice system even in the dry season; however, there is a need of blue water requirement during a dry season to support the irrigation and water supply.

4. Challenges and future perspectives

Meeting the growing demands for water, energy, and food becomes more challenging and complex with the combined effect of climate change, particularly in the developing

Table 5
Blue water withdrawal and water deprivation for both seasons

State	Blue Water Withdrawal Rice (m^3)		WSI	Water Deprivation (m^3H_2Oeq/year)	
	Main Season	Off Season		Main season	Off Season
Johor	3,542.67	3,709.00	0.011	5.88E+04	5.79E+04
Kedah	2,531.67	3,810.56	0.014	3.74E+06	5.73E+06
Kelantan	2,500.00	3,750.33	0.010	1.06E+06	6.04E+05
Melaka	2,956.44	3,804.11	0.068	2.88E+05	3.54E+05
Pahang	3,371.00	3,626.00	0.010	2.06E+05	1.64E+05
Perak	3,011.67	2,926.56	0.033	4.03E+06	3.88E+06
Perlis	2,945.44	4,664.56	0.013	9.85E+05	1.56E+06
Selangor	3,111.11	3,460.00	0.018	1.05E+06	1.17E+06
Terengganu	2,292.33	2,871.89	0.018	4.77E+05	4.15E+05
Nsembilan	3,744.00	3,285.00	0.014	5.71E+04	4.36E+04
Penang	2,495.56	3,080.56	0.999	3.19E+07	3.94E+07

Table 6
Previous studies on water footprint of rice

Region/area	Period	Water footprint (m^3/t)				Author
		Green	Blue	Gray	Total	
Global	2000–2004	636	583	106	1,325	Chapagain and Hoekstra [8]
*average scale (33 countries main rice producers)						
Global	1995–2005	1,154	335	184	1,673	Mekonnen and Hoekstra [17]
Indonesia	2000–2004	2,535	729	208	3,473	Bulsink et al. [13]
Central Asian	1992–2007					Aldaya et al. [12]
Kazakhstan		205	2,430	–	2,635	
Uzbekistan		225	4,015	–	4,240	
Turkmenistan		237	6,777	–	7,014	
Tajikistan		291	3,741	–	4,032	
Kyrgyzstan		693	2,805	–	3,498	
South Korea	2004–2009	296	498	51	844.5	Yoo et al. [20]
Nepal, India	1994–2008	1,881	1,254	383	3,483	Shrestha et al. [18]
Haryana, India						Chakrabarti et al. [14]
*Transplanted rice (TR)		364	439	268	1,071	
*Direct seeded rice (DSR)		505.5	257.5	190.8	953.8	
Thailand	2009–2011					Gheewala et al. [15]
*Major rice		1,647	520	–	2,167	
*Second rice		340	1,139	–	1,479	
China	2010	572	689	–	1,261	Wang et al. [19]
Argentina	2009–2014					Marano and Filippi [16]
*Entre Rios		434	553	–	987	
*Santa Fe		305	541	-	846	

countries like Asia. However, the water-energy-food nexus is a vital concept and strongly connected to the issue of climate change. In order to successfully deliver the sustainable development goals, the linkage between climate change and the nexus needs to be fully understood at all levels of society and stakeholders. The efficient use of water, land, energy, and other natural resources needs to be optimized so that the challenges impeding the water, energy, and food nexus could be addressed harmoniously across various stakeholder groups toward sustainable development [37].

Availability of water and conservation of water resources, followed by wise use of this very important resource is pertinent in ensuring the sustainability of environmental health for human health. Global approaches involving water withdrawals, water supply, and water usage must involve good applications of knowledge, wisdom, and behaviors. Formal, informal, or nonformal education is an important sector where water conservation and protection are being made aware of among population of Malaysia. This included aspects of modification and revamping of contents of curricula and via innovative extracurricular activities. Knowledge and experiences within the realms of many disciplines within the domains of science, technology, engineering, and mathematics must be linked with that of social sciences and humanities in endeavor to find sustainable solutions to the myriad of challenges and problems being faced by communities on the ground including water quantity and quality for livelihoods. The Malaysian Water Partnership had stated that in support of Vision 2020 (toward achieving developed nation status), Malaysia will conserve and manage its water resources to ensure adequate and safe water for all including the environment. Such is the Malaysian vision for water in the 21st century. The key objectives of the vision are as follows: (i) water for people: all have access to safe, adequate, and affordable water supply, hygiene, and sanitation; (ii) water for food and rural development: provision of sufficient water that will ensure national food security and promote rural development; (iii) water for economic development: provision of the water to spur and sustain economic growth within the context of a knowledge-based economy and e-commerce; and (iv) water for the environment: protection of the water environment to preserve water resources (both surface water and groundwater) and natural flow regimes, biodiversity, and the cultural heritage, along with mitigation of water-related hazards.

Agricultural sector requires a larger amount of water supply which drains our freshwater resources in near future time. This issue is worsening day by day especially in developing countries due to several other factors such as climate change, population growth, and water pollution. According to Mekonnen and Hoekstra [38], Asia contributed more than half of the global anthropogenic phosphorus total loads. Hence, nutrient reduction strategies and associated science assessment should be reviewed to help better guide implementation and tracking of water quality improvement practices [38–40]. In addition, nutrient management strategies for agricultural non-point source pollution control in irrigation area should be improved in order to protect water resources and to control environmental pollution in catchment area [41–43]. In this context, it is important to create and propose a good management plan in order to properly manage and distribute water supply to all sectors. There is a key difference between responses by the state and local commodities toward water shortage. Different categories of stakeholders perceived differently regarding water deprivation, which develop different coping strategies as a function of their power and capacities. Usually, the policies are emphasized by the state and local commodities response to the policies crucial in shaping the demand and its impact on the hydrological cycle. The United States of America illustrates a good example of interplay between federal and state powers as water scarcity intensifies where water governance is primarily a state responsibility, but some federal legislation is of overriding importance.

In Malaysia, the Government embarked on various efforts in managing this issue. During Tenth Malaysian Plan (2011–2015), relevant policies and legislations were reviewed to strengthen the conservation and enforcement efforts on nation's natural resources, including water resources. The National Water Resources Policy was launched by the Malaysian government in 2012, which provides holistic strategies for water resource management in Malaysia [44]. During those periods, federal government had emphasized on the restoration programme of water resources by enhancing the Integrated Water Resources Management programme where improvement on water quality in some rivers in Malaysia and water shortage problem in Klang Valley were addressed. Meanwhile, in relation to water service industry, The Ministry of Energy, Green Technology and Water (KeTTHA) had successfully established a water demand management master plan, which enables better demand management and provides tools to forecast water demand. With this master plan in Malaysia, priority was given to reduce the consumption of treated water for nonpotable uses by using alternative water resources, such as rain water harvesting [45] and storm water. In addition, communications, public awareness, and education programmes were intensified to promote more efficient and prudent use of water.

As for state level, the establishment of agencies that cover solely on water resources has efficiently helped the government in managing water resources under their jurisdiction, for instance, Lembaga Urus Air Selangor, Syarikat Air Kelantan, Syarikat Air Negeri Sembilan, Pengurusan Air Pahang Berhad, etc. These agencies are responsible in managing the river basins more effectively with the enhancement of various legislations related to water management. Furthermore, awareness campaign and activities with the cooperation of the relevant nongovernmental organizations (NGOs) to promote the wise use of water and river conservation to local commodities were conducted as well. Malaysia has several good policies to support Agenda of water conservation for better sustainability. All sectors including government agencies, private sectors, NGOs, communities, and individuals also play their role in conserving water resources in Malaysia. A clear understanding of each individual's role in improving water management has led to the introduction of system of rice intensification(SRI), an initiative made by the Malaysian Government. SRI had also been practiced in Malaysian Agricultural Sector, a sector that uses the most amount of water in Malaysia. SRI for paddy plantation is now being practiced by farmers in several parts of Malaysia and is hoped to be practiced by more farmers in years to come. SRI can reduce water consumption and requirement, increase land productivity, and is less dependent on artificial pesticides, herbicides, fertilizers, and other agrochemicals.

In future, it is recommended that a comprehensive study needs to be conducted to assess the impact of nutrient enrichment on freshwater resources by including aspect of water quality in the water footprint assessment that is fully compliant with the ISO 14046 standard. Since this study only included states in Peninsular Malaysia, other rice-growing areas in Sabah and Sarawak could be included as well in the future study. The WSI derived in this study can serve as a CF for water withdrawal at a midpoint level. In future, LCA-based water footprint could be conducted to further assess the impact of water withdrawal on areas of protection such as human health damage, ecosystem quality damage, and natural resources depletion. Furthermore, to increase the reliability, consistency, and accuracy of the water footprint assessment, selection of modelling parameters, quality, and availability of input data as well as assumptions made in interpreting the results should be made clear in the beginning of the study. In this study, the calculation was done based on the theoretical CWRs. In the future, the actual irrigation data need to be obtained, rather than using the theoretical CWRs in the calculation. As the results of the water withdrawal can differ between crop types and locations, the inclusion of local WSI and a spatially explicit factor should be considered in the water scarcity assessment to reveal the real burden or pressure by a specific river basin. As water is a localized issue, a proper regional assessment is necessary to evaluate the impact of water used that can later be used as guideline for the authority to enhance their policies in relation to water resources.

The government needs to have an appropriate measurement to manage the sustainable use of water resources in order to avoid the issue of water stress due to the rising demand on the agricultural practices especially in the production of rice. Related agencies and departments involved in the rice industry need to further increase the efficiency of water withdrawal by revising the policy related to rice production especially the rice check that has been prepared for the farmers as a guideline in cultivating the rice. The productivity of rice can be improved by improving the agronomic management, in terms of straw mulching, nutrient management, and pest control [47]. In addition, by reducing the water use for land preparation through land leveling or reducing the period of land preparation could also help a wise water governance and management in Malaysia.

5. Conclusions

In conclusion, we found that larger amount of the green water is available to grow the crops in Malaysia implying less requirement for blue water. Higher green water footprint indicates that rainfall rate is sufficient for cultivating rice in Malaysia. The present study found that the WSI and water footprint of Malaysia depend on precipitation to meet the requirement for water withdrawal activities. Estimation of water deprivation potential is one of the useful indicators to portray the relationship between WSI and blue crop water used for rice cultivation. States with a lower water deprivation values have a potentially lower impact of water withdrawal activities if the crops were grown there. In this study, the water deprivation for rice is higher in Penang compared with other states due to higher level of water stress and amount of water withdrawal. This study can serve as baseline information for Malaysian government and policy makers in identifying which areas need to be conserved and what types of recommendation should be drawn toward sustainable management of water resources in Malaysia.

Acknowledgements

This project was financially supported by the research grants DIP-2017-006 and ST-2016-015. We thank the National Water Services Commission (SPAN), Department of Irrigation and Drainage Malaysia, and Malaysian Meteorological Department for providing data on water withdrawal, water availability, and climate.

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Supporting Information

Table S1
Water withdrawal per sector in 11 states in Peninsular Malaysia

State	Sector				Total (m^3)
	Portable water demand (MCM)*	Irrigated paddy (MCM)	Non-paddy crops (MCM)	Livestock (MCM)	
Kelantan	144.2	1,190	292	6.1	1.63E+09
Pahang	356	330	33	8.1	7.27E+08
Terengganu	230.7	464	184	5.1	8.84E+08
Melaka	162	86	69	6	3.23E+08
Selangor	1,474	720	36	8.6	2.24E+09
Perak	386.2	1,476	65	22.1	1.95E+09
Kedah	486.5	2,283	146	6.5	2.92E+09
Penang	355.5	358	39	11.9	7.64E+08
Perlis	54.8	198	52	0.9	3.06E+08
Johor	550	43	99	23.4	7.15E+08
NSembilan	267	45	24	4.9	3.41E+08

*MCM - Million cubic metre

Table S2
Water Footprint of the rice cultivation in Peninsular Malaysia (2005–2013)

State	Main Season				Off Season			
	Yield (ton/ha)	Green WF (m^3/ton)	Blue WF (m^3/ton)	Total WF (m^3/ton)	Yield (ton/ha)	Green WF (m^3/ton)	Blue WF (m^3/ton)	Total WF (m^3/ton)
Johor	3.75	1,355.92	953.35	2,309.26	3.55	1,436.50	1,196.54	2,633.04
Kedah	3.85	1,712.28	668.11	2,380.40	4.34	1,213.36	881.51	2,094.87
Kelantan	3.60	1,860.07	701.90	2,561.97	3.61	1,423.26	1,044.48	2,467.74
Melaka	3.54	1,703.77	862.92	2,566.69	2.90	1,882.89	1,420.54	3,303.42
Pahang	3.42	1,706.85	1,030.56	2,737.41	3.21	1,630.21	1,148.67	2,778.87
Perak	3.58	1,803.54	855.03	2,658.57	3.71	1,676.25	828.76	2,505.02
Perlis	4.05	1,469.94	752.69	2,222.63	4.49	912.56	1,063.59	1,976.15
Selangor	5.39	1,043.17	580.56	1,623.72	5.40	962.09	662.05	1,624.13
Terengganu	4.10	1,734.50	565.56	2,300.06	3.86	1,503.62	762.88	2,266.49
Nsembilan	4.43	1,153.86	845.91	1,999.77	4.03	1,307.12	814.93	2,122.05
Penang	5.00	1,358.72	503.67	1,862.39	5.16	1,099.37	618.50	1,717.87