



Water footprint inventory database of Thai rice farming for water policy decisions and water scarcity footprint label

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Received: 17 February 2019 / Accepted: 5 June 2019 / Published online: 13 June 2019
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Abstract

Purpose Rice is a major economic crop which has created local livelihood, careers and incomes in the agricultural sector in Thailand, one of the leading rice producers at global scale. Rice is a key commodity in the agriculture sector requiring the highest portion of water demand, around 40% out of the total sector demand of 65%. This study was aimed to develop the water footprint database of rice farming at the national level to support the information for area-based water management and water footprint label based on the methodology described in ISO14046.

Methods The water footprint inventory data associated with the 8 main cultivated rice species were gathered in accordance with the ISO 14046 Water Footprint. The statistical data of rice cultivation area and production in 2016 were used as the basis for sampling to cover 62% of the national annual production with a 90% confidence interval. Eight rice species were sampled by simple random sampling method, covering 62% of the national annual production with a 90% confidence interval. The total number of samples was 817, covering 114 samples of Khao Dok Mali 105, 103 samples of Pathumthani 1, 103 samples of Phitsanulok 2, 112 samples of RD41, 112 samples of Chainat 1, 103 samples of RD6, 70 samples of San Pah Tawng 1 and 100 samples of riceberry.

Results and discussion The study found that the rice cultivation in Thailand had an average water footprint inventory of 1665 m³/t and a water scarcity footprint of 334 m³H₂Oe/t paddy rice. One hectare of rice cultivation normally required water around 6340 m³/ha on the average. The results showed that Khao Dok Mali 105 has the highest water scarcity (598 m³H₂Oe/t paddy rice) as the Northeastern area where it is cultivated, has the highest water stress index. This was followed by RD6, Riceberry, Phitsanulok 2, Pathumthani 1, San Pah Tawng 1 and RD41. Chainat 1 species has the lowest water scarcity footprint (220 m³H₂Oe/t paddy rice).

Conclusions The replacement of rice with sugarcane/cassava could potentially reduce the water scarcity footprint by more than half. The shifting of cultivation period when the average rainfall was higher could slightly decrease the amount of total water requirements, whereas the implementation of alternate wet and dry farming system instead of continuous flooding system would moderately reduce the amount of total water requirements. It is expected to use the water footprint national database for more effective water resource management for rice cultivation and to support the decisions on national water policy and the implementation of water scarcity footprint label.

Keywords Rice farming · Thailand · Water footprint inventory database · Water footprint inventory · Water stress index · Water scarcity footprint

Responsible editor: Niels Jungbluth

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1 Introduction

Of all the water on earth, 97.5% is in the ocean and freshwater accounts only 2.5% (UNU-INWEH 2017; Postel et al. 1996; Ridoutt 2009). By 2030, the freshwater requirement will be more critical as the global demand for water is expected to grow by 50% (UNU-INWEH 2017; Shiklomanov 1993; Shiklomanov 2000; Seckler et al. 1998). The population growth is projected to keep growing and by 2050, the current world population of 7.3 billion is expected to reach 9.7 billion. The Food and Agriculture Organization of the United Nations

(FAO) estimated that 57 billion m³ of water was withdrawn for agriculture, industry and households in 2007 (Okadera et al. 2014; Shiklomanov and Rodda 2003; FAO 2007). It was revealed that 1.2 billion people live in physical water scarcity area and more than 500 million people are currently facing this situation (Hoekstra and Chapagain 2007, 2008; Hoekstra and Hung 2002). Agriculture activities will be largely affected by the freshwater resources as 92% of global freshwater contributes to agricultural production (Hoekstra and Mekonnen 2011; University of Lincoln 2011; Long et al. 2005).

Thailand's economy is predominantly based on agricultural production with a contribution to the gross domestic product of almost 8.3% (Office of Small and Medium Enterprise Promotion 2017). Rice is a major economic crop which has created local livelihood, careers and incomes in the agricultural sector. The country is recognized one of the largest rice exporters in the world. About 63% of the agricultural area is accounted for rice cultivation (Rice Department 2016). In 2016, there were 426.47 million hectares for major and second rice cultivation with 31.81 million tonnes paddy yield. The total export of rice products is 9883 thousand tonnes (Office of Agricultural Economics 2017). On a different note, it has been highlighted that rice paddy cultivation consumes the highest portion of water demand in the agriculture sector, accounting for around 40% of the total sector demand of 65% (Thai Royal Irrigation Department 2011). Moreover, it has previously been reported that that global water footprint of rice was 1325 m³/t paddy rice (Chapagain and Hoekstra 2010). Out of the total water footprint of rice production based on the Water Footprint Network methodology (Hoekstra et al. 2009), 48% was the green water, 44% the blue water and 8% the grey water footprint. However, it was found that green water footprint is mainly in India, Vietnam and Thailand (Chapagain and Hoekstra 2010; Liu et al. 2009).

The studies on water footprinting of agricultural products in Thailand using the Water Footprint Network methodology was firstly applied with the ethanol production from cassava. It was reported that the water footprint was 0.267 m³/year, which was consisted of 0.185 m³/year from green water footprint and 0.082 m³/year from blue water footprint; moreover, the study assessed the water footprint for the nation and showed that the water demand would be 10 times higher in 2022 due to the national energy development plan to expand the cultivation area for cassava (Pongpinoyopas and Mungcharoen 2011). Water footprinting was also conducted for the biomass plants for feed, food and fuel and the results indicated that the second rice, maize and cassava production required the higher water demand, whereas rice required water lesser (Gheewala et al. 2013a, b). The annual WSIs of the 25 major watersheds of Thailand have also been determined by Gheewala et al. (2013a, b, 2014) using the water stress index (WSI) of Pfister et al. (2009a, b) and Ridoutt and Pfister (2010). Water footprinting was also applied

with rubber; the water scarcity footprint of ribbed smoked sheet bales (RSSB) and ribbed smoked sheet (RSS) ranged from 5.12–52.4 and 0.12–72.8 m³ H₂Oe/t from large rubber sheet factories in the southern part of Thailand (Musikavong and Gheewala 2016). For rice, the very first attempt on water inventory was performed in the central region covering the main production sites in 5 provinces; the results showed that the major rice's water use was 1051–1088 m³/t paddy rice (Mungkung et al. 2016). Recently, the water stress index was applied to identify the potential impact on water scarcity due to the agricultural policy on switching from rice to sugarcane (Gheewala et al. 2018).

The above research has highlighted the need for conducting water footprint studies in rice production due mainly to its high requirement for water during cultivation period. To be compliant with the internationally accepted norms for life cycle assessment, water footprint must be conducted according to the ISO methodology (ISO 14046 2014). The national policy has always been very supportive for rice production. But now it is very significant to gain a better understanding on the water footprint values of rice production in Thailand in order to support the policy making decision on water management for rice cultivation. This study was therefore developed aiming to collect the water footprint inventory of different rice species cultivated in Thailand leading to the supporting of national database development as well as to calculate the water scarcity footprint values of rice production at the national level to support the information for policy decisions on area-based water resource management. It was also expected to initially develop the water footprint inventory national databases for rice as well as other agricultural and food products leading to the application for private sector on water footprint labelling.

2 Materials and methods

2.1 Studied sites

Thailand has a rice cultivation area of around 9 million hectares with a paddy yield of 24 million tonnes. The average capacity of production is 2731 kg/ha (Office of Agricultural Economics 2018). “Hom Mali” rice has the highest cultivation area at 4.53 million hectares or 50% of the national rice crop cultivation followed by sticky rice (2.25 million hectares or 25%), white rice (1.97 million hectares or 12%), jasmine rice (0.25 million hectares or 3%) and colour rice and organic rice (0.01 million hectares or 0.11%), respectively (Rice Department 2016).

The rice species cultivated in Thailand can be divided into 6 groups according to the different characteristics: Thai Hom Mali rice (long-grain jasmine rice and photoperiod-sensitive variety), Thai Jasmine rice (normal jasmine rice and non-photoperiod-sensitive varieties), white rice (non-glutinous rice

with 7–33% of amylose), parboiled rice (rice that has been partially boiled with husk), sticky rice (glutinous rice with lower amylose) and coloured rice (rice with other colours such as purple and red). The main production area of Thai Hom Mali rice is in the northeast of Thailand, whereas that of Thai Jasmine rice, parboiled rice and coloured rice are in the central region. The white rice can be grown in the central, north and northeast regions (Fig. 1). There are two crops cycles in general, the major rice is commonly grown during raining season while the second rice is mostly cultivated in the area with sufficient irrigation water (Rice Department 2016). In 2017, it was reported that the country had a total water requirement at the national level of about 27,831 m³ (Institute for Good Governance Promotion 2017). The central region has the highest irrigated area accounting for 47%, followed by the northeastern region (19%), the southern region (13%), the eastern region (8%), the western region (7%) and the northern region (6%). The soil quality in the central region is mainly clay from river sediments, which is much more suitable for agricultural activities than other regions where the soils are mostly sandy.

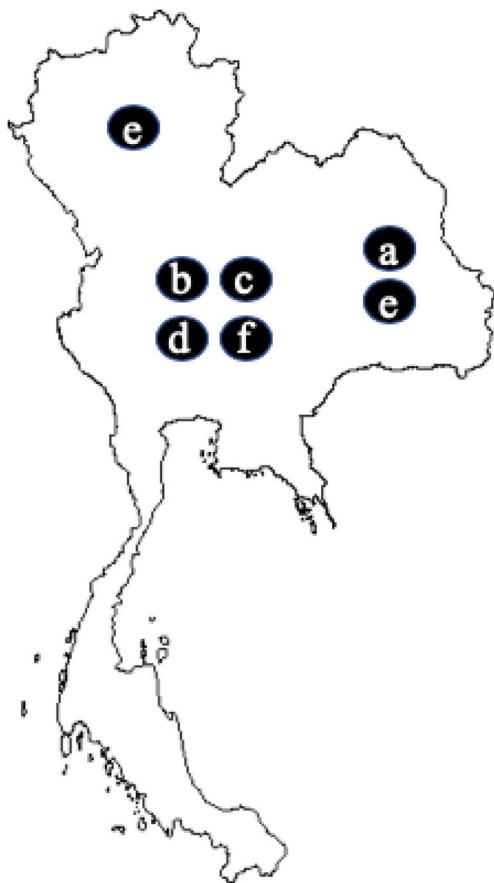


Fig. 1 The map showing key rice cultivation areas in Thailand ((a) Thai Hom Mali rice, (b) Thai Jasmine rice, (c) white rice, (d) parboiled rice, (e) sticky rice and (f) coloured rice: riceberry

The statistical data of rice cultivation area and production in 2016 were used as the basis for sampling to cover 62% of the national annual production with a 90% confidence interval (MTEC 2012). The total cultivation areas were sampled by using the published data from national statistical data (Bureau of Agricultural Economics and Department of Agricultural Extension 2016). The sample size was defined according to the sampling method described in Yamane (1967) as per Eq. (1).

$$n = \frac{N}{1 + Ne^2} \quad (1)$$

- n = corrected sample size
- N = population size
- e = margin of error (MoE), $e = 0.05$

As a whole, the rice types included were white rice, sticky rice and colour rice. Five white rice groups with the main rice species cultivated in Thailand were identified accordingly: Thai Hom Mali rice (Khao Dok Mali 105); (2) Thai jasmine rice (Pathumthani 1); (3) white rice, short-lived species (Phitsanulok 2); (4) White rice, long-lived species (RD41); and (5) Parboiled rice (Chainat 1). Two sticky rice groups with the main rice species cultivated in Thailand are (1) major rice (RD6) and (2) second rice (San Pah Tawng 1). For the coloured rice, riceberry was specified as the main species grown in the country (Table 1). In total, there are eight main cultivated rice species included in this study. Thai Hom Mali rice is predominantly grown with the highest cultivation area and maximum production (Table 1).

The samples were obtained from the main cultivation areas of each rice species. The total number of samples was 817, covering 114 samples of Khao Dok Mali 105, 103 samples of Pathumthani 1, 103 samples of Phitsanulok 2, 112 samples of RD41, 112 samples of Chainat 1, 103 samples of RD6, 70 samples of San Pah Tawng 1 and 100 samples of riceberry. The main cultivation areas for Khao Dok Mali 105 are in Ubon Ratchathani, Si Saket and Nakhon Ratchasima provinces. Pathumthani 1 species is grown mostly in Chainat, Suphanburi and Uttaradit provinces. Sukhothai, Phitsanulok and Kamphaeng Phet provinces are the main cultivation area for Phitsanulok 2. The cultivation areas for RD41 are mainly in the central region: Nakhon Sawan, Suphanburi and Ayutthaya provinces. Chainat 1 is cultivated mostly in Nakhon Sawan, Nakhon Ratchasima and Phetchabun provinces. RD6 is grown in the northeastern region: Khon Kaen, Sakon Nakhon and Udonthani provinces, while San Pah Tawng 1 is mostly cultivated in the northern region: Chiang Mai, Lampang and Phrae provinces. Riceberry spreads around

Table 1 The cultivation areas and main production sites of the eight rice species included in this study

Group	Rice species	Cultivation area (ha)	Main production sites (region)
Thai Hom Mali rice	Khao Dok Mali 105	468,053	Northeast
Thai Jasmine rice	Pathumthani 1	5193	Centre
White rice	Phitsanulok 2	48,8953	Centre
	RD41	33,022	Centre
Parboiled rice	Chainat 1	7875	Centre
Sticky rice	RD6	184,982	Northeast
	San Pah Tawng 1	10,238	North
Coloured rice	Riceberry	345	All over the country

the country, but is mostly grown in the central region especially in Kamphaeng Phet, Singburi and Lopburi provinces.

2.2 Water inventory data

The water footprint inventory data associated with the eight main cultivated rice species were gathered in accordance with the methodology described in ISO 14046 Water Footprint (ISO 14046 2014). The inputs and outputs associated with each rice cultivation stage were identified (Fig. 2). The related water footprint inventory data based on the crop production in 2017 were collected by interviewing the sampled farmers accordingly (Table 2). The inventory data related to the rice species, size of cultivation area, planting cycle and production yield, diesel use for agricultural machines and type and application rate of chemicals (fertilizers, herbicides and pesticides) were obtained from the field. For the crop water requirement, the amounts of rainfall in particular areas were collected from the national statistical data (Thai Royal Irrigation Department 2011). The total water requirement considered the water level of flooded systems that were gathered through the farmer interviews and the amount of water use for rice cultivation calculated in addition to the crop water requirement. On top of that, the farmers were interviewed about the farming management practices including straw and stubble management. The collected water footprint inventory data were validated by comparing the results with previous studies (Mungkung et al. 2016; Gheewala et al. 2013a, b; Chapagain and Hoekstra 2010; Allen et al. 1998) as well as the data validation through the expert consultation from the Department of Rice.

2.3 Water scarcity footprint

The crop water requirements under different climate conditions were calculated with consideration of crop evapotranspiration, crop coefficient, reference crop evapotranspiration and deep percolation by Eqs. (2)–(5).

$$ET_c = K_c \times ET_0 \quad (2)$$

$$CWR = \sum(ET_c + DP) \quad (3)$$

- ET_c is the crop evapotranspiration (mm/day)
- K_c is the crop coefficient (dimensionless)
- ET_0 is the reference crop evapotranspiration (mm/day)
- DP is the deep percolation (mm/day)

$$\text{Rain watercrop} = \frac{\text{Rain water use}}{\text{Yield}} \quad (4)$$

$$\text{Irrigation watercrop} = \frac{\text{Irrigation water requirement}}{\text{Yield}} \quad (5)$$

ET_c was calculated using Eq. (2) with values of K_c and ET_0 obtained from Penman Monteith equation (Royal Irrigation Department 2011). The crop water requirement was then estimated using Eq. (3), where DP was estimated from the deep percolation loss in the central region which is 1 mm/day while that of other parts is 1.5 mm/day (Royal Irrigation Department 2011; Meteorological Department 2012). The effective rainfall was calculated based on the actual rainfall obtained from the Thai Meteorological Department. The rain water and irrigation water requirements per kilogramme paddy rice were then calculated by Eqs. (4) and (5). It should be noted here that the total water use additionally included the water used for flooded systems as well as the water used for soaking the seeds (Table 4). The irrigation water requirement was calculated as the difference of crop water requirement and effective rainfall, in case the effective rainfall was lower than the crop water requirement. In case effective rainfall was higher than the crop water requirement, then the irrigation water requirement was 0. Example calculations are shown in Table 3.

The water scarcity footprint was then calculated by taking into account the water stress index (WSI) of different local watersheds obtained from the previous study (Gheewala et al. 2014). The WSI values of relevant watersheds associated with the main production sites of 8 rice species included in this study are listed in Table 2. The calculation method is specified in Eq. (6).

$$\text{Water scarcity footprint} = \text{Irrigation water} \times \text{WSI} [\text{m}^3\text{H}_2\text{Oeq}/\text{t}] \quad (6)$$

- Irrigation water is the crop irrigation requirement (m^3/t paddy rice)
- WSI is the water stress index

To demonstrate how the calculations were done, the RD41 rice species was used as the example. The cultivation area was 0.96 ha; cultivation was started on 1st July and harvesting done on 28th October with 5188 kg/ha paddy yield. Tables 3 and 4 provide the detailed calculations of the RD41’s crop water requirement and the total water consumption of RD41 as an example.

3 Results and discussion

3.1 Water footprint inventory analysis

The rice cultivation patterns vary by different geographical locations, weather conditions, management practices and accessibility to irrigation systems. In this study, around 78% of the sampled rice fields were located in the irrigation zones and 22% were outside the irrigation zones. It was revealed that most of sampled species were grown once a year only in the wet season (i.e. Khao Dok Mali 105, RD41, Chainat 1, RD6, San Pah Tawng 1 and riceberry), whereas the others were grown twice a year (Pathumthani 1 and Phitsanulok 2). Normally, the second rice is grown in the areas with sufficient water for cultivation or in irrigated zones (Rice Department

Table 2 The WSIs of relevant watersheds

Region	Watershed	WSI
Northern	Ping	0.023
	Wang	0.021
	Yom	0.044
	Nan	0.015
Northeastern	Chi	0.471
	Mun	0.927
Central	Chao Phraya	0.339
	Sakae Krang	0.031
	Pasak	0.050
	Thachin	0.287
	Petchaburi	0.022

2016). However, the paddy yields vary in different regions applying diverse cultivation systems and management practices. In the northern and central regions, overall, the farmers are likely to apply higher amount of chemicals with the expectation of obtaining higher yields. In contrast, farmers in the northeastern region relied only on rainwater and did not add other supplements. As a consequence, the rice yields in the northeastern region was lower than that in the other parts (Table 5).

The water footprint inventory analysis results indicated that the average total water requirement of eight rice species was $1557 \text{ m}^3/\text{t}$ paddy rice or $10,714 \text{ m}^3/\text{ha}$ (Table 5). The nationwide average paddy yield was 4413 kg/ha and the crop water requirement was $6340 \text{ m}^3/\text{ha}$. The results in this study were very similar to the previous studies (Chapagain and Hoekstra 2004; Hoekstra et al. 2011; Allen 1998). Overall, it was also found that the water footprint inventory value of second rice was higher than that of the major rice. The water footprint inventory results varied

Fig. 2 The inputs and outputs associated with the rice cultivation stages

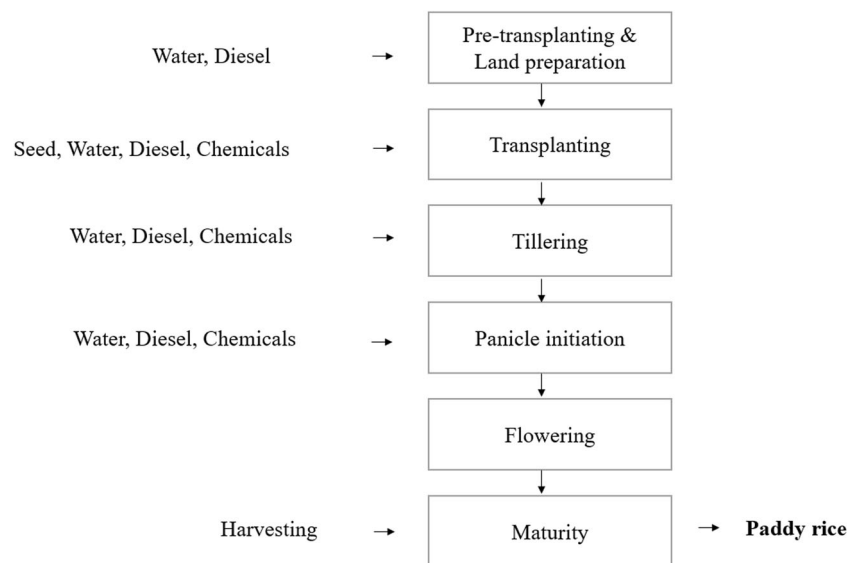


Table 3 Calculation of the RD41's crop water requirement

Inventory	Crop cultivation period			
	Jul	Aug	Sep	Oct
(1) Number of day (days)	31	31	30	28
(2) K_c of rice	1.13	1.57	1.54	0.87
(3) ET_0 (mm/day)	3.73	3.68	3.36	3.46
(4) $ET_c = K_c \times ET_0$ (mm/day)	4.21	5.78	5.17	3.01
(5) Deep percolation (DP) (mm/day)	1	1	1	1
(6) $ET_c + DP$ (mm/day)	5.21	6.78	6.17	4.01
(7) CWR (mm/month)	162	210	185	112
(8) Average rainfall in Ayutthaya province (mm/month)	133	77	146	101
(9) Effective rainfall by the Irrigation Department method (Irrigation Department 2013)	93	62	102	71
(10) Rainwater (mm/month)	93	62	102	71
(11) Irrigation water requirement (IR) (mm/month)	69	149	83	42
(11) Rainwater requirement (m^3/rai)	149	99	164	113
Rainwater requirement (m^3/ha)	931	619	1025	706
(12) Irrigation water requirement (m^3/rai)	110	238	133	67
Irrigation water requirement (m^3/ha)	688	1488	831	419
(13) Crop water requirement (m^3/rai)	259	336	296	180
Crop water requirement (m^3/ha)	1619	2100	1850	1125

due to different conditions of soil types, weather conditions, crop coefficients, percolation losses and yields. The crop water requirements were affected by those factors. Khao Dok Mali 105 rice was identified as the species with highest average total water requirement at 2726 m^3/t paddy rice, whereas the RD41 rice had the lowest average total water requirement at 1086 m^3/t paddy rice. Both Khao Dok Mali 105 and RD6, being grown in the northeastern region where the rainfall was lesser with higher deep percolation and crop evapotranspiration, had the highest crop water requirement. At the same time, the lower amount of inputs led to the lower paddy yield.

Table 4 Calculation of the total water consumption of RD41

Inventory	Quantity
1. Crop water requirement (m^3/rai)	1071
2. Other water use	
2.1 1st flooding (cm)	10
2.2 2nd flooding (cm)	10
2.3 3rd flooding (cm)	10
2.4 Water used for soaking the seeds (m^3)	241
Total water use for flooded (m^3/rai)	480
3. Total water consumption (m^3/rai)	1792
Total water consumption (m^3/ha)	9935

At 1 mm of deep percolation in 1 rai area = 1.6 m^3 of water (Royal Irrigation Department 2015)

3.2 Water scarcity footprint assessment

The weighted average water scarcity footprint of the eight rice species was 286 m^3H_2Oe/t paddy rice. Comparing among the eight different rice varieties, it was revealed that Khao Dok Mali 105 had the highest while San Pah Tawng 1 had the lowest water scarcity footprint value (Fig. 3). The highest water scarcity footprint found in Khao Dok Mali 105 was mainly because its higher irrigation water associated with higher irrigation water requirements along with the location of rice farms in the northeastern region where the WSI value was also higher. The lowest water scarcity footprint found in San Pah Tawng 1 was linked with the lowest irrigation water requirements resulting from the higher amount of rainfall together with the lower deep percolation and crop evapotranspiration.

3.3 Water scarcity footprinting of a rice product

To demonstrate how to adopt the water footprint inventory national database for water footprint labelling, the water scarcity footprint of Thai Hom Mali 105 rice product produced by the Research and Development Center for Farmers, Lopburi province, Kasetsart University was calculated. The unit of analysis was 1 kg of Thai Hom Mali 105 rice in linear low-density polyethylene (LLDPE) plastic bag. The water footprint inventory data of rice farming stage was obtained from the water footprint inventory data sets collected in the study. The inputs and outputs associated with the rice milling and processing (packaging) stages were identified and collected

Table 5 Water footprint inventory results of different rice species

Rice species	Yield (kg/ha)	Crop water requirement (m ³ /ha)	Rainwater (m ³ /ha)	Irrigation water demand (m ³ /ha)	Total water requirement (m ³ /ha)	Water inventory (m ³ /t)	Irrigation water demand (m ³ /t)	Rain water demand (m ³ /t)
Khao Dok Mali 105	2609	7491	2675	5243	10,969	2726	975	2010
RD6	3042	7572	1807	5336	10,153	2586	1683	1754
Riceberry	4327	6110	2169	4381	10,588	1376	1995	1012
Chainat 1	4695	6137	1468	3395	10,816	1310	3198	723
Phitsanulok 2	4688	5741	7995	4826	10,150	1160	586	1029
Pathumthani 1	5615	6248	7063	5037	10,984	1110	795	897
San Pah Tawng 1	5229	5906	2274	4283	10,695	1104	2300	819
RD41	5458	6050	1676	4001	11,275	1086	3257	733
Weighted average value	4413	6340	3414	4579	10,714	1557	1832	1143

through the interviewing of producers along the supply chain. The inventory analysis results indicated that to produce 1 kg of paddy rice, the following inputs were used: 0.043 kg of seed, 0.052 kg of diesel for land preparation and harvesting, 0.038 kg of diesel for water pumping inside the rice field, 0.247 m³ of water, 0.029 kg of 16-16-16 fertilizer, 0.014 kg of 0-0-60 fertilizer and 0.031 kg of 46-0-0 fertilizer for rice cultivation. At the rice mill, 0.421 kWh of electricity was used for rice milling, 2×10^{-4} kWh of electricity was used for packaging and 1.4×10^{-5} kWh of electricity was used for printing on packaging.

The results showed that water scarcity footprint of Thai Hom Mali 105 is 407 LH₂Oe/kg. The raw material acquisition stage significantly contributed to the water scarcity footprint, accounting for 89% of the total water scarcity footprint (Table 6). The rice cultivation stage was highlighted as the key contributor, accounting for 89% of the total water scarcity footprint. The rice milling and packaging stage contributed to total water scarcity footprint only at 7%, whereas the contribution from distribution, consumption and waste disposal were negligible. The water footprint inventory data sets

developed in this study could be useful for supporting the development of national databases as well as the implementation of water footprint labelling scheme.

3.4 Water policy analysis

The study also demonstrated the application of water footprint database in order to assess the risk of area-based water management scenarios. Six scenarios (S1–6) were included in this study: some referred to the current national policy options (Ministry of Agriculture and Cooperatives 2017) while some options were proposed from this study (Table 7).

3.4.1 S1: the national water scarcity footprint for annual rice production

The national water scarcity footprint for annual rice production was calculated in this scenario by using the area of rice cultivation (4.38 Mha) and yield (3588 kg/ha) in 2016. Thus, the national water scarcity footprint was 2.25 million m³H₂Oe or 85,630 m³ H₂Oe/ha/year with around 15 Mt paddy rice by

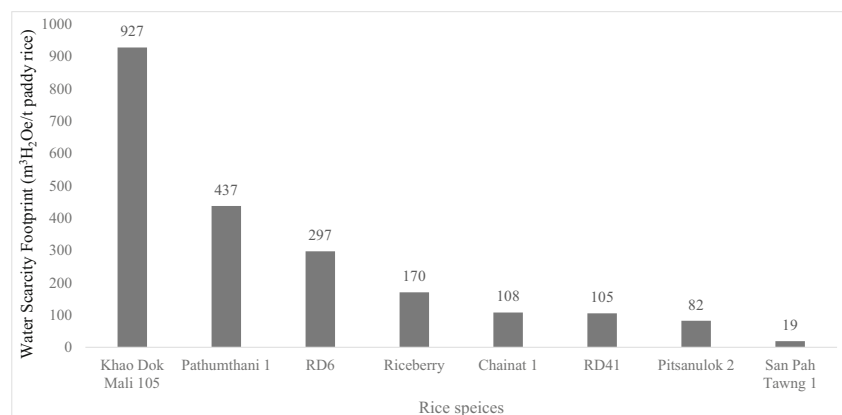
Fig. 3 Water scarcity footprint values of different rice species

Table 6 The water scarcity footprint value of 1 kg Thai Hom Mali 105 rice

Life cycle stage	Water scarcity footprint (LH ₂ Oe/kg)	Contribution (%)
Raw materials acquisition (including rice cultivation and packaging production)	361.91	89.74
Production (rice milling and packaging)	42.53	10.46
Distribution	0.00	0.00
Consumption	3.28	0.81
Waste disposal	1.14E–09	0.00
Total	406.72	100.00

using the WSI value of Thailand (Pfister et al. 2009a, b). Thailand's water scarcity footprint for rice cultivation was 334 m³H₂Oe/t paddy rice. The highest water scarcity footprint rice species was Khao Dok Mali 105 because it was grown mainly in the Mun and Chi watersheds with highest WSI values (Table 2). Moreover, Khao Dok Mali 105 is a photoperiod sensitivity rice with a higher K_c value than that of non-photoperiod sensitivity species, thus leading to the higher ET₀ value (Table 8).

3.4.2 S2: shifting the cultivation period to the period when the average rainfall was higher

This scenario proposed to adjust the cultivation calendar by using 30-year average rainfall statistical data from the Meteorological Department and the Bureau of Hydrology and Water Management (Thai Royal Irrigation Department 2015). Normally, the in-season rice (major rice) and the off-season rice (second rice) had been grown during May to August and January to April. The yield in May was also lower because of the lower amount of rainwater. Moreover, the yield in August was significantly increased as compared to the eight-year average rice production yield as well as the yield

of 2014/2015 crop production cycle (Rice Department 2016). The crop production cycle was then recommended to shift to June to September for the major rice and February to May for second rice, respectively. Khao Dok Mali 105 was selected to demonstrate the calculation, because of highest production and most-intensive water use. The results indicated that the shifting of crop production cycle could potentially reduce the crop water requirement by only 1.35% and decrease the total water requirement by lesser than 2% due mainly to the higher yield (Table 9).

3.4.3 S3: total water requirement for rice cultivation with a drought situation

This scenario applied the present crop water requirement in 2017 with the lowest average rainfall year in 2015 as the assumption of a drought situation. The 30-year average rainfall statistical data was used to calculate the present crop water requirement (Thai Royal Irrigation Department 2011). Pathumthani 1 was selected to demonstrate the calculation, as it was normally grown twice a year and the drought issue could take place during the second crop production over January–April. The results indicated that the drought situation

Table 7 Descriptions of six different scenarios for policy analysis

Scenario (S)	Description
1	This scenario was proposed in this study by calculating the water footprint at national level for annual rice production to support the national policy decisions on water resource management in agriculture activities
2	This scenario was proposed in this study by considering the fluctuating weather conditions with a suggestion that the cultivation period could be shifted to the period when the average rainfall was higher in order to reduce the irrigation water demand
3	This scenario was proposed in this study by the water footprint at national level for annual rice production if facing with a drought situation to support the national policy decisions on water resource management in agriculture activities
4	This scenario was developed from the present national policy on the implementation of alternate wet and dry (AWD) farming system instead of continual flooding system
5	This scenario was developed from the existing national policy on the replacement of rice with sugarcane in some selected areas
6	This scenario was developed from the existing national policy on the replacement of rice with cassava in some selected areas

Table 8 Total water requirement for national rice cultivation

Rice species	Water scarcity footprint (m ³ H ₂ Oe/t paddy rice)	National production (Mt/year)	Total water requirement (m ³ /ha/year)
Khao Dok Mali 105	587	1.64	10,969
RD6	559	5.91	10,695
Riceberry	302	0.002	10,984
Phitsanulok 2	297	2.07	10,588
Pathumthani 1	275	1.13	10,153
San Pah Tawng 1	243	0.47	11,275
RD41	221	3.26	10,816
Chainat 1	220	0.32	10,150
Total	334	14.80	

could possibly reduce the crop water requirement by 4.8% and total water requirement by 2.7% for Pathumthani 1 (Table 10). That happened because of the lower effective rainfall leading to the higher irrigation water requirement (increasing from 1.29 to 1.38 m³/t). In addition, the water scarcity footprint value was also higher due to higher irrigation water requirement (increasing from 439 to 467 m³H₂Oe/t paddy rice).

3.4.4 S4: implementation of AWD farming system instead of continual flooding system

This scenario was developed from the present national policy on the implementation of AWD farming system instead of continual flooding system as a way of reducing the water demand during the period of flooding system. The principle of AWD is to drain the water out of the rice field at the suitable time so as to induce the enhancement of stem and root strength, increase the yield, as well as reduce the water use (Thai Royal Irrigation Department 2015). The first flooding water level is 5 cm before the tillering stage. During the flowering stage, the water level will be increased to 7–10 cm. After that, the rice field will be dehydrated during the 35–45 days of rice cultivation period for 11 days. Then, the water will be flooded again (Fig. 4). The Department of Rice has been promoting the AWD rice farming system because it was reported in several studies that AWD could potentially reduce the water demand for flooding 20–40% (Sriphirom et al. 2018; Thai Royal Irrigation Department

Table 9 The water inventory, crop water requirement and total water requirement of Khao Dok Mali 105 with the shifting of production cycle

Items	Normal	Adjusted cultivation calendar
Crop water requirement (m ³ /ha)	7715	7611
Total water requirement (m ³ /ha)	11,193	11,009
Water inventory (m ³ /t)	2957	2917

2015; Rejesus et al. 2011; Thai Royal Department Irrigation 2011; Kürschner et al. 2010).

In this study, the total water requirement of AWD rice farming system was assumed to reduce the water use for flooding system as it was flooded twice instead of thrice during normal cultivation. RD6 was selected to demonstrate the calculation, as it is one of the AWD demonstration sites conducted by the Thai Royal Irrigation Department (2015). The result indicated that the AWD method could potentially reduce the total water requirement reduce by at least 7.5% (Table 11).

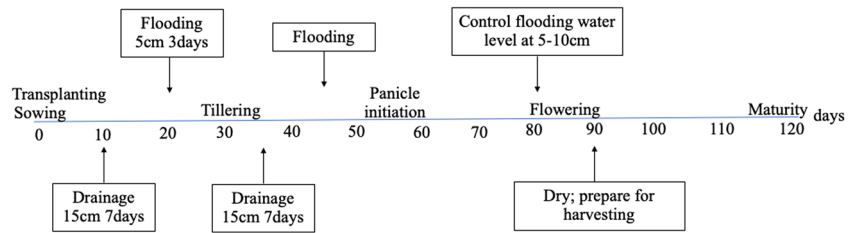
3.4.5 S5: total water requirement with the replacement of major rice with sugarcane in some selected areas

This scenario was developed from the national policy on the replacement of major rice with sugarcane covering 109,450 ha in 17 provinces in all regions of the country (Office of Agricultural Economics 2018). Over those 17 provinces, RD6 rice species was found as the largest cultivation area (55%) and used to demonstrate the calculation of total water requirement. It should be noted here that the sugarcane production cycle was from January–October, while the major rice production cycle as from May–August. Therefore, the crop water requirement of sugarcane would become much higher because of longer production cycle. The 30-year average rainfall statistical data was used to calculate the present crop water requirement (Thai Royal Irrigation Department 2015). The irrigation water of sugarcane production was taken from the secondary data (Department of Water Resource 2011). It is

Table 10 The water inventory, crop water requirement and total water requirement of Pathumthani 1 in the year with a drought situation

Items	Normal	Drought year
Crop water requirement (m ³ /ha)	12,420	11,827
Total water requirement (m ³ /ha)	21,968	21,375
Water inventory (m ³ /t)	2212	2106

Fig. 4 Flowchart of the AWD method



worth mentioning that the productivity of sugarcane in terms of yield per cultivation area is almost 16 times higher than rice. Shifting from rice to sugarcane cultivation could potentially reduce water inventory per tonne productivity around 94% (Table 12). This was largely affected by the lower crop coefficient. The results also indicated that the replacement of major rice (RD6) with sugarcane in the selected 17 provinces could possible increase the crop water requirement by about 21% but reduce the total water requirement by almost 10% (Table 12). Interestingly, the water scarcity footprint was hugely reduced by almost 80% when replacing rice with sugarcane.

3.4.6 S6: total water requirement with the replacement of major rice with cassava in some selected areas

This scenario was developed from the existing national policy on the replacement of rice with cassava covering 35,581 ha in 33 provinces spreading in all regions of the country (Office of Agricultural Economics 2018). RD6 rice species was found as the largest cultivation area (68%) in those 33 provinces and used to demonstrate the calculation of total water requirement. It should be noted here that the cassava production cycle was from January to December, while the major rice production cycle as from May to August. Therefore, the crop water requirement of cassava would become much higher because of much longer production cycle. The 30-year average rainfall statistical data was used to calculate the present crop water requirement (Thai Royal Irrigation Department 2015). The irrigation water of cassava production was taken from the secondary data (Department of Water Resource 2011). It is worth mentioning that the productivity of cassava in terms of yield per cultivation area almost 6 times higher than rice. The results indicated that replacement of major rice (RD6) with cassava in the selected 33 provinces could possible increase the crop water requirement for about 75% and increase

the total water requirement for almost 30% (Table 13). Shifting from rice to cassava cultivation could potentially reduce water inventory per ton productivity around 75% (Table 13). The water inventory was significantly reduced because of the crop water requirement per yield was much lower. The increasing crop water requirement was largely affected by the lower crop coefficient and much longer production cycle. The increasing total water requirement was largely affected by the lower crop coefficient. It was revealed that the water scarcity footprint could possibly be reduced by almost 68% when replacing rice with cassava.

Comparing the results of different policy option scenarios, the shifting of the cultivation to the period when the average rainfall was higher could slightly decrease the amount of total water requirements, whereas the implementation of AWD farming system instead of continual flooding system would moderately reduce the amount of total water requirements. In case of replacing rice with sugarcane/cassava, it was found that the water scarcity footprint could potentially be reduced by around 68–82% which would ideally be the best option. For making the policy decision, relevant socio-economic factors must be taken into account, such as skill of farmers, income from growing sugarcane/cassava compared to rice and location of sugarcane/cassava processing factories.

4 Conclusions

The water footprint inventory data and the water scarcity footprint values would be reviewed by a national expert board as well as a stakeholder consultation to finally approve the datasets as the water footprint national database. It is expected to use the water footprint national database for more effective water resource management for rice cultivation and to support

Table 11 The water inventory, crop water requirement and total water requirement of RD6 with AWD systems

Items	Normal	AWD
Crop water requirement (m ³ /ha)	7577	7577
Total water requirement (m ³ /ha)	10,158	9394
Water inventory (m ³ /t)	2491	2491

Table 12 The water inventory, crop water requirement and total water requirement of water requirement of RD6 if replacing the major rice (RD6) with sugarcane in some selected areas

Items	Normal	Sugarcane
Crop water requirement (m ³ /ha)	7577	9190
Total water requirement (m ³ /ha)	10,158	9190
Water inventory (m ³ /t)	2491	157
Water scarcity footprint (m ³ H ₂ Oe/t yield)	295	55

Table 13 The water inventory, crop water requirement and total water requirement of water requirement of RD6 if replacing the major rice (RD6) with cassava in some selected areas

Items	Normal	Cassava
Crop water requirement (m ³ /ha)	7577	13,242
Total water requirement (m ³ /ha)	10,158	13,242
Water inventory (m ³ /t)	2491	598
Water scarcity footprint (m ³ H ₂ Oe/t yield)	295	93

the decisions on the national water policy especially which areas should not grow rice twice a year due to a high risk of water scarcity as well as the potential increasing of water scarcity associated with the policy options on replacing rice with sugarcane or cassava. All scenarios offered the different options for reducing the water use and impacts from rice supply chain especially rice farming. However, the most suitable that can be quickly implemented was to shift the crop calendar according to the rainfall together with the AWD system to additionally reduce the water use. Recently, the water footprint labelling system was initiated and developed by the Water and Environmental Institution for Sustainability, the Federation of Thai Industries, with the first focus on water scarcity footprint. The water footprint methodology was according to ISO 14046 and the WSI of 25 local watersheds were applied. The rice databases developed in this study would also be useful for supporting the calculation of water footprint of rice products as well as other products using rice as a raw material towards the application of water scarcity footprint label.

Acknowledgments Acknowledgement is given to the Agricultural Research Development Agency (Public Organization) under the project “Water footprint databases of rice farming for area-based water management and water footprint label” (Grant No. PRP6005020020) for the financial support.

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